Journal of Theoretical and Applied Information Technology
30th June 2013. Vol. 52 No.3

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

TOPOLOGY CONTROL ALGORITHM FOR BETTER SENSING COVERAGE WITH CONNECTIVITY IN WIRELESS SENSOR NETWORKS

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ABSTRACT

The Wireless Sensor Network (WSN) consisting of a large number of sensors are effective for gathering data in a variety of environments. Since the sensors operate on battery of limited power, it is a challenging aim to design an energy efficient routing protocol, which can minimize the energy and thereby extend the lifetime of the network. However, in the context of Wireless Sensor Networks routing, Connected Dominating Set (CDS) principle has emerged as the most popular method for energy efficient topology control (TC) in WSNs. A virtual backbone is formed in a CDS-based topology control technique, which allows communication between any arbitrary pair of nodes in the network. In this paper, we present a CDS based topology control algorithm, TC1, which forms an energy efficient virtual backbone. In our simulations, we compare the performance of TC1 with three prominent CDS-based algorithms namely energy-efficient CDS (EECDS), CDS Rule K, A3 and A3 Lite algorithms. The results demonstrate that TC1 performs better in terms of Residual Energy and other selected metrics. Moreover, the TC1 not only achieves better connectivity under topology maintenance but also provides better sensing coverage when compared with other algorithms.

Keywords: *Wireless Sensor Network (WSN), Connected Dominating Set (CDS), Topology Control (TC).*

1. INTRODUCTION

Wireless Sensor Network (WSN) consists of small in size sensor nodes, which form an ad-hoc distributed sensing and data propagation network to collect the context information on the physical environment. WSN is widely used to collect reliable and accurate information in the distance and hazardous environments, and can be used in National Defence, Military Affairs, Industrial Control, Environmental Monitor, Traffic Management, Medical Care and Smart Home etc. The sensor whose resources are limited is cheap, and depends on battery to supply electricity, so it's important for Routing to efficiently utilize its power in both military and civilian applications such as target tracking, surveillance and security management.

Although WSNs have evolved in many aspects, nodes have limited communications capabilities, due to which a source node can cover only within its maximum transmission range. On the other hand, it causes nodes to relay messages through intermediate nodes to reach their destinations. Due to this reason, routing related tasks become much more complicated in WSNs since there is no predefined physical backbone infrastructure for topology control. This drawback motivates a virtual backbone to be employed in a WSN. Conceptually, a virtual backbone is a set of active nodes, which can send message to the destination by forwarding the message to other neighboring active nodes. These set of active nodes provides many advantages to network routing and management. This is due to the reason that routing path gets reduced to the set of active nodes only, which provides an efficient fault-tolerant routing. Moreover, the reduced topology reacts quickly to topological changes and is less vulnerable in terms of collision problems caused due to flooding based routing algorithms.

CDS based topology control (TC) has emerged as the most popular method for energy efficient (TC) in WSNs. TC has two phases namely: Topology Construction and Topology Maintenance. In the Topology Construction phase, a desired topological property is established in the network while ensuring connectivity. Once the topology is constructed, Topology Maintenance phase starts in which nodes switch their roles to cater for topological changes. In CDS-based TC schemes, some nodes are apart of the virtual backbone, which is responsible for relaying packets in the WSN. These nodes are also called dominator nodes or active nodes. Non-CDS nodes or dominates relay information through the active nodes. Hence, a CDS works as a virtual backbone in the reduced constructed topology.

The CDS size remains the primary concern for measuring the quality of a CDS. Mohammed et al. (2005) and Kim et al. (2009) prove that a smaller virtual backbone suffers less from the interference problem and performs more efficiently in routing and reducing the number of control messages. However, most studies do not consider the impact of topology maintenance, under which many nodes gets disconnected from sink node. This is due to the reason that for small virtual backbones, fewer nodes handle the bulk of the network traffic and consequently deplete their batteries quickly. This causes the reduction in the virtual backbone size, which affects the coverage region of WSN.

