A Survey on Distributed Topology Control Techniques for Extending the Lifetime of Battery Powered Wireless Sensor Networks

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Abstract—**Large-scale, self-organizing wireless sensor and mesh network deployments are being driven by recent technological developments such as The Internet of Things (IoT), Smart Grids and Smart Environment applications. Efficient use of the limited energy resources of wireless sensor network (WSN) nodes is critically important to support these advances, and application of topology control methods will have a profound impact on energy efficiency and hence battery lifetime.**

In this survey, we focus on the energy efficiency issue and present a comprehensive study of topology control techniques for extending the lifetime of battery powered WSNs. First, we review the significant topology control algorithms to provide insights into how energy efficiency is achieved by design. Further, these algorithms are classified according to the energy conservation approach they adopt, and evaluated by the trade-offs they offer to aid designers in selecting a technique that best suits their applications. Since the concept of "network lifetime" is widely used for assessing the algorithms' performance, we highlight various definitions of the term and discuss their merits and drawbacks.

Recently, there has been growing interest in algorithms for non-planar topologies such as deployments in underwater environments or multi-level buildings. For this reason, we also include a detailed discussion of topology control algorithms that work efficiently in three dimensions.

Based on the outcomes of our review, we identify a number of open research issues for achieving energy efficiency through topology control.

Index Terms—**Wireless sensor networks (WSNs), topology control, connected dominating set (CDS).**

I. Introduction

A WIRELESS sensor network (WSN) consists of devices equipped with radio transceivers that cooperate to form and maintain a fully connected network of sensor nodes [3]. The devices can be stationary or mobile [22], [23]. WSNs do not have a fixed infrastructure and do not use centralized methods for organization. This flexibility enables them to be used whenever a fixed infrastructure is unfeasible or inconvenient, hence making them attractive for numerous applications ranging from military, civil, industrial or health. Because of their unique structure, and limited energy storage, computational and memory resources of WSN nodes, many of the existing protocols and algorithms designed for wired or wireless ad hoc networks cannot be directly used in sensor networks. WSNs are also different from other networks in the following aspects : they are densely deployed, nodes are susceptible to failure, and heavily rely on broadcast communications. Their topology is dynamic, in which node-to-node links are established and broken quite often due to various reasons, including deliberate changes to the transmission power of the nodes, node failure or mobility. In summary, maintaining a fully connected topology for such networks is a challenge and requires careful application of topology control.

Nowadays, applications of very large scale WSNs are becoming a reality. Examples are being the Smart Grid [10], [48], [70], [89], The Internet of Things [6], [47], [49], Machine-to-Machine (M2M) communications networks [20], [24], [52], [86], and smart environments [18], [58]. It is expected that topology control techniques will play an important role in managing the complexity of such highly complicated and distributed systems through self-organization capabilities. For example, huge number of sensor nodes of the smart metering networks [10], [89] demand a reliable communication support between the energy utility and the customers [10], and also need to have the capabilities for resiliency and adaptability to topology changes to ensure proper coordination [12]. Therefore, such systems would require efficient distributed topology control methods that will be able to cope with the unreliability of the links in efficient ways (for example conservation of the limited energy supplies of battery powered nodes). In this survey paper, we review various topology control solutions from this viewpoint.

We cover the recent developments, and update the information provided by the earlier works, especially by Santi [64] and Srivastava et al. [71]. We also provide a comprehensive treatment of the issues in a number of distinct ways. Firstly, [64] explicitly narrows down topology control approaches to those that adjust a node's transmission power, and clearly excludes clustering approaches. Our work provides a more comprehensive survey by including the clustering and mode scheduling methods that contribute to energy conservation. Naturally, this leads to a different scope of work on topology control problems. Secondly, we observe that significant differences in the definitions of the "network lifetime" concept exist in the topology control literature. We include a review of these and discuss the advantages and disadvantages of adopting a topology control approach based on a particular definition of the network lifetime.

Another distinction between our survey and earlier works is the way topology control techniques are classified. Our work takes a different approach than the earlier studies, and concen-

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trates on the mechanisms used to achieve energy conservation and prolonged network lifetime for WSNs. We categorize the topology control algorithms based on the approach they use to conserve energy. Moreover, topology control techniques presented in this paper are strictly distributed approaches as opposed to [64], [71], which cover both distributed and centralized approaches.

In addition to presenting the two-dimensional (2D) control algorithms for planar topologies, we extend our work to the emerging topic of topology control in the context of non-planar networks. This is due to the expanding applications of WSN deployments in three-dimensions, with examples including underwater or multi-level buildings. This topic is not included in the earlier surveys.

Energy consumption and network lifetime are two commonly used evaluation metrics for measuring the impact of topology control algorithms on energy efficiency. However, there are also a number of other factors such as communication overhead, message complexity, space complexity and time complexity also impact energy efficiency. Because of this reason, our review provides a detailed evaluation of these factors as well.

II. Topology Control

This section formally introduces the concept and definitions of topology control as well as the classification of 2D topology control algorithms. The differences in the various network lifetime definitions used to evaluate the performance of topology control algorithms are discussed.

