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PERFORMANCE EVALUATION OF TOPOLOGY CONTROL ALGORITHMS FOR WIRELESS SENSOR NETWORKS

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ABSTRACT

Topology control is a technique implemented in wireless sensor networks to conserve energy and prolong the network lifetime while maintaining the network connectivity and coverage. The implementation of a topology control involves two phases, which are the topology construction, which builds a reduced topology, and topology maintenance, which restores, rotates or recreates the topology. This paper aims to evaluate the performance of topology control protocol based on several topology construction-topology maintenance combinations. Two energy-based topology maintenance algorithms are considered here, namely Energy Local Patching DSR and Hybrid Global Energy Topology Recreation Rotation. These topology maintenance algorithms are implemented on the underlying topology constructed by four selected topology construction algorithms known as the A3, Connected Dominating Set Rule K, KNEIGH Tree and Energy Efficient Connected Dominating Set. The experiments are conducted through a series of simulations for a 100-node network scenario by using a discrete event simulator known as Atarraya. The simulation results show that the combination of Energy Local Patching DSR and A3 consumes the least energy compared to other combinations by at least 36%. It can be concluded that CDS-based topology construction algorithms outperform KNEIGH Tree algorithm by an average factor of 6.5 in terms of the network lifetime. In addition, the Energy Local Patching DSR algorithm suits the CDS-based topology construction algorithms well, while Hybrid Global Energy Topology Recreation Rotation algorithm enhances the energy efficiency of the KNEIGH Tree algorithm.

Keywords: topology control, energy efficiency, wireless sensor network.

INTRODUCTION

Wireless sensor networks (WSNs) are the best alternative to replace the traditional wired systems in monitoring applications because they offer a lower installation and maintenance cost. The wireless virtual infrastructure built in WSNs makes it possible for them to be deployed in hazardous and remote area. In addition, these networks are very versatile in such a way that they have the self-organization capability, flexible and scalable [1]–[3]. Despite the advantage of having the wireless solutions implemented in various applications such as environmental monitoring, factory automation, tracking systems, patient monitoring and disaster relief, WSNs are still facing a major issue, which is the scarcity of energy resource.

One of the strategies used to enhance energy conservation in WSNs is by implementing a topology control protocol [1, 4, 5]. Topology control is an iterative process which consists of two levels of mechanisms. The first mechanism is the topology construction that executes the process of building a reduced topology, while the second mechanism is the topology maintenance that restores, rotates or recreates the reduced topology when it is triggered.

The techniques applied in topology control are designed to efficiently consume the available energy resource while preserving other important network properties such as connectivity and coverage. An efficient topology control protocol is very important to accommodate an efficient data transmission and routing protocol at the upper layer of the protocol stack.

This paper aims to evaluate the performance of several topology construction-topology maintenance combinations. Two energy-based topology maintenance algorithms are considered in this paper. The first algorithm is called Energy Local Patching DSR, which is a local approach topology maintenance algorithm. The second algorithm is the Hybrid Global Energy Topology Recreation Rotation (HGETRecRot), which is a global approach topology maintenance algorithm. These topology maintenance algorithms are implemented on the underlying topology constructed by four selected topology construction algorithms, namely the A3 (a tree), Connected Dominating Set (CDS) Rule K, KNEIGH Tree and Energy Efficient Connected Dominating Set (EECDS). Three performance indicators are measured to examine the performance of topology control protocols, which are the total energy spent ratio, the number of active nodes from the sink and the network lifetime.

The rest of the paper is organized as follows. The following section gives an overview of the topology control. Then, the experiments carried out on topology control performance evaluation are described, followed by the simulation results and performance analysis. The final section concludes the paper.

TOPOLOGY CONTROL OVERVIEW

The implementation of a topology control involves two phases, which are the topology construction and topology maintenance. The first phase involves the mechanism of finding a reduced topology while preserving the network connectivity and coverage. The second phase maintains the network performance by changing the

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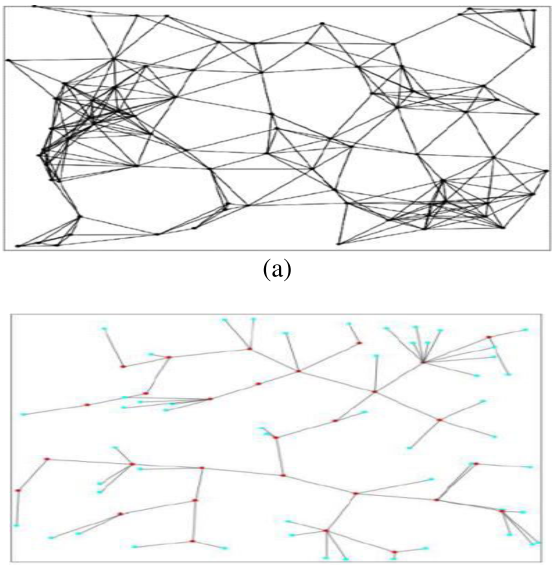
topology based on predetermined criteria such as residual energy and timeout period. The choice of the topology construction algorithm and topology maintenance algorithm will affect the energy consumption and therefore affect the network lifetime.

