A Survey on Topology Maintenance Techniques to Extend the Lifetime of Wireless Sensor Networks

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Abstract. Wireless Sensor Network (WSN) is a well known technology due to its applications in diverse fields including both civil and military domain. However, being battery powered, the network lifetime of WSN is hugely dependent on how efficiently this battery power is utilized. Topology Control consisting of Topology Construction and Topology Maintenance, is a popular technique to conserve energy and extend the lifetime of WSN by building and maintaining a reduced topology that offers both connectivity and coverage. Topology Maintenance rebuilds a new topology once the current topology is no longer optimal. In this survey, our focus is on the issue of energy efficiency and we have presented a thorough analysis of current topology maintenance techniques for prolonging the battery lifetime of wireless sensor nodes. We have classified Topology Maintenance according to the energy conservation technique adopted by each algorithm, and have evaluated them on the basis of trade-offs offered by each approach to guide designers in opting for a technique that fulfills their application needs. In addition, we also provide insight with the help of simulation results.

Keywords: Topology Maintenance, WSN lifetime , Energy conservation.

1 Introduction

Recent advancements in technology have made it possible to deploy small, low-power, low-cost, and distributed devices, that are able to perform self-processing, self configuration and having capability of wireless communication [1]. These devices are known as motes or sensor nodes and the network formed by these devices is known as a Wireless Sensor Network (WSN). Because of the limitation in size and cost, each node in the WSNs can support only restricted processing, however, when coordinated with the data received from countless other nodes present in the network they have the capability to measure and report a given physical environment in elaborate detail [2].

The significant challenges for the realization of WSNs are its resource restraints. Being minute in size and inexpensive WSNs are susceptible to failure. The most fundamental issue in the functioning of WSNs is that wireless sensor

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nodes have a very constrained allocation of energy [3]. Most of the sensor nodes are battery powered and battery is not an infinite source of energy, therefore the energy of battery powered sensor nodes depletes after a period of time. It is not practical to change these batteries frequently particularly in harsh or unreachable environments and conditions. Therefore, the only viable option left is to use whatever available energy there is wisely, so that the nodes battery lifetime can be extended. The lifetime of the WSNs greatly depends upon individual nodes energies. Therefore, energy efficiency is the most critical issue in WSNs. In order for nodes to have an extended period of autonomy, algorithms/protocols that enable in optimizing battery usage are required, so that the life of individual nodes and the lifespan of the network as a whole can be extended [4].

To guarantee network longevity, reliability, security and survivability, WSNs are required to have strong network recovery capabilities. Therefore, the requirement of network maintenance algorithms/protocols becomes more and more important [5].

Topology Maintenance (TM) is a critical issue in WSNs. Once the initial topology built by Topology Construction (TC), is no longer optimal, Topology Maintenance is invoked which recreates the existing topology, thus extending the lifetime of network. Many TM algorithms/protocols exist in literature. The choice of topology maintenance algorithm plays an important role in the lifetime and functioning of network.

In this survey paper, we have examined and analysed various topology maintenance techniques existing in literature. We have covered recent developments in this area including prior work done in this area. What differentiates our survey from earlier works is manner in which topology maintenance techniques are classified. We have characterized TM schemes into two classes, distributed and centralized.

The rest of the paper is divided as follows. Section II provides an overview of Topology Control. Section III gives a description of the main types of Topology Maintenance techniques and gives a brief overview of the latest and most popular topology maintenance techniques existing in literature. Section IV presents the performance evaluation. Finally, the paper is concluded in Section V.

2 Related Work

Topology Control is an efficient way of conserving energy of battery powered sensor nodes. Topology control is comprised of two components namely; topology construction and topology maintenance.

Topology construction is the initial process of building a reduced topology once the sensor nodes are deployed and activated [6].Topology construction mechanisms ensure that the new topology built will result in better energy conservation at the same time making sure that the network remains connected and provides maximum coverage.