A. Overview of Topology Control

Topology control is an important technique used in WSNs to achieve energy conservation and extend network lifetime without affecting important network performance such as connectivity and throughput. The idea of topology control is to grant sensor nodes a sense of control over certain parameters such that these parameters can be manipulated in a way that benefit the network. In particular, sensor nodes have the capacity to adjust the transmission range of their radio, switch to the various modes of operation or even decide on the eligibility of the nodes joining the network backbone. These features are the parameters that are exploited in enforcing a reduced topology to achieve energy saving and prolong network lifetime.

In WSNs, a topology provides information about a set of nodes and connectivity (links) between a pair of nodes in the set. To construct a network topology, each sensor node discovers its neighbors and relative links using its maximum transmission power. Based on the information gathered, the node can make decisions to build a network. The downside of this approach is that the network created might be either too dense, (which is vulnerable to excessive interference) or too sparse, (which is highly susceptible to network partitioning) [26]. To avoid this problem, a proper topology control should be employed to eliminate the unnecessary links in the dense network without sacrificing the network performance.

The main objectives of topology control are two-fold. The first objective is to save energy and prolong the lifetime of the sensor node and network. Topology control offers a mechanism that allows sensor nodes to vary their transmission range which potentially reduces the energy consumption involved during transmission. As a result, the long distance communication links are dropped while the short distance communication links are chosen. From the perspective of energy consumption, a direct communication over short distance is more energy efficient that the long distance communication [65]. Therefore, reducing the transmission power will eliminate the long distance links that can waste energy resources. The second objective is to overcome collisions. Other than discarding the inefficient links, the use of minimal transmission range successfully removes the long distance nodes, thus resulting in a sparse network. The effects of this include a reduction in the packet retransmissions and interference and an improvement in the network capacity.

Topology control can be implemented in three ways. As discussed before, minimizing the power incurred during transmission by means of adjusting the transmission range of the wireless radio of sensor nodes is a common approach adopted. In addition, sensor nodes that are sitting idle, not participating in transmitting and receiving can turn-off their radios or they can transit to sleep mode. This approach can provide a substantial energy saving since the energy consumption during the idle mode is quite significant in comparison with the energy consumed during the sleep mode [21]. Finally, topology control can be performed through a clustering approach. Based on selection criteria, sensor nodes select a set of nodes to form a cluster. This provides control over the topology to achieve energy saving and permits a structured hierarchical network architecture. The potential selection criteria are residual energy, the number of neighboring nodes or the node identifier. In clustering, data forwarding and aggregation activities are dedicated to the nodes in the set to restrict the number of packet retransmission and maximize energy resources.

B. Definitions of Topology Control in WSNs

The phrase topology control has been interchangeably used with power control and its concept is defined in many contexts. In this paper, we define topology control as a technique that uses any controlled network parameter to generate and maintain a topology for the benefits of reducing energy consumption and achieving a desired property for an entire network. The possible controlled parameters that can be modified to gain a desired topology are transmission power, modes of nodes and role of nodes.

Our definition differs from other topology control definitions that are conventionally adopted in the topology control field in the following respects. For example, many authors [11], [13], [42], [44], [64], [53], [79] consider topology control as a technique whereby nodes dynamically change their transmission range to gain energy saving and/or improve throughput. According to this definition clustering techniques are not considered as topology control because the transmission power of nodes is usually not adjustable. In our case, we do not restrict our definition to techniques that strictly modify node transmission range. As long as the techniques use any controlled parameter to configure the network topology for achieving energy saving, we consider them as topology control. Thus, clustering techniques do fulfill our definition of topology control since a set of nodes called clusterheads is capable of controlling their set of neighbors in the network.

Another definition for topology control used by other authors is *power control* [50], [69], [78]. Although this technique involves controlling the nodes' transmission power, it does not aim to achieve the energy efficiency of an entire network. Paolo [66] describes *power control* as a technique in which nodes adjust the transmit power to achieve a nodewide perspective such as energy efficient algorithms of the wireless transceiver. Another example of power control mentioned in [66] is the technique that aims to select the best transmit power level for a single wireless transmission, possibly involving several hops. In this case it has a channel-wide perspective. Similarly, we do not classify *power control* as topology control because we are concerned with techniques that aim to achieve the energy efficiency of the entire network instead of a nodewide or channel-wide perspective .

C. Definitions of Network Lifetime

The ability of a network to prolong network lifetime is typically evaluated based on its definition. There are various definitions of network lifetime used by the authors. In this section, we review the definitions widely used in designing topology control algorithms. The implication of these definitions and their impact on the topology control performance are discussed in Section III-E. The various definitions of the term are as follow:

- The first node to die: The first node which fails in the network is used to define the network lifetime [34]. The failed node is often called a critical node.
- The number of alive nodes: The number of alive nodes as a function of time [40], [28] is taken as a measure of network lifetime. A higher number of alive nodes is used to describe a longer network lifetime.
- The fraction of alive nodes: The network lifetime is described by the fraction of surviving or alive nodes as a function of time [85]. The network is alive while the fraction of surviving nodes remains above a target threshold value.
- The time until the network fails to construct a backbone: As used in [88], this is the time in periods until the network can no longer construct a backbone. A period defines the time that a particular set of nodes will form a backbone based on their available energy. This set is changed at each period in order to prolong the overall network lifetime. It is applicable to networks employing a clustering method.
- The fraction of connected dominating set (CDS) nodes that remain alive: It is commonly used in CDS techniques to officially assess the lifetime based on the fraction of connected dominating set nodes that remain alive [16]. The network fails if the fraction of alive connected dominating set nodes falls below a given threshold.
- The time t until the packet delivery ratio drops drastically: This definition evaluates the lifetime based on the time until the packet delivery ratio drops drastically [85]. The packet delivery ratio is typically set to a predefined threshold value. The network dies at time t when the packet delivery ratio drops below the threshold.
- The number of nodes that remain connected to the base station: The survival rate of the network is evaluated based on the number of nodes remaining connected to the base station [40]. It captures the issue of connectivity of the network to the base station. The number of nodes that must stay connected to the base station can be predetermined.