Figure-1(a) shows an initial connected graph of a WSN with high density active nodes. The topology shown in the figure guarantees a full network coverage and connectivity where there is at least one route available to connect one node to another. However, the possibility of interference and occurrence of collisions is very high when many nodes are sending and receiving data simultaneously [4]. In addition, there will be tremendous redundant data received by the sink node as well intermediate nodes since the nodes are located very close to each other and apparently will be sensing and sending the same data. Too many data transmission and reception will rapidly drain the energy and therefore shorten the network lifetime. Then again, interference and collisions produce low data throughput and therefore degrades the network performance. For that reason, topology reorganization is crucial to reduce interference and eliminate the redundant data generation.

Reorganization of the network topology can be done by forming a communication backbone that connects the whole network via several selected nodes. The nodes that form the backbone are chosen based on their current condition such as residual energy and location. Figure-1(b) shows a reduced topology produced after implementing a topology construction algorithm. From the figure, only active nodes will activate their transceiver while other nodes will be turned off and go into sleep mode where the energy consumption is very low. During latter operation cycles, the role of the nodes will be rotated according to their current condition by applying a topology maintenance algorithm.



(a)

(b)

Figure-1(a). Original connection of a network, (b). Reduced topology after topology control is implemented.

Topology construction algorithms

In this paper, the mechanism and performance of four distributed TC algorithms, namely A3, CDS Rule K, KNEIGH Tree and EECDS are studied. The first topology construction algorithm is the A3 [6]. The A3 is a growing tree-based algorithm which uses the distance between the nodes and node's remaining energy as the selection metric. The tree creation process is initiated by the sink node and followed by the selection of minimal number of children nodes to create a communication backbone. In the children selection process, one-hop neighbor nodes communicate locally to decide which nodes will be activated based on the node's priority listed in the metric list.

The second topology construction algorithm is the CDS Rule K [7]. It is a different version of original CDS-based algorithms in which it combines marking and pruning techniques during the communication backbone creation process. In the first stage of the algorithm, most of the nodes are selected to form a preliminary topology in order to guarantee the network connectivity. Then, the pruning process will discard the redundant nodes whose neighbors have joined the tree based on the node priority. The discarded nodes are sent to sleep mode to conserve energy and will be turned on in latter cycles.

The third topology construction algorithm is the KNEIGH Tree algorithm, which is proposed by Blough and Leoncini in [8]. The main idea of KNEIGH Tree is to create a symmetric and compact sub-graph in which every node possesses k logical neighbors. With the known neighbors, the active nodes are able to control the transmission power level suitable for their neighbors' reception to conserve energy.

The last topology construction algorithm is a CDS-based algorithm called Energy Efficient Connected Dominating Set (EECDS) proposed in [9]. This algorithm applies an inversed procedure that of the A3 in which it creates several maximal independent sets (MISs) of CDS tree, then finds the best way to connect the MISs to form an optimal communication backbone.

Topology maintenance algorithms

Once the reduced topology has been established by the topology construction algorithm, a topology maintenance algorithm plays its role to further enhance the energy conservation. Topology maintenance algorithms can be categorized into three types, which are static, dynamic and hybrid algorithms [6]. There are several well-developed topology maintenance algorithms available in Atarraya, which are Static Global Time Topology Rotation (SGTTRot), Static Global Energy Topology Rotation (SGETRot), Dynamic Global Time Topology Recreation (DGTTRec), Dynamic Global Energy Topology Recreation (DGETRec), Hybrid Global Time Topology Recreation Rotation (HGTTRecRot) and Hybrid Global Energy Topology Recreation Rotation (HGETRecRot) [10].

