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Energy Efficient Topology Control in Wireless Sensor Networks with Considering Interference and Traffic Load†,*

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Energy conservation and interference reduction are the two important goals of any topology control algorithms in wireless multi-hop sensor networks, but impacts of network traffic load on interference have been largely ignored in mostly all previous works on topology control algorithms. Inspired by this challenge, we set out to investigate the impact of traffic load on nodes' energy consumption and having demonstrated its significance and, a relation between traffic load and interference was established by using collision numbers. Then we went on to formulate an optimization model for our topology control with the goal of minimizing the maximum power consumption among network's nodes. Analysis showed that due to the NP-hardness of the preliminary model it could not be used to achieve our objective in a reasonable time span.

Thus, to overcome the shortcoming of optimization model, a novel heuristic algorithm called cell based optimization tree (CBOT) was finally introduced that was capable of constructing a suboptimal topology in a reasonable time bound by considering traffic load and interference. Simulation results verified superiority of the proposed approach over a number of reported techniques in the literature.

Keywords: Interference Reduction, Nonlinear Programming, Topology Control, Wireless Sensor Networks.

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1 INTRODUCTION

A wireless sensor network consists of a number of small sensor nodes that communicate with each other in a wireless fashion. Due to the nature of these networks, it is difficult or at times impossible to recharge or replace their batteries. This necessitates devising novel energy-efficient solutions for wireless sensor network and already major efforts are being made to develop energy-aware techniques that preserve battery power.

In particular, network topology has a huge impact on energy efficiency of a sensor network. Hence, the availability of a practical and effective control on the network topology is fundamental to achieving the desired efficiency [1].

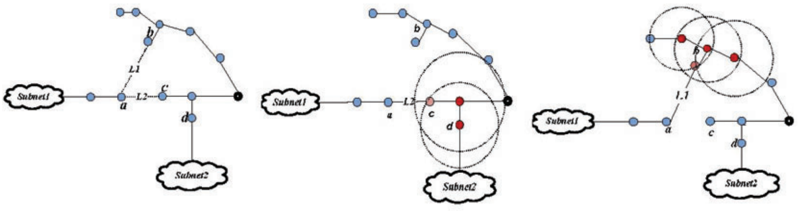
Preliminary studies on topology control such as the Delaunay Triangulation [2], Gabriel Graph [3], the minimum spanning tree [4], and the Relative Neighborhood Graph [5], solved topology control problem based on computational geometry structure. Since these algorithms were not computable locally, the second wave of topology control algorithms emphasized on locality. However, the reduction of interference is considered as one of the foremost goals of these topology control algorithms, it is often argued that sparse topologies with small or bounded degree are well suited to minimizing interference. However, Burkhart in [6] showed that low degree and small transmission power do not necessarily imply low interference and proposed a graph based definition of interference. He argued that if a set of V nodes are dispersed in environment and $D(u, r)$ be the disk centered at node u of radius r and requiring edge symmetry, the overall interference of edge e (between u and v nodes) could be defined as follows:

$$I\left(e\right)=\left|\left\{w\middle|w\in V\setminus\{u,v\},w\ is\ covered\ by\, D\left(u,|u,v|\right) or\, D(v,|v,u|)\right\}\right| \tag{1}$$

Most of interference aware topology control algorithms have used a graph based definition of interference [7-9] and a few ones such as [10] have proposed a physical model of interference.

Interference in wireless networks causes to reduce the signal to noise and interference ratio (SINR). If the SINR lies below a certain threshold then collision will be occurred,thereby the sender node have to retransmit the collided packets. Hence, traffic load on interfered and interfering nodes is obviously a major concern which should be considered in topology control algorithms. However, to the best of our knowledge, the impacts of traffic load on interference have been largely ignored in almost all interference aware topology control algorithms.

Existing topology control algorithms take the closest neighbors as logical neighbors and communicate with them. We argue that if the closest node lies within interference range of a number of high loaded nodes, occurrence of collision causes huge amount of energy waste in sensors, e.g. consider some nodes with fixed and equal rate that are distributed in an area.



a) Initial nodes deployment b) Selecting L_2 by node a c) Selecting L_1 by node a

FIGURE 1
Example of wrong function of existing TC algorithms.

As shown in Figure 1(a), Subnet 1 and Subnet 2 are two distinct subnets and node *a* can choose either bidirectional links L_1 or L_2 as a logical link. If Node *a* selects the nearest node as a neighbor or selects a node according to (1) (i.e. $I(L_1) = 3$ and $I(L_2) = 2$), it will select node *c* as the logical neighbor (Figure 1(b)).

As depicted in Figure 1(b), node *c* has been located within interference range of the two other nodes. Since traffic incurred by subnet 2 is forwarding to node *d*, this node will be high loaded and most of the time will be in transmitting state. So, if node *a* forwards its traffic through L_2, node *c* lies within the interference range of high-loaded nodes and as a result node *a* will suffer from high energy consumption due to consecutive collisions on *c*.

Let us suppose that *a* selects node *b* as its logical neighbor instead of node *c* and forwards subnet1 traffic through L_1. As shown in Figure 1(c), although three nodes will interfere on *b*, these nodes are low-loaded and they are rarely in transmitting state. Consequently, this time interference has much less influence on network throughput and retransmission numbers are much smaller than the previous case. Although a farther away node has been chosen as logical neighbor and the destination node is within interference range of more nodes, node *a* will consume less energy because of lower number of retransmissions.

