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Energy Efficient Topology Control Protocol for Wireless Sensor Networks

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Abstract

One major problem in the area of Wireless Sensor Networks (WSNs) is the topology control. Topology control protocols in WSNs construct an optimized network topology structure to satisfy the application requirements, such as network connectivity and coverage. In this paper, we deal with the topology control problem by adjusting the transition radius of the sensor nodes. We produce a cluster-based topology control scheme and propose a new Energy Efficient Topology Control Protocol called EETCP. In this protocol, proper transition radius can be determined using Harmony Search (HS) algorithm. The proposed protocol dynamically adjusts transition radius of nodes (unlike some previous protocols which should select radius values among predefined values). Thus, the proposed protocol has some advantage compared to the previous protocols. EETCP has less average number of neighbors compared to the existing protocols. Also, the energy consumption in EETCP is less than other protocols and the network lifetime will be prolonged. In addition, the network connectivity in EETCP is in the acceptable level. The proposed protocol is simulated and the above advantages are demonstrated by the simulation results.

Keywords: *Energy Consumption, Harmony Search Algorithm, Topology Control, Wireless Sensor Network*

1. Introduction

The Wireless Sensor Networks (WSNs) have a wide range of applications, for instance, habitat monitoring, battlefield surveillance, control and automation, environmental monitoring, healthcare, security and surveillance [1, 3]. The nodes in WSNs are usually powered by batteries with finite capacity and it is always impossible to replenish the power [10]. Therefore, the applications are hindered by limited energy supply, and one design challenge in sensor networks is to save limited energy resources to prolong the network lifetime [10, 17, 24]. Power saving techniques can generally be classified in two categories [10]:

- Scheduling the sensor nodes to alternate between active and sleep mode
- Adjusting the transmission or sensing radius of the wireless nodes

Different applications have different requirements, so they adopt the different network models and design assumptions, such as: network structure, sensor deployment strategy, sensing model, and transmission range [12]. Furthermore, applications differ in their requirements; therefore the sensor networks usually have different design objectives. In [12],

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these design objectives summarized such as: maximizing network lifetime, sensing coverage, and network connectivity.

One major problem in the area of WSNs is the topology control. Topology control protocols in WSNs construct an optimized network topology structure to satisfy the application requirements, such as network connectivity and coverage [12]. Choosing appropriate topology for a sensor network has much effect on networks performance, especially considering power consumption and lifetime network [19]. In this paper, we deal with the topology control problem by adjusting the transition radius of the sensor nodes. We produce a cluster-based topology control scheme, and propose a new Energy Efficient Topology Control Protocol called *EETCP*. In this protocol, proper transition radius can be determined using Harmony Search (HS) algorithm.

The remaining of the paper is organized as follows: In section 2 we present the related work in the context of topology control in WSNs. In Section 3 we illustrate the harmony search algorithm briefly. Section 4 presents the model and the assumptions made and Section 5 describes the proposed algorithm. Section 6 presents some simulation results and evaluates the algorithm for different sensor field deployments. The paper concludes with Section 7.

2. Related Works

So far, many protocols have been introduced for topology control in WSNs. Topology control protocols are divided into homogeneous and heterogeneous topology control protocols [19]. In homogeneous topology control, all network nodes use the same transition radius and topology control problem is to find a minimum value for transition radius considering the network characteristic such as network connectivity and coverage [19]. Homogeneous mode (*HOM*) [20] and *COMPOW* [15] are two examples of these methods. The basic idea in *COMPOW* is to apply a uniform transmission power to all sensor nodes, and minimize the power without decreasing network connectivity [12]. When the sensor nodes are uniformly deployed, *COMPOW* can have a good performance. But, when the sensor nodes are not uniformly deployed, the efficiency of *COMPOW* decreases, because some nodes will lead all nodes to use large transmission range, which results in more energy consumption [12].

In heterogeneous topology control, the sensor nodes can have non uniform transition radius [19]. In this group, protocols with information used for making topology are divided into three subgroups. The first subgroup consists of methods based on location. In this subgroup, nodes are informed of their location. Rodoplu and Ming (*R&M*) [18] and Local Minimum Spanning Tree (*LMST*) [11] are two examples of these methods. The second subgroup consists of methods based on orientation. In these methods, nodes don't have exact information of their location, but they can identify direction of their neighbors. Protocol Cone Based Topology Control (*CBTC*) [22] is an example of these methods. Third subgroup is methods based on neighbors. In these methods, nodes have limited information about their neighbors. This information consists of ID number, and distance or quality of node's neighbors. Extreme Topology Control (*XTC*) [23] and *k*-neighbors (*Kneigh*) [4] are examples in this group.