D. A Classification of Two-Dimensional (2D) Distributed Topology Control Algorithms

In general, energy efficient topology control algorithms can be broadly classified into centralized or distributed algorithms depending on the approach adopted for constructing the networks. Centralized approaches such as [29], [33], [61] can provide accurate global information but their implementations are expensive in practice due to significant communication overheads required for gathering information. These approaches are unfeasible for WSNs that typically have a large number of sensor nodes. For this reason, distributed approaches are preferable to centralized approaches. Hence, our work focuses on distributed topology control algorithms.

In this paper, we classify 2D distributed topology control algorithms according to their energy conservation technique. According to this criterion, we group the topology control algorithms into four categories, as shown in Figure 1. The four categories are power adjustment, power mode, clustering and hybrid. Power adjustment deals with a technique that reduces energy consumption over the WSN by varying the transmission power of nodes. We are interested on achieving the energy-efficiency of the whole network, thus, power adjustment differs from the power control techniques mentioned in Section 2.2. Power mode on the other hand saves energy by switching-off the radios of idle nodes and placing the nodes into a sleep mode. The third category known as clustering approaches conserve energy by critically selecting a set of neighbor nodes to construct an energy efficient backbone in the network. Finally, hybrid approaches further improve the energy saving by integrating the clustering approach with either power mode or power adjustment approaches.

III. Two-Dimensional (2D) Distributed Topology Control Algorithms

In this section, we provide a discussion on a representative set of 2D algorithms. These algorithms are assigned to one of the four categories described in Section II-D.

A. Power Adjustment Approach

The power adjustment approach allows nodes to vary their transmission power to reduce energy incurred in transmission. Rather than transmitting at maximum transmission power, nodes work in a collaborative manner to adjust and find the appropriate transmission power to form a connected network. We describe three power adjustment algorithms in the following sections.

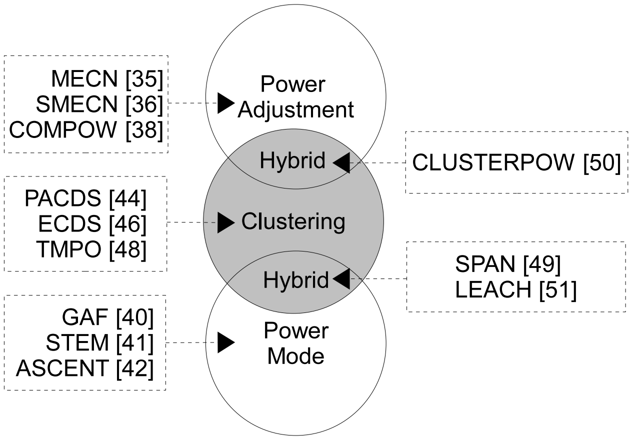

Fig. 1. The four classifications of 2D distributed topology control algorithms and twelve representative algorithms.

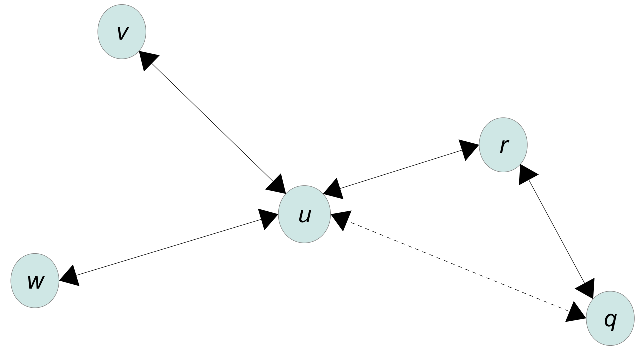

Fig. 2. Neighbors of the node u: It can directly exchange packets with v, w, r and q, but discovers that relayed packet transmissions to q via r is more efficient then direct communications. So, it does not include q in its neighbor set.

1) Minimum Energy Communication Network (MECN): Rodoplu et al. [62] proposed a localized and position-based algorithm that minimizes the energy involved in transmission of packets in a WSN. The idea of this algorithm is to construct a topology consisting of lowest energy paths to transmit from any wireless sensor of the network to a sink node by using the concept of "relay transmission".

The MECN algorithm operates in two phases. In the first phase, each node finds its neighbor set. Note that, the authors do not use the "neighbor set" definition in the conventional sense in their paper. Usually, a neighbor set of a node contains all the nodes that are within its communication range. Here, a node adds into its neighbor set only the ones it can communicate directly by spending minimum packet transmission energy. In other words, a node only accepts another node into its neighbor set if

- it can communicate with this node directly, and
- there is no other way of communicating with this node by using relays and spending smaller amount of transmission energy than direct communication.

Figure 2 illustrates this distinction. Algorithm 1 describes the neighbor set construction process.