While TC is invoked only once at the start, TM is a continuous process that starts after the initial topology has been constructed. TM is described as the process that recreates or rotates the topology of the network, whenever the current topology is no more sufficient.

The topology maintenance protocols leverage node redundancy. These algorithms maintain the topology of the network and the state of the nodes, rotating the role of nodes between an active and sleep state. The main idea behind the application of these techniques is to keep as few active nodes as attainable [7]. The active nodes selected by these protocols should be adequate to provide network connectivity and/or the sensing coverage. This scheduling of nodes, keeping only those nodes active that will keep the network connected and covered, results in extending the network lifetime.

The main focus of this survey is on topology maintenance schemes that extends network lifetime by maintaining active and inactive nodes.

2.1 Design Issues in Topology Maintenance

For an efficient topology maintenance process that provides the anticipated outcome in terms of prolonging the network lifetime, it is important that the TM techniques must be designed such that they fulfill the following conditions:

Energy efficiency: The topology maintenance technique must be energy efficient and the topology maintenance process should result in reducing the energy consumption.

Low overhead: Number of messages exchanged should be controlled as it creates an overhead and ultimately results in extensive consumption of energy.

Low convergence time: When a new topology takes over the old one, there is a transition time during which the takeover takes place and during this time the network or part of the network remains inactive. Therefore, it is important to keep this transition time/convergence time as low as possible.

Memory consumption: As sensor nodes have limited memory, it is important to design our algorithms that take into account this aspect.TM techniques such as static global (described later) that pre-calculate and store all the possible topologies beforehand use up a lot of memory.

2.2 Classification of Topology Maintenance Algorithms

Topology maintenance can be classified into several categories based on when TM process takes place, the triggering criteria and their scope.

Time of Building Reduced Topology. Based on time of creating the new topology, TM techniques are classified as Static, Dynamic and Hybrid TM techniques.

The protocols based on Static TM rotate existing topology with any one of the pre calculated topologies when needed. Static TM algorithms pre-calculate all possible topologies at the time of topology construction and store these topologies in memory. Although static techniques take an additional time during TC as they have to calculate several possible topologies, but they take least amount of time during TM process. A drawback with static techniques is that these protocols do not take into account the current status of the network.

Dynamic Topology Maintenance algorithms as the name implies are dynamic creating topologies on the fly. Although dynamic TM techniques take longer during recreating topologies and take extra resources every time they are run, but the obvious advantage is that dynamic techniques use the current network information while recreating topologies.

Hybrid Topology Maintenance technique is a combination of both static and dynamic techniques. In Hybrid TM, several topologies are calculated during the TC process as in static techniques. However, when the static topologies can no longer be applied the mechanism finds a new topology dynamically.

Triggering Criteria. Another important criteria when designing and selecting a TM protocol is the triggering criteria, that is what triggers the TM process. Triggering criteria plays an important role in the functioning of WSNs in terms of their energy consumption, coverage and/or reliability. Most of the TM protocols are either time- based, energy based or in some cases failure or density based.

Scope of the network. Scope of TM may either be global or local. Global or Centralized TM algorithms involve all the network nodes during TM for making a global optimal decision. In most cases, the global technique involves the sink node, which makes topology recreation decision and all the other nodes change their topology accordingly. In most of the cases, global TM switches the complete network topology.

On the contrary, a local or distributed TM technique involves only a small subset of nodes while making a local optimal decision. The advantage that this technique offers is that as it involves only a limited subset of nodes, this technique results in consuming less energy as compared to a global technique.

In this survey paper, we have focused on distinguishing the existing centralized topology maintenance schemes from distributed schemes. In the next section, a detailed analysis of both of these schemes is given including their inherent benefits and drawbacks.

3 Centralized vs. Distributed Topology Maintenance Schemes

As discussed in Section II, in centralized TM solutions, the sink node makes the recreation decision. The new topology is then broadcast to the entire network. Although centralized or global approaches are applicable in most of the scenarios and are easier to develop, these approaches have a single point of failure and may result in increased overhead particularly when the network size is increased and information has to transverse through several hops. Distributed TM schemes work on a small scale of nodes particularly those nodes that are in the neighbors of the node that has to be replaced. Some prominent global and local TM schemes are discussed below.