These arguments simply imply that traffic and interference are strictly correlated and consideration of interference alone could not achieve a viable topology control solution.Therefore, we solved the problem of topology control in WSNs as an optimization problem with the goal of minimizing maximum energy consumption among network nodes. Solving optimization problem will provide the optimal solution of network topology but because of Np-hardness property of this optimal solution, it is not practical in the large-scale network. However, topology obtained from optimization model could be used as a lower bound on network energy consumption. Furthermore, we put forward a heuristic algorithm to solve topology control problem by considering traffic and interference in acceptable time.

The rest of the paper is organized as follows: Section 2 presents related works and different topology control schemes. Section 3 describes the assumptions we make about the network environment and Computation of nodes energy consumption. Section 4 are devoted to the explanation of Mixed Integer Nonlinear Programming (MINLP) approach and heuristic algorithm, respectively. Simulations results and comparisons against other methods are the main topic of section 5. Finally, section 6 concludes the paper and suggests some future work.

2 RELATED WORK

In recent years great efforts have been made in literature to propose energy conserving topology control algorithms for wireless sensor networks [7-9,14].These algorithms are designed to meet different objectives such as minimizing network energy consumption while maintaining the network connectivity. These objectives can be achieved either by considering the interference or neglecting it. We will examine both options respectively, as follows:

2.1 Non Interference Aware Topology Control Algorithms

Li and Hou [4] devised a Local Minimum Spanning Tree (LMST) algorithm for topology control and management. In the algorithm, each node builds its local MST independently according to link weight which makes transmission power the first consideration. They have analytically proved that: a) the protocol preserves network connectivity, b) the node degree of any node in the generated topology is bounded by 6 c) by removing of all asymmetric links the topology could be transformed into one with bidirectional links without impairing connectivity. However, LMST requires location information that could be obtained only with a considerable hardware and/or message cost.

XTC [8] is a link quality based topology control algorithm that does not require availability of node position information. The algorithm operates with a general notion of a decreasing order of link quality over a node's neighbors. Nodes exchange the order information with its 1-hop neighbors, then they can select its neighbors in the final topology with respect to the link quality. XTC builds a topology which is connected whenever the max-power communication graph is connected. In [15], Zarifzadeh et al. formulate topology control problem as an optimization algorithm. They not only consider transmission range of node as a factor for topology control, but also take into account traffic load that each wireless node experiences. They proposed an approach based on mixed integer programming to achieve the optimal solutions.

All of these algorithms consider interference only superficially at most or not at all. However, newly emerging studies are no longer ignoring the impact of interference that we will investigate them in the following subsection.

2.2 Interference Aware Topology Control Algorithms

Interference aware topology control approach has also inspired a lot of research in recent years and a number of efficient solutions have been published that take interference constraint into account. Recent works on topology control have dealt with interference explicitly as a graph property, similar to other topology control properties. Burkhart et al. [6] present a traffic-independent model and defines the interference of a link $e = (u, v)$ as the cardinality of the set of nodes covered by two disks centers at u and v with radius $\|uv\|$. They also introduced two centralized methods, LIFE and LISE, for the MIN-MAX link interference with a property bounded Euclidean spanning ratio. LIFE simply employs Kruskal's algorithm to compute an interference-minimal structure while LISE finds the graph with the lowest possible maximum edge coverage that also is a Euclidean t-spanner. The authors also developed LLISE to further improve LISE which is a localized algorithm executed at all eligible edges of the given network.

Interference model used in [6] implicitly assume that the node u will send message to v and node v will send message to u at the same time. Moaveni-Nejad et al. in [16] argued that when u sends data to node v, typically node v only has to send a very short acknowledge message to u. Furthermore, they used a more realistic model of interference and state that interference on receiver node v occurs when v is inside the transmission region of sender u and inside the interference region of another node w, and both node u and node w transmit signal simultaneously. Then, they developed several centralized algorithms such that the maximum (or average) link (or nodal) interference of the topology was either minimized or approximately minimized.

In [9] Shen et al. proposed two distributed algorithm, the interference-aware local minimum spanning tree based algorithm (IALMST) and the interference-bounded energy-conserving algorithm (IBEC). IALMST builds local MST of each node independently with respect to the costs of interference and energy consumption. Also, in IBEC each node commonly selects the edge with the least energy consumption while the interference should not exceed a predefined bound.

While most of works on interference aware topology control adopted a graph based model of interference, Gau et al. in [10] derived a centralized algorithm called Spatial Reuse Maximizer (MaxSR) based on the physical model of SINR. MaxSR algorithm combined a power control algorithm T4P with a topology control algorithm P4T. T4P tried to optimize transmission range assignment to minimize the average interference degree while, P4T based on the power assignment made in T4P constructs a new topology by deriving a spanning tree that gives the minimal interference degree.

In [11] the authors proposed a Cooperative topology control scheme to improve the network capacity in MANETs by jointly considering both upper layer network capacity and physical layer cooperative communications. The topology control scheme presented in that paper tried to improve the network capacity in MANETs by jointly optimizing transmission mode selection, relay node selection, and interference control in MANETs with cooperative communications.