In the second phase, the nodes run the Bellman-Ford shortest path algorithm to determine the minimum energy path to the sink node. Each node broadcasts the cost of using itself as a relay towards the sink (here, the cost is the minimum power consumption required to send a packet to the sink). When a node u receives the cost information from a neighbor node v, it calculates the minimum cost of the path to the sink relayed through v as

$$\mathrm{Cost}(u,v) = \mathrm{Cost}(v) + \mathrm{d}(u,v)^{\mathrm{n}} + \beta \tag{1}$$

where, $\mathrm{d}(u,v)$ is the Euclidean distance between the nodes u and v (it is assumed that the nodes know their locations), n is the path loss exponent and β is the power consumed at a receiver acting as a relay node.

Based on the costs, node u chooses a path which involves minimum packet transmission cost among its neighbors. The chosen node with the minimum cost is the next node to initiate the minimum energy path construction. The cost calculations are kept updated and broadcast to neighbors. To further optimize the energy consumption, a node can switch to sleep mode after the completion of the second phase if it is not transmitting any messages.

To handle the dynamic changes in the environment (fluctuations in the propagation paths, faulty nodes etc.), the MECN algorithm also includes a mechanism called "Flip" by the authors. It is used to handle the following cases:

1) nodes are removed from the neighbor set if it is found that direct communication with them is not efficient any more (i.e., it is possible that, due to the dynamic changes in the environment, communication with this node could become more efficient if another neighbor is used as relay), or
2) a node is added to the neighbor set since direct communication with them become more efficient. A freshly added node triggers the cases mentioned in item 1 above.

For the details of the Flip mechanism, [62] can be referred.

Algorithm 1 Discovery of neighbors that are energy-efficient to communicate

$\mathrm{P}_{u\to v\to q}$ is the total transmit power used for sending a packet from node u to q via node v
$N(u)$ is the neighbor set of node u that is energy-efficient to communicate directly

```
procedure FindNeighborSet(u)
    N(u) ← ∅
    for all received beacon packets do
        q ← Sender of the beacon
        if q ∉ N(u) then
            P_{u→q}                          ▷ Compute the power cost
            N_candidate ← true
            for all v ∈ N(u) and N_candidate = true do
                if P_{u→v} + P_{v→q} < P_{u→q} then
                    N_candidate ← false
                end if
                if N_candidate = true then
                    N(u) ← N(u) ∪ {q}
                end if
            end for
        end if
    end for
end procedure
```

2) Small Minimum Energy Communication Network (SMECN): The SMECN algorithm [40] is an extension of the MECN algorithm. It aims to construct a network that is simpler, faster and more energy efficient than the one generated in MECN [62]. The objective of SMECN is to generate a subgraph G' which is smaller than the subgraph G in MECN. Being a variant of MECN, SMECN uses the same energy model and assumptions as in MECN. The implementation of SMECN also consists of two phases that resembles MECN. The only difference between SMECN and MECN lies in the method of determining the nodes for the enclosure graph. In SMECN, nodes that are once considered as neighbors are never removed from the neighbor set and they are all included in the enclosure graph. Therefore, SMECN does not require the "Flip" heuristic as in MECN [62]. The work in SMECN proved that the constructed subgraph G' is smaller than that constructed by MECN if broadcasting at a given power setting is able to reach all nodes in a circular region around the broadcaster. An energy efficient reconfiguration algorithm that is based on SMECN was later proposed in [41]. The proposed algorithm was able to construct a minimum energy graph under dynamic topology changes.

3) COMPOW: The energy conservation strategy in COMPOW [51] finds and uses the minimum common power level that is sufficient to maintain the connectivity of the entire network. Based on theoretical studies, the authors argued that the minimum common power level can provide several benefits to networks including improvement in the traffic carrying capacity, energy consumption and contention at the MAC layer. The choice of using the smallest common power level also results in bidirectional links, an important feature required for efficient routing and proper communication at the MAC layer. This protocol is the first that was implemented in a real wireless testbed and explored various power levels available in a CISCO 350 series Aironet WLAN access points. COMPOW combines both power control and routing due to the fact that they both affect each other.

COMPOW adopted parallel modularity at the routing layer to achieve asynchronous and distributed operations. This is done by having each node running several routing daemons in parallel, one daemon for each transmit power level P_n. Thus, each node constructs multiple routing tables for all available power levels through exchanged hello messages. Initially, each node constructs a routing table using the maximum power level to find all nodes in the network. Then, it constructs a routing table for the remaining power levels and finds the smallest power level whose entries of the routing table are equal to the entries of the routing table at the maximum power level. The smallest power level is chosen as the optimum power level and its routing table is installed as the master routing table to be used by the kernel to transmit packets between nodes.

B. Power Mode Approach

The power mode approach is the technique that exploits the feature of the operating mode available in the network interface of sensor nodes to gain energy saving. There are four operating modes of the nodes: sleep, idle, transmit and receive modes. The energy consumed during the transmit and receive modes is generally higher than that in the sleep mode [36]. In order to transmit or receive packets, nodes must transit to idle mode. However, continuous listening of incoming packets that are not addressed to the idle nodes can contribute to high energy dissipation that is quite significant compared to those in sleep mode [21]. This suggests that the redundant nodes sitting in idle can be switched to energy saving mode by placing them in the sleep mode. This feature has been used in topology control to optimize the energy and prolong the network lifetime without sacrificing the network capacity and connectivity. In this section, a discussion on three power mode algorithms that deal with powering-off idle nodes as well as coordinating the sleep and wake-up scheduling of the nodes is presented.