In this paper, we propose a distributed topology control algorithm referred to as the TC1 for wireless sensor networks, models the topology as a connected network and finds the set of active nodes to form a CDS. The TC1 uses node IDs of different nodes and a node selection criteria for nodes to calculate their timeout. In this way, nodes turn-off themselves and later repeat the process after the timeout expires to discover neighbors desiring them to work as an active node. In this way, a reduced topology is formed while keeping the network connected and covered. To achieve energy efficiency, the TC1 forms the CDS comprising of high energy nodes in a single phase construction process. In addition, it also forms a proportionate set of active nodes in order to provide better sensing coverage. Moreover, it adapts to the topological changes in the network based on the remaining energy of the nodes. This allows better topology maintenance among different set of nodes, which increases the network lifetime.

We compare the performance of the TC1 with Energy Efficient CDS (EECDS), CDS Rule K and A3 algorithms. For this purpose, we perform extensive simulations under varying network sizes to analyze the message complexity and energy overhead in terms of spent energy and remaining energy in the CDS. We also analyze the performance of the algorithms under topology maintenance to verify the nodes connectivity in terms of number of unconnected nodes. The results show the proposed TC1 has low message complexity. Moreover, it also provides better residual energy resources while having less number of unconnected nodes under topology maintenance.

2. RELATED WORK

The CDS based topology construction in WSNs has been studied extensively. Some of the existing algorithms consider using the transmission power of WSN nodes to achieve energy efficiency while some used geographical location of the nodes. However, power control and location awareness are difficult to realize in practical WSN deployments.

Wan et al. (2002) and Alzoubi et al. (2002a, 2002b) first proposed distributed algorithms for constructing CDSs in unit disk graphs (UDGs), which consists of two phases to form the CDS. They form a spanning tree and then utilize nodes in the tree to find an MIS. At start, all the nodes in an MIS are colored black. In the second phase, more nodes are added which have a blue color to connect the black nodes to form a CDS. Later, Yuanyuan et al. (2006) proposed an Energy-Efficient CDS (EECDS) algorithm that computes a sub-optimal CDS in an arbitrary connected graph. They also use two phase strategy to form a CDS. The EECDS also uses a coloring approach to build the MIS. The EECDS algorithm begins with all nodes being white. An initiator node elects itself as part of the MIS coloring itself black and sending a Black message to announce its neighbors that it is part of the MIS. Upon receiving this message, each white neighbor colors itself as gray and sends a Gray message to notify its own White neighbors that it has been converted to gray. Therefore, all white nodes receiving a Gray message are neighbors of a node that does not belong to the MIS. These nodes need to compete to become Black nodes. For this, a node sends an Inquiry message to its neighbors to know about their state. If it does not receive any Black message in response and it has the highest weight, it becomes a Black node, and the process starts again. In EECDS, the second part of the algorithm is to form a CDS using nodes that do not belong to the MIS. These nodes, called connectors, are selected in a greedy manner by MIS nodes using three types of messages namely Blue, Update, and Invite messages.

Another solution is proposed by Wu et al. (2006), which uses marking and pruning rules to exchange the neighbors lists among a set of nodes. In the CDS Rule K algorithm, a node remains marked if there is at least one pair of unconnected neighbors. The node unmarks itself if it determines that all of its neighbors are covered with higher priority. The node's higher priority is indicated by its level in the tree.