In [12] the authors present a solution for minimizing the average interference of a node while receiving a message. They assume the receiver centric interference model where the interference on a node is equal to the number of the other nodes whose transmission ranges cover the node. The authors proposed a polynomial algorithm that can minimize the average interference for one-dimensional (1D) networks based on the no-cross property and dynamic programming. In addition for two-dimensional (2D) networks using computational geometry, they proofed that the maximum interference can be bounded while minimizing the average interference. The bound is only related to the distances between nodes but not the network size. Based on the bound, their algorithm computes the minimum average interference in 2D networks.

In [13] an energy efficient and low interference topology control technique in wireless sensor networks was developed in the form of the SBYaoGG algorithm which is a variation of the standard Yao Gabriel graph with the regions boundaries depend on the distribution of neighbors around a node. Each node in the network makes local decisions about its transmission power and the culmination of these local decisions produces a network topology that preserves global connectivity. The SBYaoGG looks to develop as sparse a topology as possible with good power spanner properties. This is achieved by computing a Gabriel Graph from the original Unit Disk Graph and then computing the Yao Graph on the Gabriel Graph using smart region boundaries.

In [14] the authors formulized the problem of topology control in wireless sensor network as an optimization problem with the goal of minimizing maximum energy consumption among network nodes. In that paper they formulated traffic and interference aware topology control problem as a mixed integer nonlinear programming (MINLP) algorithm. However, the optimal solution of interference aware topology control has been presented in that paper is unable to find such optimal solutions within polynomial time due to the NP-hardness.

Nevertheless, what all these contributions have in common is they did not present a polynomial time algorithm that consider traffic influence on interference or consider it implicitly.

3 NETWORK ASSUMPTIONS

To begin discussion of the proposed algorithm, we first define the network assumptions. Investigated wireless sensor networks have the following features:

A set of n stationary nodes $V = \{v_1, v_2, \ldots, v_n\}$ that are uniformly distributed over a fixed $D * D$ square area. All nodes have Omni-directional antenna and can adjust their transmission power from 0 to P_{max}. Traffic generation rate in all nodes follows Poisson distribution with mean λ and we used single path routing in which all input traffic went out from one link. The lifetime span of the network is from the network start-up time till the first node of the network stops working.

We used a physical model of interference as follow:

Definition 1: Node $v_k \in V$ has been considered as *interfering* node v_j to on transmitting from node v_i to v_j if [10]:

$$\frac{p_t(i)d_{i,j}^{-\alpha}}{N + p_t(k)d_{k,j}^{-\alpha}} < \beta \tag{2}$$

Equation (2) indicates that if v_k is transmitting at power $p_t(k)$, no other simultaneous transmission can take place over link (v_i, v_j). In other words, if such simultaneous transmission were to occur, the receiver would not be able to detect the transmitted packets.

In order to transmit a bit-stream at rate r over Euclid distance d, the minimal power consumed by sender node is [15]:

$$E_t\left(a, d\right) = r * C * d^{\alpha} \tag{3}$$

Where C and α are a constant coefficient and the path loss exponent, respectively. We assume that $C = 1$ and α is 2 for the free-space communications.

4 PROPOSED METHOD

Earlier algorithms on interference aware topology control have not considered nodes traffic however, it is obvious that this factor has significant effects on interference. As expressed by (3), sender node's energy consumption has a direct relation with sender and receiver nodes' Euclidian distance and sender's traffic load. Moreover, collision with interfering nodes' packets can cause packets retransmission from sender, which increases energy consumption of sender node. Therefore, in order to determine nodes' energy consumption, the number of retransmissions needs to be computed.

If traffic generation rate follows Poisson distribution with mean of λ_u packets per second, then the rate of output traffic (Λ_u) will be computed as follows:

$$A_u = \{k \mid path\ of\ node\ k\ to\ sink\ goes\ through\ node\ u\}$$
$$\Lambda_u = \sum_{\forall k \in A_u} \lambda_k + \lambda_u packet\ /\ times\ lot$$

Where A_u is a set of nodes whose path to sink goes through node u, Λ_u is output traffic of node u per time slot where time slot is the time required to transmit one packet (i.e. time slot = L/B), L denotes packet size and B is transmission rate of wireless channel [17].

Lemma 1. If k_1 to k_m be nodes with their path to sink going through node u, then output traffic of u will follow Poisson distribution with mean of $\lambda'_u = \lambda_{k_1} + \lambda_{k_2} + \ldots + \lambda_{k_m}$.

Proof: This Lemma could easily be proved by definition of Poisson distribution ■

Given that in this context we are using single path routing and tree structure, there is only one output path for incoming traffic. Let v be next hop node of u where the traffic of u will be forwarded to v. Likewise, suppose that node w be an interfering node for node u, in this case due to collision, node v is not able to receive the transmitted packets of u. Since node u will not be receiving any acknowledgment for a while, the collision will be detected and node u will retransmit corrupted packets. Retransmitting corrupted packets cause additional traffic on the network. Hence, we now proceed to compute the expected number of required transmissions for successful detection of the packet by receiver node.