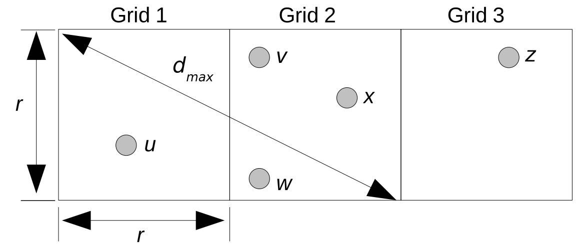

Fig. 3. The virtual grid structure in GAF.

1) Geographical Adaptive Fidelity (GAF): The main principles of GAF [85] are to have a sufficient number of nodes that remain active for communication, and to place the redundant nodes to sleep mode without affecting the network connectivity. In order to identify the active nodes from the redundant nodes, GAF divides the network area into small sized virtual grids. All nodes are associated with these grids through the use of location information and an idealized radio model. Figure 3 shows an example of three virtual grids. The length of the grid r is chosen such that any two nodes in adjacent grids can reach each other. The size of the virtual grids is based on the nominal radio range R and they are all equal in size. The longest possible distance between nodes in adjacent grids is the length of the diagonal connecting the two adjacent grids, which can be calculated using

$$r \le \frac{R}{5} \tag{2}$$

GAF uses the term "equivalent nodes" to define its neighbor set suitable for routing. The "equivalent nodes" describe nodes that are capable of communicating with all nodes in their adjacent grids. The equivalent nodes can be exploited to conserve energy by keeping only some of them alive for routing while the remaining nodes can sleep. For example in Figure 3 [85], nodes v, w and x are equivalent nodes because in order for node u to communicate with node z it can relay packets through either v, w, or x. In this example, energy saving is achieved by placing nodes w and x into sleep mode while node v performs data forwarding and they alternate between being sleeping and active. This process can be described by the state transition diagram in Figure 4 which is redrawn from [85]. There are three operating states of GAF mainly, the sleeping, discovery and active states. In the

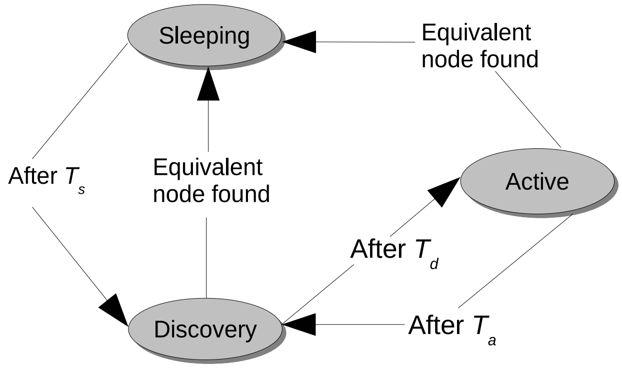

Fig. 4. State transitions in GAF.

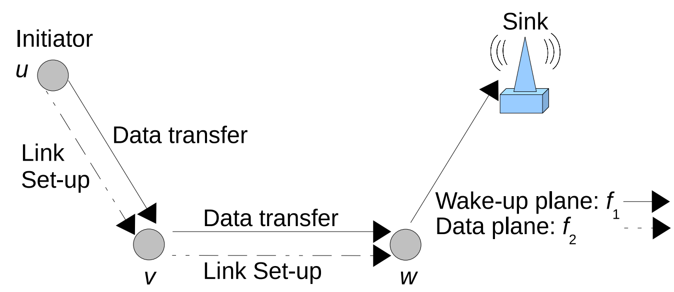

Fig. 5. Radio setup of a sensor node in STEM.

discovery state, nodes identify their neighbors in the grid by turning on their radios and exchanging discovery message. The discovery message contains the node id, state, grid and active node time T_{act}. The T_{act} value is used to decide on the duration the neighboring nodes remains to sleep. It is set to the time the node is depleting half of its energy resource. In the active state, nodes participate in routing. In the sleeping state, nodes turn off their radio and remain inactive. All nodes initially begin with the discovery state. During this state, nodes set their discovery time for T_d seconds, broadcast discovery message to locate nodes within the same grid and then enter active state. Nodes that enter into active state set their timer to a timeout value T_a to define the duration they stay in active state. After T_a, nodes will return to discovery state and rebroadcast their discovery message at every T_d seconds. Nodes in discovery or active state may switch to sleeping state if they find other equivalent nodes to handle routing. When transitioning to sleeping, nodes cancel all pending timers and power down their radios. They will sleep for the duration of T_s, which is a random time between $T_{\text{act}}/2$ and T_{act}. The information on whether these nodes are able to receive messages in sleep state or not is not provided in [85].

In order to maximize network lifetime, nodes that participate in routing are ranked based on several rules. The rules guarantee that only one active node exists in each grid and nodes with a longer expected lifetime are used first. There are several rules for deciding the rank. First, the node in the active state has a higher rank than the node in discovery state. Second, if nodes are in the same state, GAF gives a node with a longer expected lifetime a higher rank. Third, node IDs are used to break ties. GAF also adopts a load balancing strategy to distribute the load evenly among nodes to prevent nodes from exhausting their energy. By setting the timeout value T_a, nodes that are in active state will eventually switch to discovery state to allow other nodes with a higher energy level within the same grid to become active. GAF considers system-level behavior to adapt to high mobility to prevent high rates of packet dropping. This is possible by estimating the time, T_{mob} each node remains in the grid. This T_{mob} value is included in the discovery message and sent to neighbors. Its neighbors that are about to transit to sleeping state use the T_{mob} along with the T_{act} to determine their T_s duration.