Mostly, all the approximation ratios mentioned above are concerned with CDS size. While for efficient routing, not only a smaller CDS size is desired, but extra requirements like energy efficiency also needs to be considered. For this purpose, Wightman and Labrador (2008) have proposed a topology construction algorithm that produces an approximate solution to form a sub-optimal CDS. The A3 use four types of messages for topology discovery. As the nodes receive a hello message from the parent, they send back the information regarding remaining energy and signal strength with parent recognition message. The parent node on receiving the parent recognition message sends back the sorted list to all its children. This sorted list contains the timeout information of all the children belonging to the parent. As the timeout expires, nodes further explore their neighbors by repeating the same steps to form the reduced topology. The nodes not receiving any message in reply to their hello message enters into sleep mode by broadcasting a sleeping message. Further, the authors extend their work in Wightman and Labrador (2011) by proposing A3Lite, which uses less number of messages when compared with A3 algorithm. In A3Lite, two messages are used for topology construction namely hello message and parent recognition message. The node on receiving a hello message from the parent node change their status to Waiting Active and do not reply back to the parent node. Nodes itself calculates their selection metric based on their remaining energy and signal strength from the received message and uses different timeouts to register the sender as its parent node by sending a parent recognition message. In this way, nodes reduce the need of sending a large size children recognition message from the parent node. Similarly, timeouts exchange also eliminates the need of exchanging a sleeping message, which further reduces the complexity of the algorithm.

3. THE TC1 ALGORITHM

As the paper focus is on energy efficient reduced topology, the fundamental design application that we use to reduce the size of the backbone nodes is with the help of signal strength and energy based timeout criteria. The nodes selection criteria for timeout is given by

$$T_{d,s} = (E_d / E_i) + (RSS_s / RSS_c) \quad (1)$$

Where d and s represents the children node and parent node, E_d is the remaining energy level of the children node and E_i is the initial energy level. Similarly, RSS_s is the signal strength of parent node received by the children node and RSS_c is the minimum required signal strength to ensure connectivity. The selection criteria allow high energy nodes with better signal strength to be selected. This is due to the reason that the neighbors of the node select a low value for time out if they calculate a high value for selection criteria. The selected nodes serve as a virtual backbone for all the nodes in the network and hence forming a CDS.

3.1 Working of TC1 Algorithm

The TC1 constructs the topology in one phase. At start, the initiator node first discovers its neighbor. Similarly, the neighbors of the initiator node discover their neighbors as their timeout expires in the second phase. This process continues until the complete topology is formed with nodes acting as virtual backbone (CDS) for rest of the nodes in the network.

We describe the construction of the reduced topology formed with the TC1 with the help of an example network shown in figure 1. The topology construction starts in TC1 by a node called an initiator node. For algorithm implementation, we selected a random node as an initiator node and if more than one node initiates the process, the node with the largest ID is chosen. In figure 1(a), the initiator node A broadcasts a hello message to start the topology construction process. The parent node then waits to hear a message with parent ID set to its own ID. We would like to point out that the parent ID field is empty in case of the initiator node.

The nodes B, F and H, which are located within the transmission range of A receive the hello message (see figure 1(b)).The nodes after the reception of the hello message, calculates the time out and enters into sleep mode according to the value of the calculated timeout. As the time out expires, these nodes discover their neighbors further at different times and sends another hello message with parent ID field now set to node A. This allows node A to become an active node. Nodes B and F are located within each others transmission range also receives the broadcasted message by both of them. Since in both messages, the parent ID is the same, both nodes recognize them as the children of the same parent node. Similarly, node C also receives the message from nodes B and node F. In addition, node E and node I receive the message from node H and node F respectively as shown in figure 1(c).

Node E and I change the parent ID field to node H and F respectively and broadcasts the message after the timeout expires. In this way, node H and F becomes dominators/active nodes. Similarly, node C and D chooses node B as an active node by sending a message with parent ID field set to node B. It is worth noting that node C and D selected node B as their parent since they received the message firstly from node B due to low value of timeout(see figure 1(d)).This message from node D is also received at node E, which also sent the same message with different parent ID to node D. Since node E do not receive any message with its own parent ID, it discovers itself as a non-active node. Similarly, node I also perform in the same manner (see figure 1(e)).

The node G and K broadcasts the message with parent ID set to node D, which allows node D to work as an active node. On the other hand, node C gets aware due to the message reception from node J as shown in figure 1(e). In the end, node G, K and I do not receive any message with parent ID set to their own ID and therefore enter into sleep mode after the expiration of calculated timeout. In this manner, a reduced and covered topology is formed, in which some nodes work as a virtual backbone for rest of the nodes in the network as shown in figure 1(f).