Radius Adaptation Algorithm-2 Level (*RAA-2L*) is another topology control protocol. In this protocol, each node chooses one of two transition radius R_S or R_W ($R_W<R_S$) [21]. If a node with transition radius of R_W could communicate with a neighbor with transition radius R_S, it chooses the transition radius R_W, else it chooses the transition radius R_S. In Radius Adaptation Algorithm-3 Level (*RAA-3L*), each node chooses one of three transition radius: Rt, R_S or R_W ($R_W<Rt<R_S$). In our previous work [7], we proposed a Genetic Algorithm-based Topology Control protocol for wireless sensor networks called *GATC*. Like the *GATC*, the proposed protocol in this paper is based on *RAA-3L*, but has less overhead.

3. Harmony Search Algorithm

HS algorithm, originated by Geem *et al.*, [6], is based on natural musical performance processes that occur when a musician searches for a better state of harmony [2, 16, 14]. HS has several advantages with respect to traditional optimization techniques such as the following [2]:

- HS imposes fewer mathematical requirements.
- HS is free from divergence.
- HS does not require initial value settings of the decision variables, thus it may escape the local optima.
- HS can handle both discrete and continuous variables.
- The HS algorithm optimization procedure consists of the following five steps [2] [16] [14]:

Step 1: Problem and algorithm parameter initialization
Step 2: Harmony memory initialization and evaluation
Step 3: New Harmony improvisation
Step 4: Harmony memory update
Step 5: Termination criterion check

We give the pseudo-code for HS algorithm as follows [14]:

The pseudo-code for HS algorithm

Step 1:
- Initialize the problem parameters:
  Objective function (*f(x)*)
  Decision variable (x_i)
  Number of decision variables (*N*)
- Initialize the algorithm parameters:
  Harmony Memory Size (*HMS*)
  Harmony Memory Considering Rate (*HMCR*)
  Pitch Adjustment Rate (*PAR*)
  The Number of Improvisations (*NI*)
  Distance bound wide (*bw*)

Step 2:
- Initialize the Harmony Memory (HM) with random vectors as many as the vectors of HMS
- Evaluate HM

Step 3:
With probability HMCR:
- Select a new value for a variable from HM
  With probability 1-PAR:
  - Do nothing
  With probability PAR:
  - Choose a neighbouring value

With probability 1-HMCR:
- Select a new value from the possible value set

Step 4:
If New Harmony vector is better than existing harmony vectors in the HM then
- Update HM

Step 5:
- Checking Termination criteria met and jump to step 3

4. The Network Model and the Assumptions

In this section, we present the network model and the assumptions used in this paper.

4.1. Adjustable Transition Radius

Define that the sensor set is $S=\{n_1, n_2, n_3, \dots, n_n\}$ and the transition radius set is $R_T=\{R_1, R_2, R_3, \dots, R_n\}$, where R_i is the transition radius of node n_i.

We assume that each sensor node ni has adjustable transition radius which can be between a minimum and a maximum transition radius:

- R_{min}: transition radius with minimum power
- R_{max}: transition radius with maximum power
- R_i : selective transition radius of node n_i

The value of R_i should be between the R_{min} and R_{max} ($R_{min} \le R_i \le R_{max}$). Value of the transition radius R_{min} and R_{max} will be calculated based on Rt. Value of transition radius Rt is determined proportional to the network density [20].

When the distance of both nodes is less than R_{max}, we assume they are neighbor. Each node has three different neighbor sets. Sets of A_{min}, A_T and A_{max} are obtained by (1):

$$\forall n_i, n_j \in S=\{n_1, n_2, n_3, \dots, n_n\}, \quad i \neq j: \qquad (1)$$

$$\begin{cases} n_j \in A_{min}(n_i) & \text{if } Dis(n_i, n_j) \le R_{min} \\ n_j \in A_T(n_i) & \text{if } R_{min} < Dis(n_i, n_j) \le R_i \\ n_j \in A_{max}(n_i) & \text{if } R_i < Dis(n_i, n_j) \le R_{max} \end{cases}$$