2) Sparse Topology and Energy Management (STEM): The principle of STEM [67] is to put as many nodes as possible into sleep mode such that the energy consumption is reduced and network lifetime is extended. The authors argued that this idea is relevant for a network that spends most of its time in monitoring activity and has less data forwarding activity. The idle nodes that are monitoring activity can be powered down and woken up only when they have data to forward to the base station. The common challenge of the power down approach is to manage nodes' sleeping transition such that the sleeping nodes are activated only when an event occurs. STEM solves this challenge by periodically turning on the node's radio for a short time to listen for incoming communications.

There are two operations involved in STEM, these are the wake-up and data transmission processes. The wake-up process ensures that the radio of sleeping nodes is turned on to allow nodes to listen for incoming message then the data transmission process ensures that data is safely transferred between a source and sink. In STEM, each node sends a wake-up message and transmits data in two different frequency bands using two separate radios to avoid interference. The wake-up message happens in the wake-up plane operating on radio frequency f_1 while data transfer happens in the data plane operating on radio frequency f_2. The operation of STEM is illustrated in Figure 5. Assuming that node v and w are sleeping, suppose that node u detects an event and wants to transmit data to the sink through node v and w. Node u then sends a wake up message to the target node v on radio frequency f_1 and waits for a response from node v. After receiving the response, both nodes turn on their radios and start data transfer on radio frequency f_2. This process is repeated between node v and node w with node v now becoming an initiator while node w becomes a target until the data is successfully received by the sink.

A later development integrates STEM with GAF to achieve two objectives. The first objective is to gain additional energy saving. GAF ensures that each grid must contain one active node acting as a leader, but this leader may not have data to transfer. Thus by running STEM on the leader in each GAF's grid, the leader which is sitting idle waiting for data transfer can be turned off to reduce power consumption. The result shows that in comparison to a network without any topology control, integrated STEM reduces the energy consumption by up to 7 percent. This improvement is equivalent to an increase by a factor of 14 in a node lifetime as reported in [67]. The second objective is to improve STEM's latency. STEM makes use of the leader election process in GAF to minimize

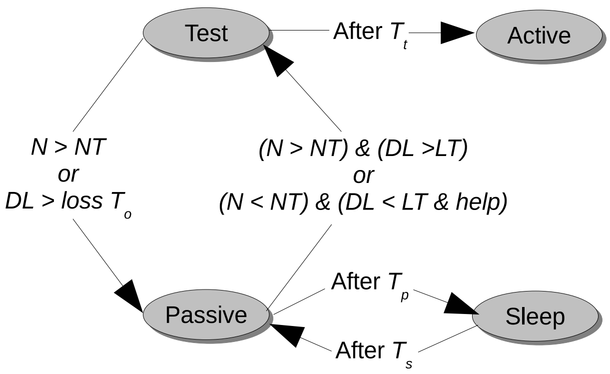

Fig. 6. State transitions representing the operation of ASCENT (redrawn from [14]).

the number of interferences during the wake-up process and speeds up the link set-up phase.

3) Adaptive Self-Configuring Sensor Network Topologies (ASCENT): ASCENT [14] is a self-reconfigurable algorithm that allows nodes to locally measure the operating conditions. Based on these conditions, nodes then decide whether they need to participate in routing or not. To achieve energy efficiency, ASCENT selects a subset of nodes to remain active to serve as a routing backbone. The remaining nodes in the network stay passive, listening to other nodes and periodically checking in case they need to join the routing backbone. For instance, when the packet loss is high the passive nodes are activated to preserve connectivity. Otherwise these nodes turn-off their radio to conserve energy.

Nodes in ASCENT will stay in one of four states, namely test, passive, active and sleep as depicted in Figure 6. Nodes in a passive state stay in listening mode to participate in routing if required, thus the radio of the nodes remains active. Nodes in the active state perform data forwarding and monitoring, while nodes in the sleep state switch-off their radios to save energy. Nodes in the test state check the conditions on whether the network has enough active nodes to maintain connectivity. If there are insufficient active nodes, nodes in the passive state will join the active nodes or else they switch to sleep state to reduce energy consumption.

All nodes initially remain in the test state. The nodes then set their timer T_t and send neighbor announcement messages to discover their neighbors. While in the test state, a node will check whether the number of active neighbors N is above a neighbor threshold NT, or the average data loss rate DL is higher than the average loss T_o before entering the test state. If the condition is true, the node transits into the passive state. The higher node ID in the announcement message is used to break a tie if multiple nodes compete to transit to the test state. If the condition is false, the node remains in the passive state and later moves into the active state upon the expiry of timer T_t. In the active state, the node participates in routing until it runs out of energy. The active node sends help messages when DL is greater than the loss threshold LT.