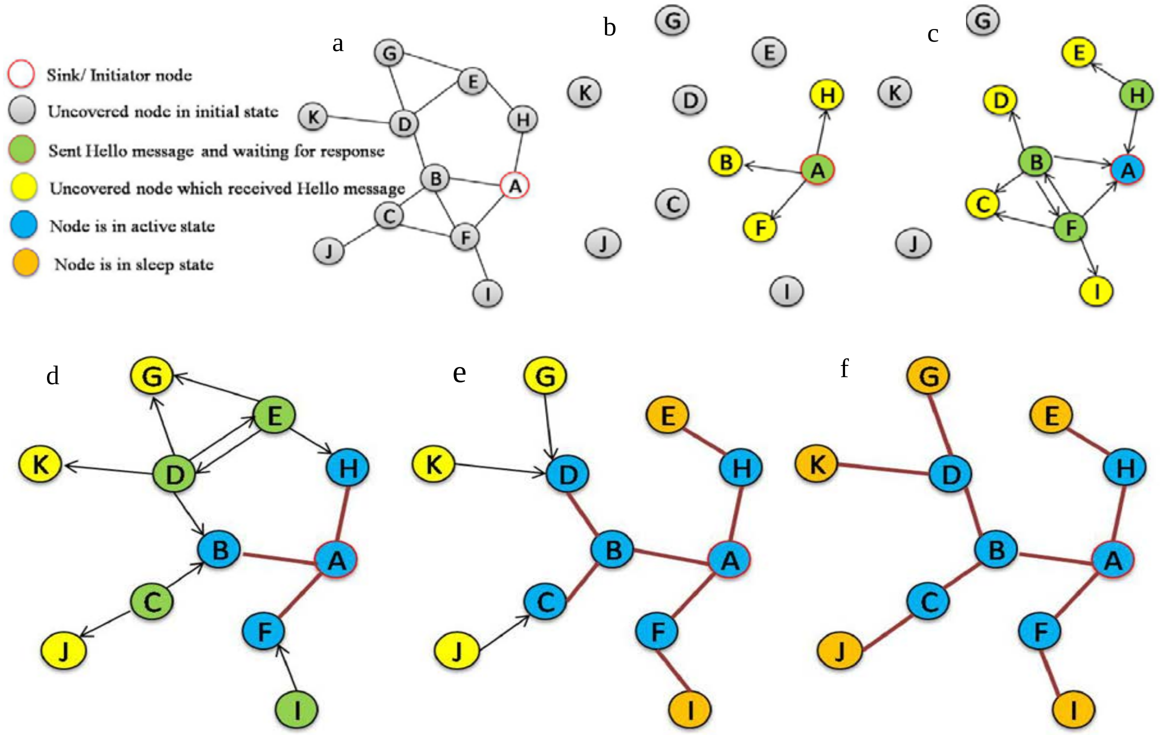

Figure 1: The TC1 Algorithm.(A) A Sample Topology.(B) Sink Node (A) Broadcasts Hello Message, Which Is Received By Nodes (B, F And H) Under Its Coverage Area. After Receiving Hello Message, B, F And H Calculate Their Time Out. (C) When Time Out Expire, B, H And F Further Broadcasts Hello Message At Different Times After Changing The Parent Id To A, Due To Which A Recognizes Its Child Nodes. A Turns Itself Active And Becomes A Parent Node. Covered Nodes B And F, Recognizes One Another As Neighbors Belonging To Same Parent Node. (D) Next Level Nodes Again Broadcast The Hello Message After Changing The Parent Id To Their Respective Parent Ids. Node D And C Chooses Node B As Its Parent Node While Node I Choose Node F As Parent Node. Similarly, Node E Chooses Node H As Its Parent Node. (E)Node G And K Broadcasts Hello Message With Parent Id Set To Node D. Similarly Node J Broadcasts Hello Message With Parent Id Set To Node C. Time Out For Hello From Children Expires At Node E And Node I, In Which These Nodes Do Not Receive Any Hello Message With Their Own Ids As Parent Id. Therefore, These Nodes Consider Themselves As Leaf Nodes And Go Into Sleep Mode. (F) Node G, K And J Do Not Receive Any Hello

Message With Their Node Id As Parent Id And Therefore Consider Themselves As Leaf Nodes To Form The Final Reduced Topology. .