In (1), $Ax(n_y)$ shows the Ax set of node n_y, and $Dis(n_j, n_i)$ is the distance between node n_i and n_j. Therefore, for each node $n_i \in S=\{n_1, n_2, n_3, \dots, n_n\}$:

$$A_{max}(n_i) \cup A_T(n_i) \cup A_{min}(n_i) = \text{All neighbors of node } n_i \qquad (2)$$

$$A_{max}(n_i) \cap A_T(n_i) \cap A_{min}(n_i) = \{\} \qquad (3)$$

We define the number of links for the sensor network:

$$\text{Number of links} = \sum_{i=1 \text{ to } n} \text{All neighbors of node } n_i \qquad (4)$$

$$= \sum_{i=1 \text{ to } n} |A_{min}(n_i) \cup A_T(n_i) \cup A_{max}(n_i)|$$

Where n is the number of the sensor. Thus, the average number of neighbors is defined as:

$$\text{Average number of neighbors} = \text{Number of Links} / n \qquad (5)$$

Also, the average of transition radius is calculated as:

$$\text{Average of transition radius} = \sum_{i=1 \text{ to } n} R_i \,/\, n \qquad (6)$$

The main problem in this study is choosing minimum transition radius R_i between R_{min} and R_{max} for each node $n_i \in S=\{n_1, n_2, \dots, n_n\}$ without decreasing the network connectivity.

4.2. The cluster-based Architecture

Similar to the cluster-based coverage control scheme introduced in [10], we use a cluster-based topology control scheme in this paper, which is scheduled into rounds. In each round, firstly, the target area is divided into several equal squares. Then the node in each square having the largest energy will be chosen as the cluster-head. The procedure of selecting the cluster-head is the same works in [10] [9]. The cluster-head has full control of the square and it will choose transition radius of nodes. In the next round, another sensor set will be selected as the cluster head. So the energy consumption among all the sensors can be balanced well [10].

4.3. Energy Consumption Analysis

According to different energy consumption models, the energy consumed by a sensor node to deal with a transmission task is proportional to r^2 or r^4, where r is the transition radius of node [10, 13]. In this paper, we take the energy consumption of the transition task as $u.r^2$, where u is the factor.

$$E\,(r) = u.r^{2} \qquad (7)$$

Thus, the energy consumption of the sensor set, which is related to the sum of the sensor's transition radius squared, is defined as [10]:

$$E_{total} = E(R_T)= \sum_{i=1\ to\ n} E(R_i) = u.\sum_{i=1\ to\ n} R_i^{\,2} \qquad (8)$$

So, the energy consumption per area is shown as the following:

$$E_{per\text{-}Area} = E_{total} / A_{area} = u. \sum_{i=1\ to\ n} R_i^{\,2} / A_{area} \qquad (9)$$

Also, for the brief of the energy consumption analysis, we only consider the energy consumed by the transmission function, and do not include the energy consumption of calculations and sensing [10].

4.4. The Complete Connectivity of the Sensor Network

In this paper, we will deal with the nodes deployed randomly. Assume that each one knows its own location which can be achieved by using some location system [10, 5].

A WSN can be modeled as a graph $G= (V, E)$, where V is the set of sensor nodes and E is the set of wireless links [8]. The complete connectivity of the sensor network means the ability of communicating with all of network nodes. Thus, we will define the complete connectivity of the sensor network, $Con\,(R_T)$, as (10):

$$Con\,(R_T) = \begin{cases} 1 & MCP = n \\ \varepsilon & Else \end{cases} \qquad (10)$$

Where MCP is the biggest connected component of the sensor network and n is the number of the sensor nodes. Also ε shows a very small positive number. Thus, we will define the probability of the complete connectivity, P_C, as (11):

$$P_C = \Sigma_{i=1\ to\ Nd}\ Con_i\,(R_T) / N_d \qquad (11)$$

In (11), N_d is the number of different configuration of the sensor network.

5. The Proposed Protocol

In this section, we propose a topology control solution based on harmony search algorithm and try to decrease the average of transition radius without decreasing the connectivity of the sensor network.

In the proposed algorithm, at first a primary population of transition radii set are selected randomly. Each transition radius set represents one configuration of the sensor network. We consider the mentioned population as Harmony Memory (HM). Then we try to improve the harmony memory by creating a new transition radius set. If the new transition radius set is better than the worst transition radius set existing in the harmony memory, the worst one will be replaced with it. The process of providing new transition radius set and replacing the worst transition radius set with the new one continue until meeting termination criteria. Algorithm continues until achieving a certain number of iteration. Finally, the best transition radius set existing in the harmony memory is selected as the response. So, the proposed algorithm is presented briefly in some steps as follows:

Phase1. The problem and the algorithm parameter initialization:

- Step1: Initialize A_{min}, A_T and A_{max} sets for each node.
- Step2: Produce lower bound and upper bound of the transition radius for each node.
- Step3: Initialize the algorithm parameters.
- Step4: Initialize the harmony memory with the transition radius sets randomly.