3.1 Distributed Topology Maintenance Schemes

Distributed or local topology maintenance schemes involve a limited number of nodes. Recent research has been focused on developing distributed Topology Maintenance techniques as these techniques can guarantee efficient energy consumption. Some of the latest and most popular TM techniques in this area are discussed below.

DL-DSR. Dynamic Local DSR or DL-DSR is a distributed energy based distributed and dynamic TM technique which follows the Dynamic Source Routing (DSR) [8] protocol for wireless networks. DL-DSR follows CDS based approach where nodes are arranged hierarchically in a parent child manner. It is a dynamic protocol which is initiated whenever the energy of a node drops below a threshold.

The protocol works in two phases to find substitute for a node whose energy has depleted to a specific level. The substitute node must be able to take over the new orphaned child nodes. The protocol explained in [9] sends Wakeup and Route Request messages to the neighboring nodes to replace the parent node whose energy has depleted with a new parent node which takes over all orphaned nodes.

The topology is recreated locally, without the need of involving the sink node. The benefit of this protocol is that it has small message overhead as compared to global techniques. The main advantage is that with the increase in the node density, the message overhead remains almost constant.

Efficient Topology Maintenance Scheme for Wireless Sensor Networks. Efficient Topology Maintenance Scheme for Wireless Sensor Networks or EETMS [10] is also a distributed and dynamic TM protocol. This protocol is failure based.

EETMS recreates topologies by controlling the transmission power of the neighboring nodes of the failed node, such that the network remains connected. There are two strategies proposed in [10] that achieves this goal. The first strategy is to connect all immediate neighbors of faulty node by adjusting the transmission power of all immediate nodes. This approach connects all immediate nodes of faulty node with the shortest link.

In the second strategy, the approach is to achieve a connected local network with the minimal possible power (the sum of the path lengths) using a Breadth First Search (BFS) mechanism.

Authors in [10] have shown that EETMS results in lesser power stretch factor which indicates lower energy consumption as compared to similar protocols that work on the same principle such as RLS [13] and other new power based Topology Maintenance scheme proposed in [11], [12]. The authors have also shown that over time EETMS gives more number of active neighbors as compared to RLS thus indicating an increase in lifetime of the network. The drawback of this approach is that, although it conserves the network energy in an efficient manner but it is a failure based approach that means that a nodes energy is completely drained out before it starts the maintenance process. This means high convergence time as there may be several dead nodes in the network.

ASCENT. Adaptive Self-Configuring Sensor Network Topology or ASCENT [7] is a distributed protocol capable of self-reconfiguration. This protocol allows nodes to monitor operating conditions locally. On the basis of these conditions, nodes make a decision whether or not they should be participating in routing. For achieving efficiency of energy, ASCENT picks only a subset of nodes to stay in an active state that act as routing backbone. Rest of the nodes in the network remain in a passive state. The nodes that are passive periodically listen to other neighboring nodes for inspecting whether they have to become part of the routing backbone by changing to active state. For instance, when there is a higher rate of packet loss, the passive nodes are turned active in order to preserve connectivity. Otherwise the passive nodes keep their radios turned off to save battery power.

Nodes in ASCENT remain in one of the four states, namely test state, passive state, active state and sleep state [7].

The advantage of this protocol is that it is self-reconfigurable and adaptive to react to applications dynamic events. However, its disadvantage is that due to uneven load distribution it may result in rapid energy depletion among active nodes.