3.2 Description of Topology Discovery Messages

There are several factors, which impact energy efficiency. However, energy efficiency is mainly dependent on packet size and continuous listening in promiscuous mode. Energy consumption increases with the increase in size of packets and affects both sending and receiving nodes in the network. In A3, children recognition messages contain ordered list of all the children of sender. This list is used by children to set a timer to compete for an active node. When the network is dense, this list increases with the increase in the message size and hence consumes more energy. The more the children, the more the length of the message and it will result in more energy consumption per children recognition message. Due to this reason, the A3 uses a 100 bytes size for children recognition message apart from other messages of size 25 bytes. On the other hand, the EECDS uses broadcast packet size of 25 bytes with six types of messages for topology construction, which does not exceed broadcast packet size. Similarly, the CDS Rule K also uses 25 byte broadcast packet.

In order to improve the energy efficiency, the TC1 uses only one type of message for CDS formation. A hello message of size 25 bytes contains the parent ID of the sender discovers the reduced CDS topology. The parent node do not decide the timer value for its children by sending an explicit children recognition message. Instead, children nodes calculate and set a time out period on their own after the reception of a hello message. This calculated time out is independent of time out of other nodes due to different energy and distance characteristics of the nodes. In this way, energy efficiency is achieved during topology construction and life of the network is prolonged.

The A3 and A3Lite algorithms use a selection metric that gives priority to nodes with higher energy and which are farther away from the parent node. In this way, smaller CDS set is formed, which imposes energy constraint on few nodes. On the other hand, larger CDS set provides a mechanism for active set of nodes to consume their energy in a proportionate way. In addition, larger set of active nodes provides better coverage, but cannot provide better network reliability, since average path length among nodes gets increased. Therefore, forming a larger CDS set or a smaller CDS has a tradeoff between sensing coverage and reliability. In TC1, distant nodes are not prioritized to form the reduced topology. Moreover, the nodes do not explicitly reply back to the parent node and exploits inherent broadcast medium to construct the reduced topology, when compared with A3Lite algorithm.

4.EMPIRICAL EVALUATION FRAMEWORK

This section explains the empirical evaluation framework used for the evaluation of the TC1 and other CDS algorithms, namely EECDS, CDS Rule K, and A3. For the simulations, we assumed a 600m x600m virtual space, in which nodes are randomly deployed. We have two system parameters, the number of nodes in the space and the common transmission range of nodes. The number of nodes is increased from 10 to 100 nodes. We also performed experiments for the node density beyond 100 nodes; however, the trend remains the same for all the four algorithms. Similarly, the maximum transmission range was set to 42m in order to have a connected topology. In addition, nodes sensing range was set to 10 m. In addition, to use the data unit in the experiments, the message sizes of all the four algorithms were used as explained in earlier section. In the subsequent section, the topology maintenance techniques are explained. We then provide the definitions of the evaluation metrics, on which the algorithms are evaluated.

4.1 Topology Maintenance Techniques

Topology maintenance is a process, in which a certain desired topological property is maintained to increase the network lifetime. Topology maintenance techniques are broadly classified into two categories: static maintenance and dynamic maintenance. In static maintenance, a possible set of disjoint topologies are build at the start of the maintenance operation. The pre-constructed topologies are then rotated based on the time or energy based triggering mechanism. However, static techniques calculate the overhead of pre-constructed topologies at the start, which in most cases, do not represent a realistic scenario as the backbone nodes chosen at the start can behave differently at the later stage. On the other hand, dynamic topology maintenance techniques form a new topology based on the present condition of the network, e.g. as the threshold is reached.