Phase2. Repeat the main loop of algorithm until meeting termination criteria:

- Step5: Improvise a new transition radius set.
- Step6: Update the harmony memory.
- Step7: Check the stopping criterion.

In next sections, we describe the proposed algorithm in detail.

5.1. Step1: Initialize A_{min}, A_T and A_{max} sets for each node

At first, according to (12), the transition radius of each node is set between R_{min} and R_{max}.

$$\forall R_i \in R_T = (R_1, R_2, R_3, \ldots, R_n) : R_i \leftarrow R_t \qquad (12)$$

As mentioned before, *Rt* is determined proportional to the network density [20].

5.2. Step2: Produce Lower Bound and Upper Bound of the Transition Radius for each Node

The process of calculating lower bound and upper bound of the transition radius for each node $n_i \in S = \{n_1, n_2, \ldots, n_n\}$ is as follows:

At first, according to (1) as mentioned before, A_{min}, A_T and A_{max} sets for all nodes is created. Then, A_{min}, A_T and A_{max} sets are updated for node n_i. For this purpose, according to (13), whenever one node of $A_T(n_i)$ and $A_{max}(n_i)$ sets is accessible through nodes that are in $A_{min}(n_i)$ set, that will be removed from these sets and adds to $A_{min}(n_i)$ set (see Figure 1(*a*)). Also, whenever one node of $A_{max}(n_i)$ sets is accessible through nodes that are in $A_T(n_i)$ set, that will be removed from $A_{max}(n_i)$ set and adds to $A_T(n_i)$ set (see Figure 1(*b*)).

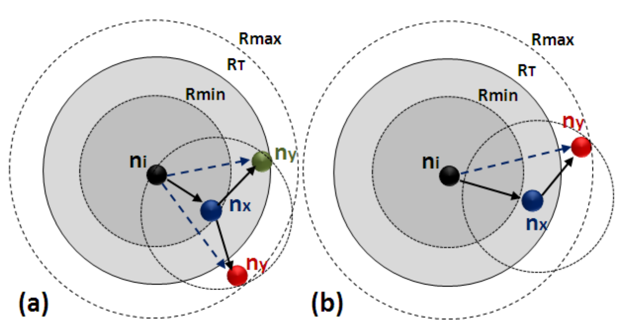


Figure 1. Updating the A_{min}, A_T and A_{max} Sets

$$n_i \in S=\{n_1, n_2, n_3, \ldots , n_n\}: \qquad (13)$$

$$\forall n_x \in A_{min}(n_i)\ \exists n_y \in A_{min}(n_x)\ AND$$
$$(n_y \in A_T(n_i)\ OR\ n_y \in A_{max}(n_i)) \Rightarrow$$
$$\begin{cases} A_{min}(n_i) \leftarrow A_{min}(n_i) + n_y \\ A_T(n_i) \leftarrow A_T(n_i) - n_y\ \ OR\ \ A_{max}(n_i) \leftarrow A_{max}(n_i) - n_y \end{cases}$$

$$\forall n_x \in A_T(n_i)\ \exists n_y \in A_{min}(n_x)\ AND\ n_y \in A_{max}(n_i) \Rightarrow$$
$$\begin{cases} A_T(n_i) \leftarrow A_T(n_i) + n_y \\ A_{max}(n_i) \leftarrow A_{max}(n_i) - n_y \end{cases}$$

In (13), $A_X(n_i)$ shows the A_X set of node n_i . Then, regarding $A_T(n_i)$ and $A_{max}(n_i)$ conditions, we determine the transition radius range for node n_i . The method of determining the transition radius range is calculated according to the four conditions:

$$n_i \in S=\{n_1, n_2, n_3, \ldots , n_n\}: \qquad (14)$$
$$If\ A_T(n_i) = \varphi\ And\ A_{max}(n_i) = \varphi\ \ Then$$
$$R_{range}{\hat{}}_{i} = [R_{min} , R_{min}]$$
$$Else\ If\ A_T(n_i) \neq \varphi\ And\ A_{max}(n_i) = \varphi\ \ Then$$
$$R_{range}{\hat{}}_{i} = [R_{min} , R_i] = [R_{min} , R_t]$$
$$Else\ If\ A_T(n_i) \neq \varphi\ And\ A_{max}(n_i) = \varphi\ \ Then$$
$$R_{range}{\hat{}}_{i} = [R_i , R_{max}] = [R_t , R_{max}]$$
$$Else\ If\ A_T(n_i) \neq \varphi\ And\ A_{max}(n_i) \neq \varphi\ \ Then$$
$$R_{range}{\hat{}}_{i} = [R_{min} , R_{max}]$$