Lemma 2. The minimum number of node u required transmissions to send to node v in the presence of interfering node w is equal to:

$$n_{succ}(u,v) = 1 \Big/ 1 - \left(1 - e^{-\Lambda_u}\right)(1 - e^{-\Lambda_w})$$

Proof: Let Λ_u be the amount of traffic on link uv. As traffic follows Poisson distribution, the probability of transmitting l packets in node u will be:

$$P\left(l, \Lambda_u\right) = \frac{\Lambda_u{}^{l} e^{-\Lambda_u}}{l!}$$

So transmission probability of node u could be computed as follows [18]:

$$P_{Trans}(u) = 1 - P_{Idle}(u) = 1 - e^{-\Lambda_u}$$

Since the transmission of node *u* and *k* are independent, collision probability on *v* will be computed as follows:

$$p_{coll}(uv) = \left(1 - e^{-\Lambda_u}\right)(1 - e^{-\Lambda_w})$$

Thus the number of required transmissions to achieve the first successful transmission is:

$$n_{succ}\left(uv\right) = \frac{1}{p_{succ}\left(uv\right)} = \frac{1}{1 - p_{coll}\left(uv\right)} = \frac{1}{1 - \left(1 - e^{-\Lambda_u}\right)(1 - e^{-\Lambda_w})} \quad (4)$$

Therefore, energy consumed by sender to transmit Λ_u packets over distance *d* in the presence of interfering node *w* is given by [17]:

$$e\left(uv\right) = n_{succ}\left(uv\right) * \Lambda_u * C * d^{\alpha} = \frac{\Lambda_u * C * d^{\alpha}}{1 - \left(1 - e^{-\Lambda_u}\right)(1 - e^{-\Lambda_w})} \quad (5)$$

Since total traffic is the sum of new and retransmitted packets, there has to be a trade-off between each node's traffic and its neighbors' traffic. In order to establish this trade-off an optimized model interference aware topology control (OMIT) has been developed.

4.1 OMIT Model

According to (5), if a huge amount of input traffic is imposed on sender node and/or if receiver lies in the vicinity of high-loaded nodes then successive collisions will cause large amount of energy dissipation. Thus, instead of connecting to the nearest node, a farther node, (i.e. one that is in the vicinity of lower interference), can be selected as a logical neighbor. In this case, because of less retransmission sender node could save much more energy. On the other hand, sending traffic to a farther node at higher power not only causes more energy consumption of single packet transmission but also can place more nodes within interference range of this link. Therefore, a trade-off between sender node's traffic and traffic of the nodes that are interfering with the receiver node is needed.

We formulated traffic and interference aware topology control problem as a mixed integer nonlinear programming (MINLP) problem.

Let's begin by defining a set of notations which is used by the formulation [14]:

index	description
$x_{i,j}$	Boolean variable, with $x_{i,j} = 0$ if no link exists between node *i* and node *j;* otherwise $x_{i,j} = 1$
$x_{i,j}^{sd}$	Boolean variable, where $x_{i,j}^{sd} = 0$ if the route from s to d goes through the link (i, j); otherwise $x_{i,j}^{sd} = 1$
$f_{i,j}$	Amount of traffic passing through link (i, j)
V	Set of nodes in the network $\|V\| = n$;
V_s	Set of sink nodes in the network
Φ_i	Amount of output traffic passing through node *i,* including new and retransmitted traffic
δ_i	Distance between node *i* and its farthest logical neighbor
p_i	Transmission power of node *i*
$Pc_{i,j}$	Collision probability when transmitting from node *i* to node *j*
$I_{i,j}^{k}$	Boolean variable, where $I_{i,j}^{k} = 1$ if simultaneous transmission of nodes *k* with transmission *i* to *j* causes collision on reception of packet by *j*; otherwise $I_{i,j}^{k} = 0$
$Nsucc_{ij}$	Expected number of transmissions for successful transmission of *i* toward *j*
λ	Traffic generation rate of each node, following Poisson distribution
$d_{i,j}$	Euclidean distance between node *i* and *j*
R_{max}	Maximum transmission range of each node
$RXmin$	Threshold for the receiver to decode the received signal correctly
β:	SINR threshold

TABLE 1
Notations

OMIT formulation:

Optimization goal: Minimize the maximum energy consumption of nodes:

$$Minimize\,(\max_{\forall i \in V}(\Phi_i * \delta_i^{\alpha})) \tag{6}$$

Constraints:

$$\forall s \in V, d \in V_s, i \in V \bigcup V_s : \sum_{\forall j \in V \bigcup V_s} x_{i,j}^{s,d} - \sum_{\forall j \in V \bigcup V_s} x_{j,i}^{s,d} = \begin{cases} +1 & s = i \\ -1 & d = i \\ 0 & otherwise \end{cases} \tag{7}$$

$$\forall s \in V, d \in V_s, i, j \in V \bigcup V_s : x_{i,j}^{s,d} \le x_{i,j} \tag{8}$$

$$\forall i \in V : \lambda * \sum_{\forall s \in V, d \in V_s} \sum_{\forall j \in V \bigcup V_s} x_{i,j}^{s,d} = \lambda * \sum_{\forall s \in V, d \in V_s} \sum_{\forall j \in V \bigcup V_s} x_{ji}^{s,d} + \lambda \tag{9}$$

$$\lambda * \sum_{d \in V_s} \sum_{i,s \in V} x_{i,d}^{s,d} = n * \lambda \tag{10}$$