4.2 Definitions Of The Evaluation Metrics

In this section, we now provide formal definitions of the key concepts/metrics used in the evaluation process.

Message overhead is defined as the total number of sent and received packets in the whole network during construction of the topology.

Energy overhead is defined as the fraction of the network energy spent during an experiment.

Residual energy is defined as the remaining energy in the active set of nodes at the end of an experiment.

Unconnected nodes is defined as the number of nodes, which are disconnected from the sink/initiator node at the end of topology maintenance operation.

Connected sensing area is defined as the area covered by the connected nodes at the end of topology maintenance operation.

Most of the studies in Section 2 consider topology construction as the major process thereby ignoring the importance of topology maintenance. Our choice of parameters considers both procedures as integral parts of a topology control. Our choice of message overhead is an extremely important metric as it directly affects the energy consumed in the network. Many authors only consider the number of sent messages as the message overhead. However, we believe that message reception is also critical and, therefore, our definition of message overhead is set accordingly.

Under topology maintenance, it is important to consider the algorithms performance in terms of network connectivity. To analyze this, we selected unconnected nodes parameter to elaborate the performance of the algorithms. Finally, covered sensing area at the end of topology maintenance operation is also another important metric. This metric allows us to judge the capability of an algorithm in terms of connected nodes covering the area. An algorithm is better if it covers more area. Therefore, any algorithm designed for WSNs must try to maximize this metric. In the end, an average backbone path length differentiates an easily negotiable network from one, which is complicated and inefficient, with a shorter one stated being more desirable in many studies.

5.DISCUSSION ON SIMULATION RESULTS

We have divided the discussion on simulation results into four subsections. We start by discussing the performance of the algorithms under varying node densities. Subsequently, we discuss the performance of the algorithms under dynamic topology maintenance. We then discuss the impact of CDS size on coverage area of WSNs. In the last subsection, we compare the performance of the TC1 with A3Lite algorithm.

5.1 Impact of Node Density

The Residual energy results for varying node densities are shown in figure 2.The number of exchanged messages increases with the increase in the network size. This is due to the reason that increase in the number of nodes also leads to an increase in node degree, which also increases the number of exchanged messages. This trend is same for all the four algorithms. However, two phase topology construction leads to high message overhead for EECDS and CDS Rule K. On the other hand, A3 incurs less message overhead due to single phase topology construction. Moreover, it uses less number of messages for topology construction when compared with EECDS and CDS Rule K algorithms. In comparison, TC1 constructs the topology using one message and has less message overhead than EECDS and CDS Rule K algorithms. As can be intuitively argued, an increasing node density leads to higher energy overhead due to an increase in the number of received packets. However, TC1 consumes less energy for the construction of the topology.

Figure 2 shows the residual energy among active set of nodes for all the four algorithms. Usually, high energy overhead leads to lower residual energy. But, we observed that CDS Rule K ends up with better residual energy resources. This is due to the reason that A3 tries to reduce the virtual backbone by selecting far nodes from the parent node. This results in non-uniform distribution of communication overhead, which drains the battery of fewer nodes resulting in lower residual energy levels among nodes in the network. On the other hand, TC1 provides better residual energy when compared with all the three algorithms. This is because the nodes calculate the timeout with selection criteria, which results in balanced virtual backbone.