Thus, we perform a transition radius ranges set, R_{range}, as:

$$R_{range} = \{ R_{range}{\hat{}}_{1} , R_{range}{\hat{}}_{2} , \ldots , R_{range}{\hat{}}_{n} \} \qquad (15)$$

Now, the transition radius of each node can be only within its determined range:

$$\forall n_i \in S=\{n_1, n_2, \ldots , n_n\}: R_i \in R_{range}{\hat{}}_{i} = [R_{low}{\hat{}}_{i} , R_{up}{\hat{}}_{i}] \qquad (16)$$

5.3. Step3. Initialize the Algorithm Parameters

In this step, the optimization problem is specified as follows:

$$Maximize\ f(R_T) = Con(R_T) \times (1/(E_{total}(R_T) + \gamma)) \qquad (17)$$

Where R_T is the transition radius set; γ shows very small positive number that should be selected properly such a way that $f(R_T)$ function value doesn't exceed the threshold value. The amount of function Con (R^i_T) is calculated according to (10).

As mentioned before, E_{total} (R_T) is the transition energy consumption of the sensor network based on (8), so:

$$If\ Con(R_T)=1 \Rightarrow f(R_T) = (1/(E_{total}(R_T) + \gamma)) \Rightarrow \qquad (18)$$
$$Maximum\ f(R_T) = f(R_{MIN}) \quad , R_{MIN} = (R_{min}, R_{min}, \ldots R_{min}).$$

Therefore, according to (18), $f(R_T)$ function value is in inverse ratio to the energy consumption.

Also, the HS algorithm parameters are also initialized in this step [14]:

- *HMS*: The harmony memory size (or the number of the transition radius sets in the harmony memory.
- *HMCR*: The harmony memory considering rate.
- *PAR*: pitch adjusting rate.
- *NI*: The number of improvisations, or stopping criterion.

5.4. Step4.Initialize the Harmony Memory

The Harmony Memory (*HM*) is a memory location where all transition radius sets are stored. In this step, we consider a Harmony Memory consists of one *HMS* group of the transition radius sets according to Fig. 2. Each the transition radius set, $R^i_T = (R_1^i, R_2^i, \dots, R_n^i)$, represents one configuration of sensor network such a way that the transition radius of each j th node equals to R^i_j. The fitness value of this configuration is shown by $f(R^i_T)$.

$$\text{HM} = \left[\begin{array}{ccccc|c} R_1^1 & R_2^1 & \cdots & R_{n-1}^1 & R_n^1 & f(R^1) \\ R_1^2 & R_2^2 & \cdots & R_{n-1}^2 & R_n^2 & f(R^2) \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ R_1^{HMS-1} & R_2^{HMS-1} & \cdots & R_{n-1}^{HMS-1} & R_n^{HMS-1} & f(R^{HMS-1}) \\ R_1^{HMS} & R_2^{HMS} & \cdots & R_{n-1}^{HMS} & R_n^{HMS} & f(R^{HMS}) \end{array}\right]$$

Figure 2. The Harmony Memory (HM) is a Memory Location where all Transition Radius Sets are Stored

So, one $n \times HMS$ matrix of transition radii will be obtained. According to (19), these transition radii are initialized randomly:

$$R^i_j = R_{low\hat{}i} + rand() \times (R_{up\hat{}i} - R_{low\hat{}i}) \quad j = 1, 2, \dots, n \quad i = 1, 2, 3, \dots, HMS \qquad (19)$$

Where *rand()* is a random number between 0 and 1. *HMS* is harmony memory size (*i.e.*, the number of the transition radius sets in the harmony memory) and n is the number of nodes.

The fitness value of each transition radius set R^i_T is represented by $f(R^i_T)$ and it is calculated by (20):

$$f(R^i_T) = Con(R^i_T) \times (1/(E_{total}(R^i_T) + \gamma)) \qquad (20)$$
$$R^i_T = (R_1^i, R_2^i, R_3^i, \dots, R_N^i), \; i = 1, 2, 3, \dots, HMS$$

As mentioned before, $E_{total}(R^i_T)$ is the transition energy consumption based on (8) and the amount of function $C(R^i_T)$ is calculated according to (10).