A node that enters the passive state sets up a timer T_p. It sends new passive node announcement messages to be used by active nodes to estimate the total density of nodes in the neighborhood. While in the passive state, a node decides whether it has to transit to the test state to support the routing backbone or transit to sleep state to save energy. The decision to transit to the state is made locally if either one of two conditions is met: 1) The number of neighbors is below NT and DL is higher than LT or 2) The number of neighbors is below NT, DL is below LT and the node receives a help message from an active neighbors. Otherwise it will remain in the passive state until the timer T_p expires. The node later moves into sleep state and switches off its radio to conserve energy. Upon the expiry of the timer T_s, it will transit into the passive state.

In ASCENT, the neighbor threshold NT and loss threshold LT values can be set to suit the requirement of applications. NT can be adjusted to improve network capacity and LT can be chosen to reduce packet loss. Other parameters such as T_t, T_p and T_s are determined dynamically at running time to improve power consumption but trade-off link quality.

C. Clustering Approach

The idea of clustering is to select a set of nodes in the network to construct an efficient topology. The selection of neighbors can be made on various criteria namely, energy reserve, density of the network or node identifier. Unlike in power adjustment or power mode approaches, the clustering approach constructs a topology with hierarchical structures that are scalable and simple to manage. The advantage of clustering is that a certain task can be restricted to a set of nodes called clusterheads and they can be assigned for collecting, processing and forwarding packets from non-clusterheads. This mechanism provides an efficient network organization. Other attractive features of the clustering approaches include the load balancing and data aggregation or data compression offered for prolonged network lifetime. In some clustering approaches, the selection of the clusterheads remains fixed. Hence, clusterheads typically experience faster energy depletion because they are heavily loaded with various tasks. This problem is overcome by randomizing the selection of clusterheads to distribute loads fairly among nodes in the network.

Many of the clustering approaches construct the virtual backbone using the connected dominating set (CDS) concept. A CDS has been widely used as a topology control to conserve network energy resources. A dominating set (DS) is defined as a subset of nodes in a graph such that each node not in the subset has at least one direct neighbor that belongs to the subset [19]. If the nodes in the dominating set form a connected graph, the set is called a CDS. Figure 7 shows an example of a CDS generated in a network that consists of fourteen nodes. In this figure, nodes u, v, w, x, y and z form the backbone to perform data forwarding while the remaining nodes do not participate in data forwarding. This strategy reduces the communication overhead and energy. The following section discusses three clustering algorithms used for topology control.

1) Power Aware Connected Dominating Set (PACDS): Wu et al. [34] proposed a simple algorithm based on the CDS concept that finds a CDS using a simple marking process. PACDS improves the work proposed in [84] to achieve two

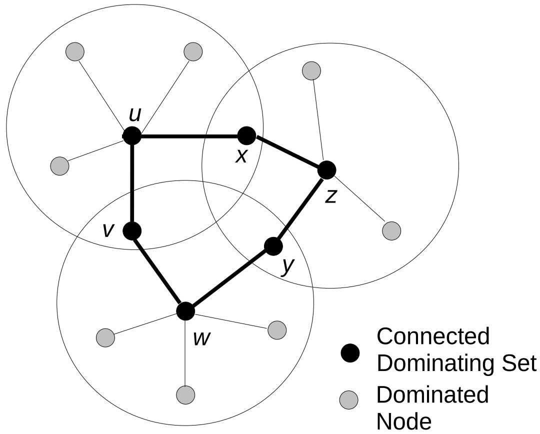

Fig. 7. A backbone in the network built using a connected dominating set.

goals. The first goal is to construct a small size CDS while the second goal is to prolong the lifetime of nodes. In a CDS, nodes in the backbone are commonly overloaded with various tasks and they are the first in the network to drain energy. Load balancing can overcome this problem by randomizing the role of the backbone among nodes with higher residual energy.

The construction of PACDS involves two stages as shown in Algorithm 2. The first stage is the formation of a CDS. Initially, node u broadcasts a hello message to gather neighbor information. If node u has two unconnected neighbors, it will be marked as a CDS node. The second stage is the pruning process, in which redundant CDS nodes are removed to reduce the size of the CDS constructed. The pruning process is required because the size of the CDS formed during the first stage is not minimal. Two rules that are based on node ID are used for the CDS removal. The pruning rules state that if node u has a neighbor with higher ID which can cover all of its neighbors or if u has two connected neighbors with higher ID which can cover all of its neighbors, u can be eliminated from the CDS.

Other than using node ID, PACDS introduces additional pruning rules to the CDS using node degree and residual energy. The first additional pruning rule uses node degree with an aim to keep the size of CDS as small as possible. The second additional rule uses the residual energy to gain prolonged node lifespan. The residual energy rule gives higher priority to nodes with a higher energy level to become a clusterhead and removes the lower energy level nodes from the CDS.

2) Energy Efficient Distributed Connecting Dominating Sets (ECDS): Yuanyuan et al. [88] presented ECDS to solve the energy constraints in wireless sensor networks and minimize the size of a CDS. ECDS is a CDS based topology control algorithm. The features of ECDS are improvement in network lifetime and fair energy distribution achieved through load balancing. Contrary to the PACDS [34], ECDS first constructs a dominating set which is a maximal independent set (MIS) and then finds gateway nodes to connect the MIS. Moreover, ECDS does not use any pruning process as in PACDS [34]. A MIS is defined as an independent set (IS) that is not a subset of any other IS [39]. An IS of graph G