It is worth mentioning that ASCENT takes topology control as a single process and does not separates the maintenance part. Therefore, it cannot be used with many TC algorithms such as A3 [14], EECDS [15], A1 [16]. For the maintenance part of such algorithms, we require a topology maintenance algorithm that should be integrated with topology construction algorithms. To the best of our knowledge, such algorithms are very rare and each algorithm is designed to fill its own gap. As an example, EEMTS only takes failure as the criterion to switch the topology. However, in many critical applications, we want to trigger the topology based on the energy threshold. Similarly, distributed CDS based topology construction algorithms have been proposed (A3, EECDS, A1), but their topology maintenance part is completely centralized. Table 1 distinguishes the three distributed topology maintenance algorithms based on their design principles.

3.2 Centralized Topology Maintenance Schemes

Centralized TM schemes such as Dynamic Global Energy based Topology Recreation (DGETRec) and Dynamic Global Time based Topology Recreation (DGTTRec) are very prominent TM algorithms/protocols due to their simplicity and practicality. Although the focus of recent research has shifted to distributed techniques, but global techniques continue to be employed in WSNs. Centralized TM protocols are divided on the basis of when the topologies are built. The three main types of centralized topology maintenance schemes are discussed below.

Static Global Topology Rotation (SGTRot). The Static Global Topology Rotation is a centralized and static approach for rebuilding topologies. It can

Table 1. Comparison of Distributed Topology Maintenance Algorithms

Design issues	DL-DSR	ASCENT	EETMS
TM Mode	CDS based	CDS based	Power control
TC/TM	TM	both TC and TM	TM
Triggering criteria	Energy based	Energy based	Failure based
Energy Efficiency	High	Medium	High
Message overhead	Low	Medium	Low
Integration with TC algorithms	All CDS TC algos	TC algo same as TM algo	not applicable on CDS based TC algos

either be time triggered or energy triggered. SGTRot builds multiple reduced topologies during TC phase and these topologies are rotated when the current topology needs to be changed. The main assumption of Static Global techniques is that nodes keep track of several Virtual Network Interfaces, or VNIs at a time. These VNIs include information pertinent to a node regarding each individual reduced topology created in the network like: address, state of the node (active, inactive or sink), routing information, etc. Whenever a topology has to be rotated, each node quickly converges to a new VNI.

The protocol is quite simple. Whenever a trigger is initiated in any of the nodes, it will transmit a Notification Message to the sink node thus intimidating the sink node that its trigger has gone off. On receiving the Notification message, the sink node decides whether the occurrence of the triggering event is sufficient enough to initiate the rotation process. If the sink node decides that it does not have sufficient active nodes in the neighborhood it will rotate the topology by moving on to the next VNI. After each rotation, the sink node evaluates whether there is at least one active neighboring node. If there are no active nodes in the sinks neighborhood, the network is considered dead.

Dynamic Global Topology Recreation. The Dynamic Global Topology Recreation (DGTRec) is perhaps the most frequently employed topology maintenance techniques as it is the simplest technique and does not require any pre calculated information or VNI and can be easily employed over any type of sensor network. Another reason for their popularity is because these protocols are closely associated with the topology construction protocols.

Based on the triggering criterion, DGETRec is further classified into two types namely Dynamic Global Energy-based Topology Recreation (DGETRec) and Dynamic Global Time-based Topology Reconstruction (DGTTRec). DGETRec is an energy based scheme, thus a topology is recreated once the energy of a node drops below a threshold while DGTTRec is a time based approach which is initiated after particular time intervals.

Similar to SGTRot, topology maintenance is initiated whenever the triggering criterion is met. The bottleneck node will send a Notification Message to the sink node, notifying the sink node that an event has occurred. On the arrival of the Notification message to the sink node, the sink node makes a decision whether or not the occurrence of this triggering event is reason enough to initiate the topology rotation process. In the scenario, in which sink node considers that a rotation is crucial for the network, the sink node will transmit a Reset Message and, if it is the only sink in the topology, it will schedule a new execution of the topology construction protocol initially applied to reduce the topology. On receiving a Reset Message, a node will immediately forward that message to all its neighboring nodes and then the node will get rid of all the information related to the current reduced topology, and will move itself into the initial state of the topology construction protocol, where it waits for new execution [17].