5.5. Step5. Improvise a Transition Radius Set

Generating a new transition radius set is called ‘improvisation’. A new transition radius set, $R'_T = (R'_1, R'_2, \dots, R'_N)$, is generated based on three rules [14]:

- Memory consideration
- Random selection

- Pitch adjustment

In this step, memory consideration, pitch adjustment or random selection is applied to each radius of the new transition radius set $R'_T=(R'_1, R'_2, \dots, R'_n)$ in turn [14]. Each variable of the new transition radius set, $R'_i \in R'_T$, is calculated as follows:

In the memory consideration, the value of the transition radius R'_i is chosen from any of the transition radius values in the specified harmony memory range $(R'^1_i, R'^2_i, \dots, R'^{HMS}_i)$. The *HMCR* is the rate of choosing one value from the historical transition radius values stored in the harmony memory.

Also, every transition radius $R'_i \in R'_T = \{R'_1, R'_2, \dots, R'_n\}$ obtained by the memory consideration is examined to determine whether it should be pitch-adjusted [14]:

Pitch adjusting decision for $R'_i \in R'_T=(R'_1, R'_2, \dots, R'_n)$:

$$R'_i = \begin{cases} \textit{Yes} & \textit{with probability PAR} \\ \textit{No} & \textit{with probability (1-PAR)} \end{cases} \quad (21)$$

PAR parameter is the rate of the pitch adjustment. The value of *PAR* defines the rate of doing pitch adjustment, and the value of (1-*PAR*) defines the rate of doing nothing. If the pitch adjustment is applied, R'_i is changed as follow:

$$R'_i \leftarrow R'_i \pm rand() \times ((R_{up}\hat{}_i - R_{low}\hat{}_i) \times \mu) \quad (22)$$

Where μ is a constant factor between 0 and 1 (e.g. μ=0.5).

In the random selection, the value of the transition radius R'_i is chosen from the possible range of values randomly (*i.e.*, one value between $[R_{low}\hat{}_i, R_{up}\hat{}_i]$). (1-*HMCR*) is the rate of the random selection. Thus:

$$R'_i \leftarrow \begin{cases} R'_i \in \{R_i^1, R_i^2, R_i^3, \dots, R_i^{HMS}\} & \textit{With probability HMCR} \\ R'_i = R_{low}\hat{}_i + rand() \times (R_{up}\hat{}_i - R_{low}\hat{}_i) & \textit{With probability (1-HMCR)} \end{cases} \quad (23)$$

Where *rand()* is a random number between 0 and 1. Also, as already stated, $R_{low}\hat{}_i$ and $R_{up}\hat{}_i$ are the lower and upper bounds for transition radius of node n_i.

5.6. Step6. Update the Harmony Memory

If the new transition radius set, $R'_T=(R'_1, R'_2, \dots, R'_n)$, is better than the worst transition radius set existing in the harmony memory, the worst one will be replaced with it.

$$((\forall R^j \in HM \quad f(R^{worst}) \le f(R^j)) \text{ and } f(R^{worst}) \le f(R'_T)) \Rightarrow \quad (24)$$

$$R^{worst} = (R^w_1, R^w_2, \dots, R^w_n) \leftarrow R'_T = (R'_1, R'_2, \dots, R'_n)$$

5.7. Step7. Check stopping criterion

The main loop of algorithm continues until achieving a certain number of iteration. According to (25), after terminating the main loop of algorithm, the transition radius set with most objective function is selected among transition radius sets existing in the harmony memory.

$$R^{Best} = (R_1^{Best}, R_2^{Best}, \dots, R_N^{Best}) \textit{ is answer if:} \quad (25)$$

$$\exists R^{Best} \in HM : \forall R^{j} \in HM \Rightarrow f(R^{Best}) \geq f(R^{j})$$

Thus, according to (26):

$$R^{Best} = (R_1^{Best}, R_2^{Best}, \ldots, R_N^{Best}) \text{ is answer if:}$$

$$\forall n_i \in S = \{\hat{n}_1, \hat{n}_2, \ldots, \hat{n}_n\} : R_i \leftarrow R_i^{Best} \qquad (26)$$

6. Simulation Results

In this section, our proposed protocol is simulated and compared to *RAA-2L*, *RAA-3L* [21], and *HOM* [20] using NS2 simulator.