$$\forall s \in V : \lambda * \sum_{\forall d \in V_s} \sum_{\forall j \in V \bigcup V_s} x_{s,j}^{s,d} = \lambda \tag{11}$$

$$\forall i \in V \cup V_S : \max_{\forall j \in V \cup V_S} \{d_{i,j} * x_{i,j}\} \leq R_{max} \tag{12}$$

$$\forall i \in V : (\delta_i)^{\alpha} * RXmin \leq p_i \tag{13}$$

$$\forall i,k \in V, j \in V \bigcup V_s : I_{i,j}^{k} = \begin{cases} 0 & \beta * d_{i,j}^{\alpha} * p_k \leq d_{k,j}^{\alpha} * p_i \\ 1 & otherwise \end{cases} \tag{14}$$

$$\forall i \in V, j \in V \bigcup V_s : f_{i,j} = \sum_{\forall s \in V} \sum_{\forall d \in V_s} x_{i,j}^{s,d} \tag{15}$$

$$\forall i \in V, j \in V \bigcup V_s : Pc_{i,j} = \left(1 - exp(-f_{i,j})\right)\left(1 - exp\left(-\sum_{\forall k \in V} \Phi_k * I_{i,j}^{k}\right)\right) \tag{16}$$

$$\forall i \in V, j \in V \bigcup V_s : Nsucc_{i,j} = \frac{1}{1 - pc_{i,j}} \tag{17}$$

$$\Phi_i = \sum_{\forall j \in V \bigcup V_s} f_{i,j} * Nsucc_{i,j} \tag{18}$$

$$\sum_{i \in V \bigcup V_s} \sum_{j \in V \bigcup V_s} x_{ij} = 2(N-1) \tag{19}$$

$$\forall i,j \in V \bigcup V_s, \qquad x_{i,j} = x_{j,i} \tag{20}$$

Remarks: Constraint (7) is energy conservation constraint and ensures that an intermediate node continues to forward input traffic through output links. Constraint (8) states that no traffic can be directly exchanged between any two nodes if there is no link connecting them. Constraint (9) ensures that outgoing traffic from node *i* is equal to the sum of its own traffic and traffic that it relays. Constraint (10) means that all sensed traffic by sensor nodes arrive at sink nodes. Constraint (11) indicates that each node senses the environment and generates traffic at rate λ. Constraint (12) states that the transmission range of every node should be no higher than the maximum range $r_{\max}$. Constraint (13) implies that transmission power of each node must be at least equal to power required to reach a farther logical neighbor. Constraint (14) indicates whether or not there is a collision at receiver node j, due to simultaneous transmission, of node k and transmission of node i to j. Constraint (15) computes the traffic passing through every link. Constraint (16) computes probability of collision on a particular link. Constraint (17) computes the required number of transmissions for successful reception of packet. Constraint (18) means that output traffic of a particular node is equal to the sum of input and sensed traffic of node multiplied by the required number of transmissions for successful transmission. Constraint (19) ensures the treeness property of the network graph. Constraint (20) ensures that all links of network are bidirectional.

Unfortunately, the MINLP formulation under discussion is NP-hard which means, it is infeasible for any large scale network application. So, a Cell Based Optimization Tree (CBOT) algorithm has presented in next section.

4.2 CBOT Algorithm

Although, the optimal solution of interference aware topology control has been presented in the previous section, it is impossible to find such optimal solutions within polynomial time due to the NP-hardness of MINLP problems. To overcome this obstacle, we need to introduce a more advanced approach based on heuristic algorithm, namely CBOT, which solves the problem within an acceptable time.

In CBOT algorithm, a large-scale problem will be divided into smaller scale and solvable one by employing Divide and Conquer approach. The topology obtained by this technique is close to the optimal solution and could be achieved within a reasonable time span.

As mentioned in section 3, $|V| = n$ nodes uniformly distributed over a $D * D$ area. Each node has tunable transmission power between 0 and P_{max} where $G_{max}(V, E_{max})$ is communication graph induced when all nodes transmit at maximum power. Topology control algorithms aim to devise the sub-graph $G''(V, E'')$ from G_{max} in which E'' edges set is corresponds to logical topology links.

To perform algorithm, the network has been divided into $L * L$ $(L \leq D)$ cells. Suppose, these cells are numbered from 1 to m and let $\mathcal{M} = \{C_1, C_2, \ldots, C_m\}$ be the set of cells created over the network. The dividing of the environment causes that each sensor node lies exactly within one cell (i.e. subset V^{C_i} of network nodes will be inside cell C_i).

Now $\mathcal{M}'$ set can be constructed by removing the empty cells from $\mathcal{M}$ set as follows:

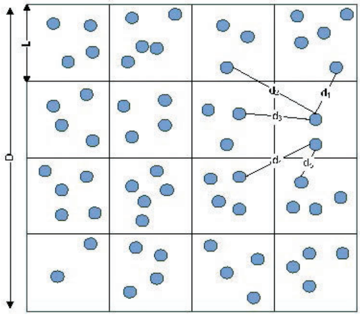


FIGURE 2
Dividing network into cells-d_i represents minimum distance between each cell and neighboring cell.

$$\mathcal{M}' = \{C_1, C_2, ..., C_{m'}\},\ m' \le m \qquad \text{Where } V = \cup_{i=1}^{m'} V^{C_i} \tag{21}$$

Definition 2: Two cells of $\mathcal{M}'$, say C_i and C_j, are neighbors, if at least one edge exists between sensor nodes in the C_m and C_n when each node transmits at maximum power.