Hybrid Global Topology Recreation and Rotation. HGTRecRot or Hybrid Global Topology Recreation and Rotation combines the best of both static and dynamic techniques giving us a protocol that works both statically and dynamically. Like a static protocol, HGTRecRot creates several VNIs at the start of TC and when needed these VNIs can be applied as in the case of static protocols. However, once the calculated VNIs cannot be applied for example when the sink node detects it has been isolated from the network, HGTRecRot invoke dynamic topology maintenance. The sink node then transmits a Reset message to all its neighbors which is forwarded to rest of the network. By sending a Reset message the sink node invokes the TC to update the current VNI as in DGTRec. After resetting the current VNI, the sink node still remains isolated, it will eliminate the current VNI from the list of available ones and will rotate to the next VNI. If there are no more VNIs available, then the sink will determine that the network is dead [17].

4 Performance Evaluation

In order to evaluate the algorithms, in this section, we summarize our findings by performing simulations to study the performance of some topology maintenance algorithms. All simulations are done in Atarraya [18], an event driven simulator that caters for topology construction, maintenance and sensor and coverage protocols. The purpose of these simulations is to determine which TM algorithm will result in efficient energy consumption. Topology Maintenance algorithms have been applied over A3 Topology Construction algorithm [14] in both sparse and dense networks.

Although this survey paper has included TM techniques based on power control but our survey only includes CDS based TM approaches as power based approaches come under another class of power management techniques. In addition to this power based and location based approaches are expensive and difficult to implement.

The following assumptions are made in all the evaluations.

– Nodes are placed in a 2-Dimensional space.
– Nodes do not have any information about their or their neighbors location, position or orientation.
– All nodes are incapable of motion.

We have conducted analysis on number of messages exchanged during each of the TM protocol and the spent energy ratio. These two metrics can provide us with an insight into how each of the TM protocol utilizes energy, which in turn will determine the network lifetime. Table 2 shows a summary of important simulation parameters that were considered during simulation. All values have been averaged over 100 simulations each.

Table 2. Simulation Parameters

Deployment Area	300m x 300m
Number of sink nodes	1
Number of nodes	50-250
Node Location Distribution	Uniform
Node Energy Model	Mote
Communication Radius	100m
TM Energy Threshold Step	0.9

4.1 Number of Messages Sent

Communication is the most energy consuming tasks among all of the operations of WSNs. While designing topology maintenance and construction protocols reducing the number of messages exchanged is at the top priority of protocol designers.

Our analysis shows that centralized or global techniques where topology recreation messages are exchanged with the sink node result in greater message overhead. On the other hand distributed topology maintenance techniques like Local DSR results in fewer number of exchange of messages as shown in Figure 1.The trend in Figure 1 shows that as the number of nodes in the network is increased, the number of messages exchanged in centralized approaches particularly in DGETRec increases exponentially while it remains somewhat constant in distributed approaches like local DSR. Although stationery global techniques also exchange fewer number of messages but as mentioned earlier, these approaches cannot predict the status of the network and may therefore result in topologies that result in inefficient energy consumption.

As the node density is increased, in global protocols such as DGETRec, the rate of increase of number of messages goes up while in distributed protocols such as Local DSR, this rate remains somewhat constant.The reason is that in