The technique applied in a topology maintenance algorithm depends on specific triggering criteria which can be either a time-based, energy-based, random-based,

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failure-based or density-based criteria [6]. This paper focuses on two energy-based topology maintenance algorithms, which are Energy Local Patching DSR and Hybrid Global Energy Topology Recreation Rotation (HGETRecRot). The Energy Local Patching DSR [6] is a local recovery technique in which the triggering process is invoked by a node that possesses a residual energy level below the predetermined threshold. The energy depleted node will find a new parent to its children nodes in order to ensure continuous connectivity. This mechanism is very important especially for CDS-based topologies constructed by topology construction algorithms like A3, CDS Rule K and EECDS where a branch can be a parent to many other branches.

In contrast to Energy Local Patching DSR, the implementation of HGETRecRot is done at the global stage where the whole topology is rotated among the pre-planned topologies. However, like the previous mentioned topology maintenance algorithm, the energy level of the nodes is used as the triggering criteria. To a certain state where all the pre-planned topologies degrade in the connectivity, the sink will broadcast a reset message so that the topology construction algorithm is executed once again.

TOPOLOGY CONTROL PERFORMANCE EVALUATION

The experiments are executed through a series of simulation by using a discrete event simulator namely Atarraya. Table-1 summarizes the combinations of topology construction and topology maintenance algorithms that are used to run the experiments. In this paper, the Energy Local Patching DSR and HGETRecRot algorithms are chosen to examine the performance of local and global approaches respectively. Each of these two topology maintenance algorithms is implemented over the underlying topology constructed by four different topology construction algorithms, which are A3, CDS Rule K, KNEIGH Tree and EECDS.

Table-1. Combinations of topology maintenance and topology construction algorithms.

Involvement Level	Topology Maintenance	Topology Construction
Local	Energy Local Patching DSR	A3
		CDS Rule K
		KNEIGH Tree
		EECDS
Global	HGETRecRot	A3
		CDS Rule K
		KNEIGH Tree
		EECDS

The energy calculation for data transmission and reception used in Atarraya is based on the simplest energy model [11] as in Equation (1) and (2), respectively.

$$E_{Tx}(k,d) = E_{elec} * k + \epsilon_{amp} * k * d^2 \quad (1)$$

$$E_{Rx}(k) = E_{elec} * k \quad (2)$$

The term E_{elec} represents the energy used to run the transmitter circuitry in nJ/bit and ϵ_{amp} represents the energy used by amplifier to achieve acceptable signal to noise ratio (SNR) in pJ/bit/m^2. In all simulations, a sensor is assumed to spend no energy during idle time and has the ability to wake up when triggered by the algorithm, and also the sink node is assumed of an energy rich node.

Table-2 summarizes the most important simulation parameters set in the network scenario deployment. In all simulations, it is assumed that no data aggregation is implemented at the parent nodes, therefore the data from an active node will be disseminated to the sink as an individual packet. All active nodes are scheduled to send data to the sink in every 10 time units based on a simple routing algorithm. The energy threshold is set to 10% of the total energy to trigger the topology maintenance mechanism.

Table-2. Simulation parameters for scenario deployment.

Parameters	Value
Number of nodes	100
Number of sink	1
Communication radius	100 m
Sensing radius	20 m
Deployment area	600X600m
Node distribution	Uniform
Sensor and data protocol	Simple
Routing protocol	Simple forwarding
Energy distribution	Uniform
Inter query time	10 clock cycles
Energy threshold	10%
A3 Weights	$W_E = 0.5$, $W_D = 0.5$
Energy Consumption	E_{elec}= 50nJ/bit ϵ_{amp} = 10pJ/bit/m^2
Number of reduced topologies for HGETRecRot	3

SIMULATION RESULTS

Figure-2 shows the comparison of total energy spent ratio obtained when two energy-based topology maintenance algorithms are implemented on the underlying reduced topology built by the four selected topology construction algorithms. The bar chart provides two insights. Firstly, it shows the overall performance of the topology construction algorithms where it seems that the A3 offers the least energy consumption, while KNEIGH tree spends the highest energy when implemented on a 100-node network size. This reflects that the A3 builds a more compact topology since the active nodes that form the communication backbone are chosen based on the shortest distance between them. Subsequently, the data transmissions between the nodes occur within short distances and spend small amounts of energy.

Secondly, it depicts that Energy Local Patching DSR outperforms HGETRecRot when combined with all three CDS-based topology construction algorithms, which are A3, CDS Rule K and EECDS. It is apparent that energy patching technique used in the local approach attempts to maintain the reduced topology every time the algorithm is invoked. Hence, as long as a depleted node is still having healthy neighbors to replace its role, the data is transmitted at relatively short distances. On the other hand, the global approach topology maintenance is more suitable to be implemented on KNEIGH Tree since it needs a global knowledge to maintain symmetrical paths between each pair of the active nodes. Replacing some nodes by using local approach might ruin the symmetrical geometry of the topology.