6.1. Simulation Environment

We considered 500×500 m^2 area for these simulations. We deploy the sensor nodes randomly in the target area. The number of sensor nodes, *n*, in different configurations is considered from 50 to 250 sensor nodes. Each node has a transition range between R_{min} and R_{max}. R_{min} and R_{max} transition radius are considered 0.8×*Rt* and 1.25×*Rt* respectively. Table I represents the *Rt*, R_{min} and R_{max} transition values for different configurations of the sensor network. The threshold value for the number of performing the main loop of the algorithm considered 300 (*NI*=300). The parameters values for simulation are shown in Table II. The results mentioned in next sections show the average of performing protocols for one hundred random deployments.

Table I. The Minimum and Maximum Transition Radius Values for Simulation

Number of nodes	50	75	100	125	150	175	200	225	250
Rmin	109	87	77	69	64	59	57	56	55
Rt	87	70	62	55	51	47	46	45	44
Rmax	136	109	96	86	80	74	71	70	69

Table II. The Parameters Values for Simulation

Parameter	**NI**	**HMS**	**HMCR**	**PAR**	**γ**	**ε**	**Nd**
Value	300	50	0.85	0.02	1	0.001	100

Three metrics are used for evaluations. These metrics are: the average of transition radius, the average number of neighbors, and the probability of the complete connectivity.

6.2. Comparing with other Protocols

In the first experiment, we measured average of the transition radius of the network for *EETCP*, *RAA-2L*, *RAA-3L* and *HOM* protocols. The purpose of this experiment is to evaluate the ability of the proposed protocol to decrease average of the transition radius. Note that, in *MIN-RANGE*, all the nodes have minimum transition radius (R_{min}). Also, in *MAX-RANGE*, all the nodes have maximum transition radius (R_{max}). The results of this simulation are depicted in Figure 3(*a*) and Table III. As can be seen, *EETCP* has less average of transition radius and *HOM* has maximum average of transition radius. Note that, against other protocols, the proposed protocol doesn't use a predetermined transition radius.

In second experiment, the average numbers of neighbors for *EETCP*, *RAA-2L*, *RAA-3L* and *HOM* protocols are measured. The purpose of this experiment is to evaluate the ability of the proposed protocol to decrease the number of neighbors. The results of this experiment are depicted in Figure 3(*b*) and Table IV. As can be seen in Figure 3(*b*), the average number of neighbors in the *EETCP* is less than those of other protocols. Note that a lower number of neighbors results in lower interference between the nodes. Decreasing of the neighbors directly results in decreasing the transition radius. But note that decreasing the neighbors and also the transition radius is useful if the network connectivity is remained (is not removed). This problem will be evaluated accurately in next experiment.

In the last experiment, the network connectivity in *EETCP* is measured and compared to *RAA-2L*, *RAA-3L*, *HOM*, *MIN-RANGE* and *MAX-RANGE* protocols. As mentioned before, in these experiments, we supposed N_d equal to 100. The probability of the complete connectivity is depicted in Figure 3(*c*) and Table V for *EETCP*, *RAA-2L*, *RAA-3L* and *HOM* protocols. As can be seen in Figure 3(*c*), the probability of complete connectivity of the network for *EETCP*, *RAA-2L*, *RAA-3L* and *MAX-RANGE* are almost equal. So, the network connectivity in our protocol is acceptable.

Table III. Average of Transition Radius

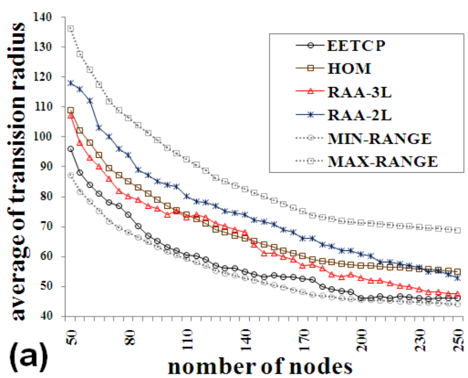
Number of nodes	50	75	100	125	150	175	200	225	250
EETCP	96.2	77.6	63.3	57.1	53.7	52.2	46.1	46.3	46.1
RAA-3L	107.3	92.1	75.1	71.5	61.1	57.1	52.6	50.1	47.4
RAA-2L	118.1	96.1	84.3	77.4	71.5	66.1	60.9	57.0	52.7
HOM	109	87	77	69	64	59	57	56	55