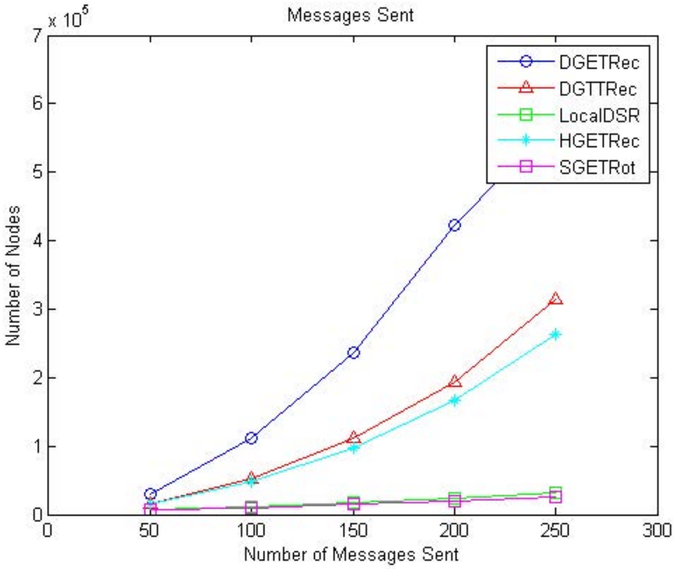

Fig. 1. The total number of messages exchanged vs. number of nodes

centralized approaches, as node density is increased, notification messages to sink and then reply message will have to transverse several hops. This means that the message overhead is increasing as the number of nodes are increased. While, in the case of distributed schemes, the message flooding is limited to a specific region, so even if number of nodes in the network increases, messages will be exchanged within a limited subset of nodes.

On the other hand, static schemes are shown to have less number of message overhead. Although static schemes may give a lower message overhead as they require fewer messages to switch to a new one, but static techniques do not guarantee an improved network lifetime.

4.2 Spent Energy Ratio

The graph on spent energy ratio of centralized and distributed TM techniques is shown in Figure 2. The figure shows that DGETRec has the highest spent energy ratio while Local DSR has the lowest. Spent Energy Ratio is consistent with number of messages exchanged. As the number of messages exchanged increases or decreases so does the spent energy ratio. This shows that amount of energy spent in topology maintenance is directly related to the number of messages exchanged. A protocol that guarantees fewer number of messages exchanged will be utilizing less energy during topology maintenance.

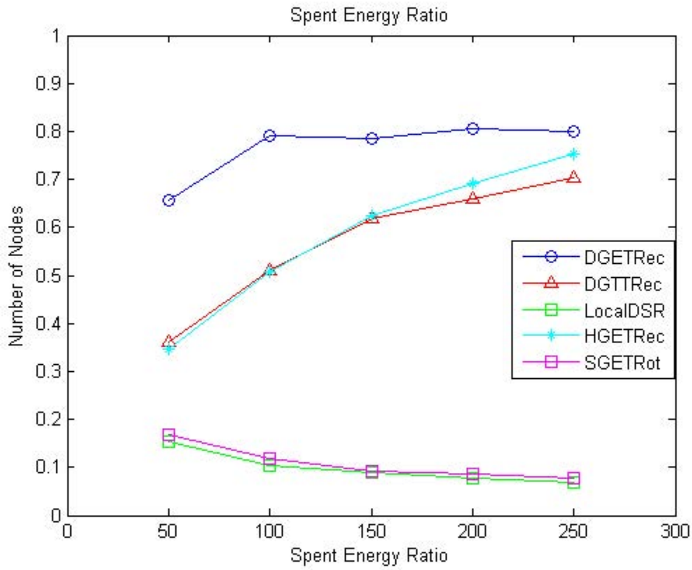

Fig. 2. Spent Energy Ratio vs. number of nodes

5 Conclusion

This papers gives a detailed analysis on Topology Maintenance and the different types of topology maintenance techniques existing in literature. The paper has distinguished centralized topology maintenance schemes from distributed topology maintenance schemes.

In addition to this, the paper includes a performance evaluation of dynamic, static and hybrid centralized and distributed topology maintenance algorithms. We have used number of messages exchanged and spent energy ratio, as a performance metric to determine energy consumption trends in various topology maintenance protocols. Our simulations have shown that local and distributed techniques provide a lower message overhead as compared to global techniques particularly in dense networks. Similarly, distributed solutions currently present are not generic and therefore distributed topology maintenance algorithms are required, which can be used with topology construction algorithms. Therefore, to the best of our believe, the research community working in this domain, would like to see generic distributed topology maintenance algorithms in future.

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