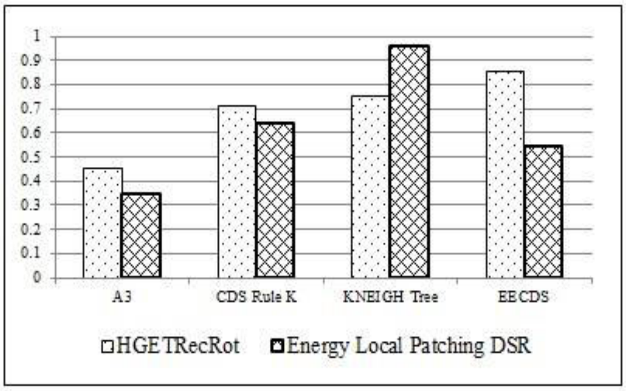

Figure-2. Total energy spent ratio for all cases.

The network lifetime measured in terms of the number of nodes reachable from the sink for Energy Local Patching DSR and HGETRecRot based on the four selected topology control algorithms is depicted in Figure-3 and Figure-4, respectively. The trend of the graphs shown in both figures is distinctive. From Figure-3, it can be seen that the number of nodes reachable from the sink decays exponentially over time. This evidence suggests that although there is a local procedure that restores the network connectivity when some of the nodes have reached the energy threshold, the nodes that are closer to the sink will die out after several rounds of protocol implementation, leaving the farther nodes unreachable from the sink. From this observation, it can be predicted that although there are still living nodes in the field, the network operation is halted since the sink is incapable to rebuild the connected tree.

Conversely, the fluctuation in the graph of Figure4 is the result of the ability to rotate and recreate the topology applied in HGETRecRot algorithm. Whenever the remaining energy reaches the energy threshold, the topology maintenance algorithm is invoked to rotate the topology among the pre-constructed ones. Then, when the performance of all pre-constructed topologies degrades, HGETRecRot will trigger the sink to recreate a new reduced topology on the fly. In this case, HGETRecRot topology maintenance algorithm triggers the A3 to recreate a new topology after 8500 time units, while the first triggering procedure in CDS Rule K, KNEIGH Tree and EECDS algorithms occurs after 3000 to 4000 time units. This shows that the topology constructed based on the A3 algorithm consumes the least energy since it takes a longer time to reach the energy threshold.

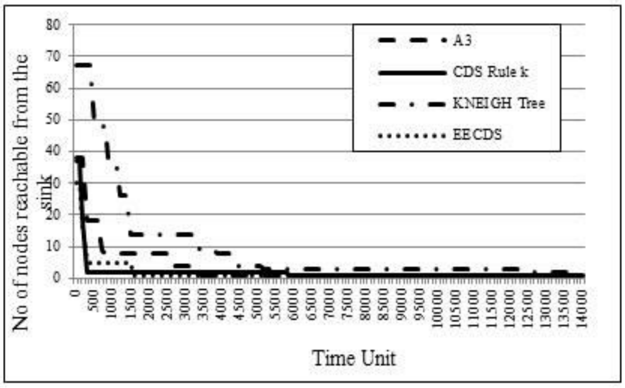

Figure-3. The network lifetime of Energy Local Patching DSR based on various topology constructions in terms of number of nodes reachable from the sink.

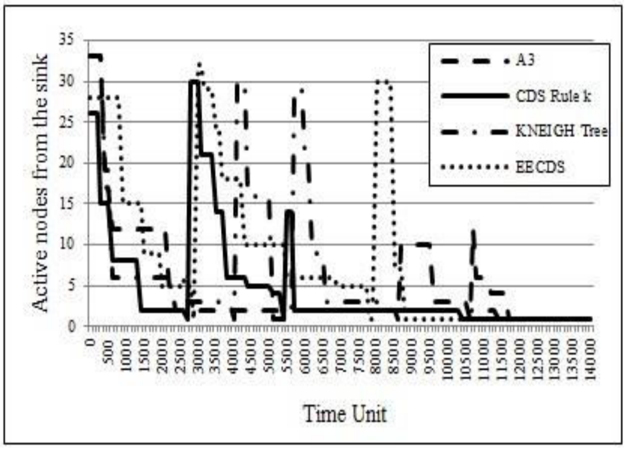

Figure-4. The network lifetime of HGETRecRot based on various topology constructions in terms of number of nodes reachable from the sink.