Table IV. Average Number of Neighbors

Number of nodes	50	75	100	125	150	175	200	225	250
EETCP	6.22	5.5	5.81	5.82	5.87	6.0	6.02	6.52	7.23
RAA-3L	6.92	6.72	6.82	7.0	7.64	7.63	7.64	7.88	8.39
RAA-2L	7.46	7.38	7.82	7.83	8.93	9.32	9.72	9.73	9.94
HOM	8.8	8.9	9.0	9.6	9.3	9.8	10.3	10.5	10.6
MIN-RANGE	5.4	4.81	5.2	5.29	5.53	5.41	5.57	5.87	7.09
MAX-RANGE	9.96	10.1	10.4	11	12.2	12	12	13.4	14.6

Table V. The Probability of the Complete Connectivity

Number of nodes	50	75	100	125	150	175	200	225	250
EETCP	0.97	9.98	0.98	0.97	9.97	0.98	0.97	0.97	0.98
RAA-3L	0.98	0.99	0.98	0.98	0.98	0.98	0.98	0.97	0.98
RAA-2L	0.99	0.99	0.98	0.99	0.98	0.99	0.98	0.99	0.98
HOM	0.06	0.08	0.07	0.07	0.05	0.06	0.07	0.05	0.08
MIN-RANGE	0.02	0.02	0.03	0.02	0.01	0.01	0.02	0.00	0.00
MAX-RANGE	0.98	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00



(a)

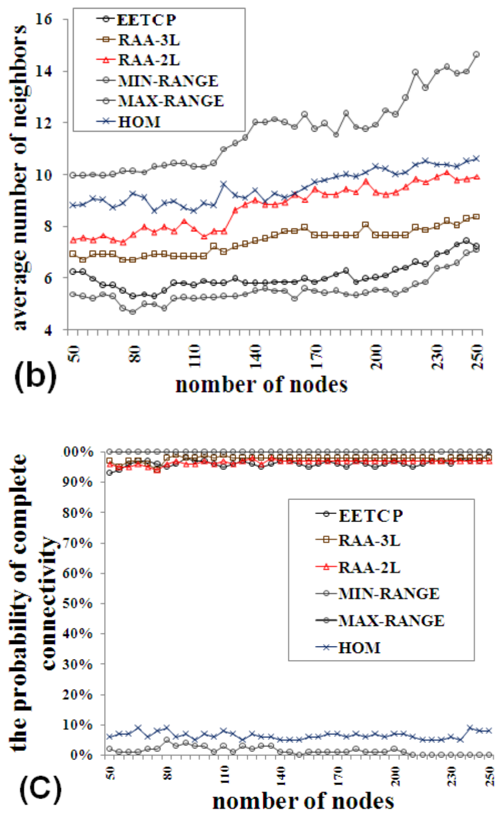


Figure 3. (*a*) Average of the Transition Radius, (*b*) Average Number of Neighbors, (*c*) Probability of the Complete

6.3. Observations

As can be seen in Figure 3, while nodes have the minimum transition radius (R_{min}), the state of the network connectivity is very undesirable. Also while the nodes have maximum transition radius (R_{max}), the number of network links are lot such a way that not only the energy consumption is very high but also the collision within transition radius is lot.

These results can show the prominence of our proposed protocol. While maintaining network connectivity, it could decrease the average of transition radius and the average number of neighbor nodes. Thus it decreases the energy consumption and the interference between sensor nodes. *EETCP* protocol has some advantages compared to the previous protocols. *EETCP* protocol dynamically adjusts the transition radius of the nodes (unlike previous protocols which should select radius values among predefined values). Thus, our protocol has the less average number of neighbors compared to the existing protocols. Also, the energy consumption in our protocol is less than others and the network lifetime will be prolonged. In addition, the network connectivity in our protocol is in the acceptable level.

7. Conclusion

In this paper, we produced a cluster-based topology control scheme and proposed a new Energy Efficient Topology Control Protocol named *EETCP*. In *EETCP* protocol, proper transition radius determined using HS algorithm. Unlike previous protocols that should select the transition radius values among predefined values, *EETCP* dynamically adjusts transition radius of nodes. Thus, the proposed protocol has some advantage compared to previous protocols. *EETCP* has less average number of neighbors compared to existing protocols. Also, the energy consumption in *EETCP* is less than others and the network lifetime will be prolonged. In addition, the network connectivity in *EETCP* is in the acceptable level. The proposed protocol is simulated and the above advantages are shown in the simulation results.

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