Lemma 3. If $L = \frac{\sqrt{c} * D}{\sqrt{n}}$ then the expected number of nodes in each cell is equal to c.

Proof: Assume that we have a $D * D$ network with cells' dimension of $L * L$. Probability of locating each node within a cell is equal to:

$$\theta = \frac{L^2}{D^2} \tag{22}$$

So, probability distribution functions of locating x nodes in each cell is equal to:

$$b(x, n, \theta) = \binom{n}{x} \theta^x (1 - \theta)^{n-x} \quad x = 0, 1, 2, \ldots, n$$

The expected value of this function could be computed as:

$$\mu = \sum_{x=0}^{n} x . \binom{n}{x} \theta^x (1 - \theta)^{n-x} = n\theta$$

On the other hand, the expected number of nodes located within each cell is c:

$$n * \frac{L^2}{D^2} = c \Rightarrow L = \frac{\sqrt{c} * D}{\sqrt{n}} \ \blacksquare \tag{23}$$

Proposed algorithm has been fully illustrated in Algorithm 1.

ALGORITHM 1
Cell based topology control algorithm

```
Input:
  $V$: a set of sensor nodes in network environment
  $V_s$: Sink node
  $R_{max}$: maximum transmission range of nodes
  $G_{max}(V, E_{max})$ that is network graph when all nodes communicate with maximum transmission power.
Output:
  Network topology: $G''(V, E'')$ where $E''$ set of links between nodes in network
Begin
  Divide network environment in square with length $L = \frac{\sqrt{c} * D}{\sqrt{n}}$ we call each square a cell
  Create empty graph $G'(V', E')$ when $V'$ is set of network cells obtained by (21)
  For all node $c_u$ and $c_v$ in $V'$ such that $c_u$ and $c_v$ are neighbors do
      Add edge $e_{c_u c_v}$ to $G'$
      Find two nodes $k, l$ where $k \in V^{c_u}$ and $l \in V^{c_v}$ and
          $\forall k' \in V^{c_u}, l' \in V^{c_v}$ $Distance(k', l')$ in $G_{max} \geq Distance(k, l)$ in $G_{max}$
      Set $weight_{G'}(e_{c_u c_v}) = Distance(k, l)$ in $G_{max}$
      In zero matrix M set $M(C_u, C_v) = k$, $M(C_v, C_u) = l$,
  End For
  Find shortest pass tree (SPT) of graph $G'$
  If $e_{c_u c_v} \in$ SPT($G'$) then
      add edge $(M(C_u, C_v), M(C_v, C_u))$ and edge $(M(C_v, C_u), M(C_u, C_v))$ to $G''(V, E'')$
      set gt($C_u$) = $M(C_u, C_v)$
  For all node $c_u$ of $G'$ do
      Find optimum topology of nodes in cell $c_u$ using OMIT (V: $V^{c_u}$, $V_s$:{gt($C_u$)})
      Add edge of optimum topology to $G''(V, E'')$
  End For
```

Thus by dividing the network into $L * L$ cells, cells' graph $G' = (V', E')$ will be constructed in which vertices in V' represent members of $\mathcal{M}'$, in other words, the set of non-empty cells constitutes vertices of the graph. An edge exists between two vertices in G' if and only if corresponding cells of these vertices be *neighbor*s (definition. 2). The weight of edge between two neighbor cells, C_u and C_v, in G' is equal to the weight of edge which connects a node of C_u to a node of C_v with minimum weight. Formally, the edge weight (C_u, C_v) in G' is defined as follows:

$$\underset{\forall k' \in V^{C_c}, \forall l' \in V^{C_v}}{W_{G'}(C_u, C_v)} = min\{w_{G_{\max}}(k', l')\} \tag{24}$$

Where $w_{G_{max}}(k', l')$ indicates length of the edge between k' and l' in G_{max}.

Suppose that $k \in V^{C_u}$ and $l \in V^{C_v}$ are nodes that minimize distance between C_u and C_v. In a zero matrix M we set entry $M(C_u, C_v) = k$ and entry $M(C_v, C_u) = l$. Now we need to construct a shortest path tree (SPT) of the graph G' using one of the well-known SPT algorithms. If topology derived under SPT algorithm contains edge (C_u, C_v). Then, corresponding edges ($M(C_u, C_v)$, $M(C_v, C_u)$) and (($M(C_v, C_u)$, $M(C_u, C_v)$) will be added to $G''(V, E'')$.

By dividing the network environment into cells, Lemma 3 states that an average of c nodes will lie within each cell. The value of c should be adjusted in a way that allows optimization model to build a topology over each cell in an acceptable time interval.

Given that the topology created for a network will be fixed and usable for a long period, the results of solving optimization model using AIMMS show that the optimization model is practical for a network with 10 nodes.

Lemma 4. probability of locating one node in cell i is independent of network dimensions.