Figure-5 plots the network lifetime measured in terms of number of nodes alive over the simulation time for Energy Local Patching DSR algorithm based on the four selected topology construction algorithms. It seems that the performance of all CDS-based topology control algorithms is marginal where the first node dies after 3000 time units. The network operation is almost constant after this point until the number of living nodes reaches 80. This is in contrast to that of the KNEIGH Tree algorithm where the first node dies after 400 time units and the number of living nodes degrades drastically after that point. It can be concluded that all CDS-based topology control algorithms outperform KNEIGH Tree algorithm by an average factor of 6.5.

Figure-6 plots the network lifetime measured in terms of number of nodes alive over the simulation time for HGETRecRot algorithm based on the four selected topology construction algorithms. The first node dies at almost the same simulation time for all topology control algorithms. However, the A3 algorithm outperforms other algorithms where the number of living nodes is maintained at over 80% for the longest period. The KNEIGH Tree and CDS Rule K have a moderate performance where they maintain the number of living nodes at almost 70% until 16000 time units. This is in contrast to that of the EECDS algorithm in which the number of living nodes degrades drastically after the first node dies.

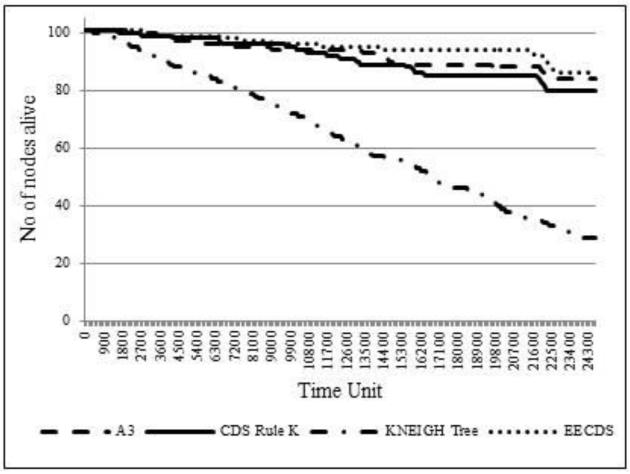

Figure-5. The network lifetime of Energy Local Patching DSR based on various topology construction algorithms.

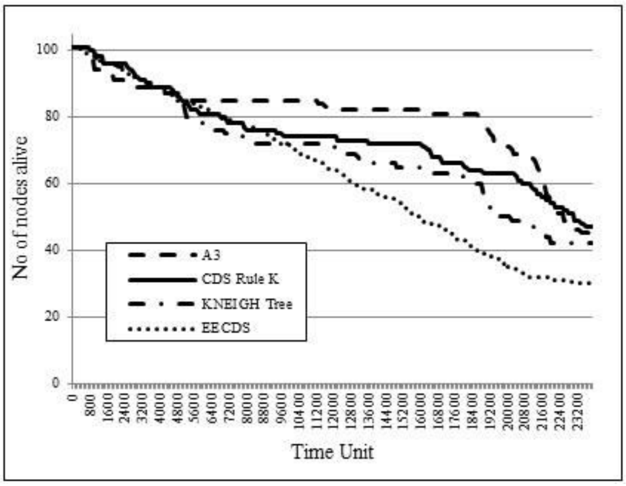

Figure-6. The network lifetime of HGETRecRot based on various topology construction algorithms.

CONCLUSIONS

This paper evaluates the performance of several topology construction-topology maintenance combinations. Two energy-based topology maintenance algorithms, which are Energy Local Patching DSR and HGETRecRot, are considered, which implement local and global approach respectively. These topology maintenance algorithms are implemented on the underlying topology constructed by four selected topology construction algorithms, namely the A3, CDS Rule K, KNEIGH Tree and EECDS. The performance of the topology construction-topology maintenance combinations are investigated by using three performance indicators, which are the total energy spent ratio, the number of active nodes from the sink and the network lifetime. It has been shown that the local approach based on the A3 topology construction algorithm consumes less energy compared to other combinations by at least 36%. In terms of the network lifetime, it can be concluded that all CDS-based topology control algorithms outperform KNEIGH Tree algorithm by an average factor of 6.5. To sum up, according to the obtained results, the Energy Local Patching DSR algorithm suits the CDS-based topology construction algorithms well, while HGETRecRot algorithm can enhance the energy efficiency of the KNEIGH Tree algorithm.

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