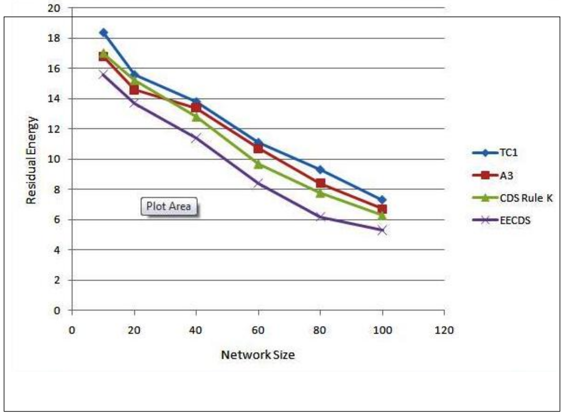

Figure 2: Performance Comparison Of Residual Energy Under Varying Network Size

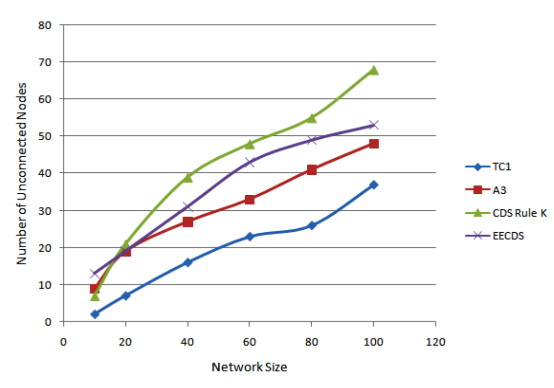

Figure 3: Performance Comparison Of Unconnected Nodes Under Dynamic Topology Maintenance

5.2. Impact of Topology Maintenance

Figure 3 shows the metric values of all the four algorithms under dynamic topology maintenance. The number of unconnected nodes increases with increase in the network size for all the four algorithms. However, CDS Rule K results in large number of unconnected nodes as shown in figure 3. In CDS Rule K, nodes remained marked if there is at least one pair of unconnected neighbors. The energy depletion of the marked node leads to higher number of unconnected nodes as compared with the other three algorithms. Moreover, it fails to provide better sensing coverage, which decreases with the increase in the number of unconnected nodes. On the other hand, A3 has less number of unconnected nodes due to its node selection process based on signal strength metric and provides better sensing coverage. In comparison, TC1 results in very less number of unconnected nodes, which on the other hand provides better sensing coverage when compared with all the three algorithms.

It is interesting to note that though the number of unconnected nodes increases in EECDS, it results in providing better sensing coverage. This is due the reason that its two phase topology construction results in forming a proportionate CDS topology with more connected nodes covering the virtual area much better than CDS Rule K.

5.3 Performance Comparison With A3 Lite

We compared the performance of the TC1 with recently proposed A3Lite. The residual energy results for random are shown in figure 4. The results demonstrate that TC1 algorithm exchanges less number of messages as part of topology construction, which on the other hand reduces the energy overhead. This allows more residual energy among CDS nodes at the end of the constructed topology.

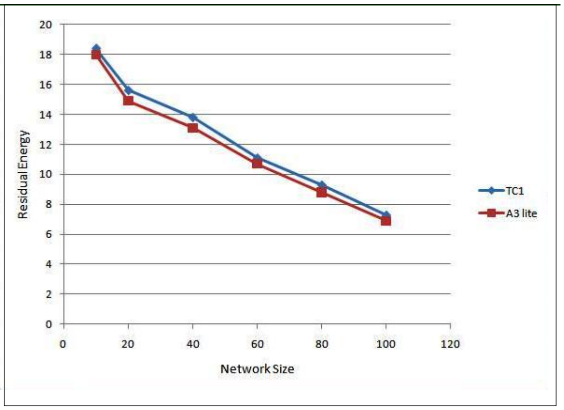

Figure 4: Performance Comparison Of Residual Energy Under Varying Network Size

6. CONCLUSIONS

In this paper, we have investigated the problem of constructing a CDS, which provides better sensing coverage in an energy efficient manner. Our observations reveal that single phase topology construction with fewer number of messages lead towards an efficient algorithm. Due to this reason, TC1 outperforms other algorithms by using far less messages for topology construction. To validate the results, simulations are performed over a large operational spectrum to compare with EECDS, CDS Rule K, and A3 algorithms. The results show that TC1 has low message complexity and incurs less energy consumption. Moreover, it covers more sensing area under its coverage region and has better connectivity characteristics when tested under topology maintenance operation. Therefore, topology maintenance should also be considered for topology construction algorithms.

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