Proof: Equation (22) implies that probability of locating a node in each cell is equal to $\theta = \frac{L^2}{D^2}$. Also, (23) tells us $L = \frac{\sqrt{c} * D}{\sqrt{n}}$. By substituting L in (22) we will have:

$$\theta = \frac{(\frac{\sqrt{c} * D}{\sqrt{n}})^2}{D^2} = \frac{\frac{c * D^2}{n}}{D^2} = \frac{c}{n} \tag{25}$$

Since the probability of locating nodes in each cell is independent of network dimensions, the probability of more than 10 nodes residing within each cell could easily be computed for any arbitrary network environment. Let $c = 5$ and $c = 6$, then from Table 1, the probability of more than 10 nodes residing in each cell for different values of n can be checked, e.g. with $c = 5$,

Number of Nodes	c = 6	c = 5
n=50	0.032	0.00935
n=70	0.033	0.0101
n=100	0.037	0.0114
n=120	0.038	0.0105
n=150	0.0392	0.011
n=200	0.040	0.0125
n=300	0.0409	0.0126
n=400	0.0413	0.0131
n=500	0.0416	0.0132
n=600	0.0417	0.0133

TABLE 1
Probability of locating more than 10 nodes in each cell.

this probability is about 0.01 which is negligible. So, when we set $c = 5$ then the optimized model OMIT is applicable to each cell. Notice that, our algorithm could be simply used for network with arbitrary nodes number by employing algorithm steps on each individual cell and dividing each cell to some other cells.

By employing the optimized model on nodes in the set $V^{C_u} \in \mathcal{M}'$ optimal topology over nodes in this cell will be obtained. Final topology will be constructed by combining the derived topologies, using the optimized model on every V^{C_u} set, and output edges set of SPT algorithm in the previous step.

5 PERFORMANCE EVALUATION

In this section, we present simulation results to demonstrate the effectiveness of OMIT model and CBOT algorithm. To evaluate the proposed approaches, the comparisons were made against a number of algorithms such as: LISE, SPT, MLSTC-CTree and ROMST in term of network energy consumption. SPT and LISE are selected because of their simple and neat solutions to the topology control problem and they are also popularly selected as a benchmark in topology control problem solving. Furthermore, MLSTC-C Tree that is an optimization model regarding both transmission range and traffic load parameters and its polynomial-time heuristic algorithm namely ROMST, are selected due to their similarity to our algorithms.

In simulation, a set of nodes are uniformly distributed over a rectangular area of $200 \times 200\ m^2$ and total of 10 networks are randomly generated for each simulation run. The path loss model adopted is Free Space Model when it has a $1/d^2$ transmit roll-off. The RX threshold is 3.6e-10 and the CP threshold 10db.Simulations results are as follows:

Since optimized model is not applicable when a large-scale networks is involved, we applied the OMIT model to networks of some 6 to 20 nodes and measured maximum energy consumption of nodes. To make measurements of maximum energy consumption, every node generated traffic at 80kbps and forwarded it to the sink node.

As shown in Figure 3, whenthe number of nodes increases, energy consumption rises throughout network nodes. It is also evident that with 20 nodes, OMIT outperforms the optimized model MLSTC-CTree by 20%.

Moving on to the next evaluation in which maximum energy consumption of nodes are gauged under different traffic load. In this case, 20 nodes were randomly dispersed across the rectangular field and nodes consumptionwere measured against varying volume of traffic. Looking at the simulation results shown in Figure 4, it is evident that as traffic load increases, energy consumption expands sharply due to collisions. Thus, under this scenario, the OMIT method performs distinctly better comparing to other solutions.

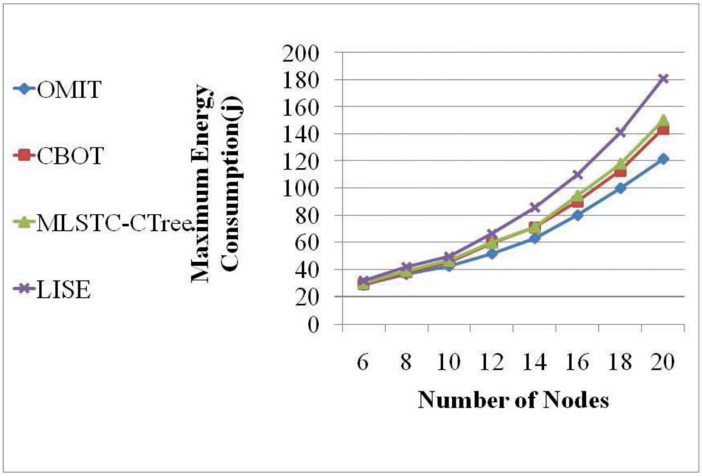


FIGURE 3
Energy consumption with changing number of nodes in small size network.

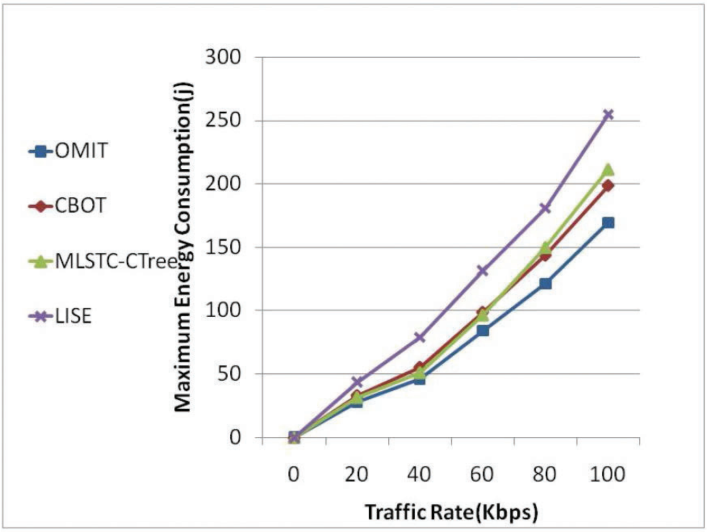


FIGURE 4
Energy consumption with changing traffic ratein small size network.

In the next simulation set up, the CBOT algorithm was compared against the other methods, in alarger-scale network where each node generated traffic at 80 kbps and directed it towards the sink nodes. Figure 5 displays the variation in maximum energy consumption of networks of between 40 to 100 nodes. Simulation results show that in the network with 100 nodes, CBOT

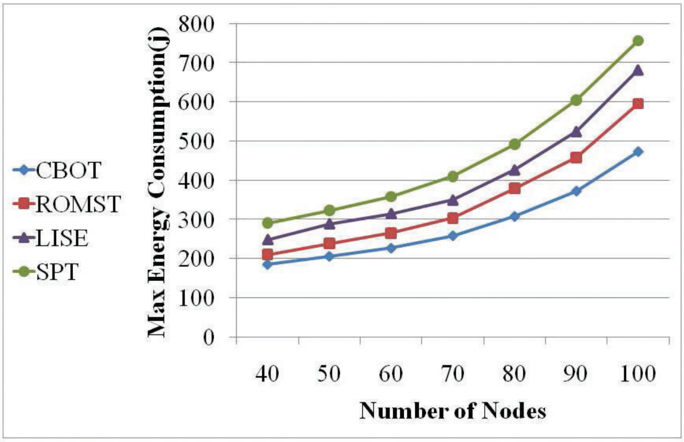


FIGURE 5
Energy consumption with changing number of nodes in large size network.

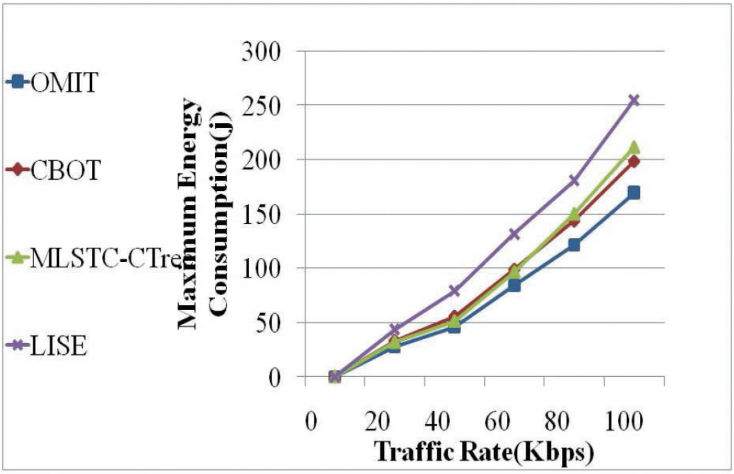


FIGURE 6
Energy consumption with changing traffic ratein large size network.

network outperforms ROMST and MST algorithms by about 25% and 55% respectively.

In the next comparison, CBOT performance is examined against those of ROMST, LISE and MST with changing traffic and the results are exhibited in Figure 6. Let's take the case of a network in which 50 nodes are scattered randomly and investigate the effect of increasing traffic load at maximum nodes energy. Simulation results confirm that as load increases, CBOT stands out with superior performance compared to the other algorithms. It can be seen that at 80 kbps CBOT behaves about 20% and 45% better versus ROMST and MST, respectively.

6 CONCLUSION AND FUTURE WORK

The lifetime of a wireless sensor network is vital to its effectiveness. Network lifetime could be increased by efficiently controlling the energy consumption in each individual node belonging to the network. In this paper, a new approach for topology control in wireless sensor networks was presented. The approach proposed in this paper argues that, instead of connecting a node to its high-loaded neighboring nodes, we could make it to communicate with a node that is farther away i.e. one that is circled by low-loaded nodes in its vicinity. Connecting to a farther node imposes some inevitable cost on the network. We see that when distance is increased consumption of energy by each transmission rises and many more nodes will be affected by interference this longer link.

In the design of our topology control, using mixed integer nonlinear programming, we suggested a trade-off of cost and gain when selecting a distant node. Due to the NP-hardness of MINLP problems, it is impossible to find such optimal solutions within acceptable time however, its results could be used as lower bound on network energy consumption. Furthermore, in this context a heuristic algorithm was designed that solves the problem within an acceptable time. Simulation results confirm that the innovative approach put forward in this paper out performs many solutions reported in literature especially in high loaded networks.

Our algorithm tries to derive an energy efficient topology in wireless sensor network by considering node's traffic. However, numerous open issues exist in thetopic that could be addressed in future work. The optimization model presented here is based on Poisson traffic pattern however; it can also be extended to develop an optimization model in the environment with some other traffic pattern. Also considering QOS parameter of network such as delay is a good research area that could be addressed in future works on topology control.

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