Algorithm 2 Construction of a CDS in PACDS algorithm

Require: Graph $G(V,E)$
Ensure: Connected Dominating Set $(CDS) \in G(V,E)$

```
procedure FormCDS(G(V,E))                    ▷ Create a CDS
    CDS ← ∅
    for all u ∈ V do
        for all v, w ∈ N(u) do
            if w ∉ N(v) then                 ▷ Unconnected neighbors
                CDS ← CDS ∪ {u}
            end if
        end for
    end for
end procedure

procedure PruneCDS(G(V,E))      ▷ Remove redundant CDS nodes
    for all u ∈ CDS do
        if u satisfies the pruning rules then
            CDS ← CDS − {u}
        end if
    end for
end procedure

procedure PACDS(G(V,E))                      ▷ Main procedure
    FormCDS(G(V,E))          ▷ Phase 1 of the CDS formation
    PruneCDS(CDS)            ▷ Phase 2 of the CDS formation
end procedure
```

is a subset of V where no two nodes within the set have an edge. The notation V refers to a set of vertices V in graph G. Therefore, every MIS is a dominating set which is not connected.

ECDS's construction consists of two phases as illustrated in Algorithm 3. The first phase computes a MIS using a coloring technique to identify the MIS nodes from non-MIS nodes while the second phase selects connectors to join the MIS. The processes involved are shown in Algorithm 4. Initially, all nodes are in white and at the end of the first phase, nodes will either be in black (MIS nodes) or gray (non-MIS nodes). The first phase starts with an initiator volunteering to be a MIS node and coloring itself black. It then sends a black message to its neighbors. The white neighbors that received the message are colored gray (non-MIS nodes) and they broadcast a gray message to their white neighbors to update their color change. The white nodes receiving the gray message are not the MIS nodes but they are the potential MIS nodes. These nodes send an inquiry message to their neighbors to know their states and weights and wait for their replies for a duration of time set by a timeout. The white nodes with the largest weight are chosen as MIS nodes. The weight is calculated based on the node's residual energy (E_{res}) and effective degree (D_{eff}). The effective degree is defined by the number of neighbors in white and transition states. If they receive a black message during timeout, they become gray nodes (non-MIS nodes). In other words, they are the neighbors of MIS and cannot be the MIS nodes. Otherwise, they stay in transition state until the timeout is over. After the timeout, if these nodes have the largest weight among all neighbors, they become a black node and the process is repeated.

The second phase identifies the gateway nodes for MIS and connects the MIS to build the CDS as shown in the

Algorithm 3 Construction of a CDS in ECDS algorithm

```
Require: Graph G(V,E) and initiator node i
Ensure: Connected Dominating Set (CDS) ∈ G(V,E)

procedure ECDS(G(V,E))                        ▷ Main procedure
    GENERATEMIS(G(V,E))                       ▷ Phase 1 of ECDS
    FINDCONNECTOR(G(V,E))                     ▷ Phase 2 of ECDS
end procedure
```

Algorithm 4 Phase 1 and Phase 2 of the ECDS algorithm

```
procedure GENERATEMIS(G(V,E))   ▷ Phase 1: Find a MIS in the network
    MIS ← ∅ ; GRAY ← ∅
    MIS ← MIS ∪ {i}
    for all u ∈ N(i) do
        GRAY ← GRAY ∪ {u}
        for all v, w ∈ N(u) do
            weight(v) ← E_res(v) × D_eff(v)
            weight(w) ← E_res(w) × D_eff(w)
            if weight(v) > weight(w) then
                MIS ← MIS ∪ {v}               ▷ Black nodes
            else
                GRAY ← GRAY ∪ {v}             ▷ Gray nodes
            end if
        end for
    end for
end procedure

procedure FINDCONNECTOR(G(V,E))   ▷ Phase 2: Find connectors to join the MIS
    CDS ← ∅ ; CONNECTOR ← ∅
    CDS ← CDS ∪ {i} ▷ Initiator invokes the connector process
    for all u ∈ N(i) do
        if u ∈ CONNECTOR then         ▷ Set of nominated connectors
            CDS ← CDS ∪ {u}                   ▷ Blue nodes
        end if
    end for
    for all v ∈ MIS do
        if v has x ∈ CDS then
            CDS ← CDS ∪ {v}                   ▷ Blue nodes
        else
            for w ∈ N(v) do
                weight(w) ← E_res(w) × D_eff(w)
                if w has max(weight) then
                    CONNECTOR ← CONNECTOR ∪ {w}
                end if
            end for
        end if
    end for
end procedure
```

Algorithm 4. These gateways are not members of the MIS. The authors run a greedy algorithm to find the connectors, where every MIS node selects the non-MIS node with the highest weight that can connect it with other MIS nodes within 2-hop communication. After the completion of the greedy algorithm, all nodes in the network are either in blue (CDS nodes) or gray (non-DS nodes) color. The second phase starts with MIS nodes sending an invite message to non-MIS nodes (gray) that have potential for being connectors. Upon receiving the invite message, the gray node calculates its weight and sends an update message to the MIS nodes. The weight is computed similarly to the one in the first phase except that the effective degree is defined by the number nodes in MIS and black states. Based on the weight calculated, the MIS nodes select the gray nodes with the largest weight to be connectors. The CDS construction stops if any MIS node colored blue terminates the algorithm or it is terminated by any non-MIS node that satisfies the following conditions, (i) it is colored blue (connector node) or (ii) all its neighbors are colored blue and gray.

3) Topology Management by Priority Ordering (TMPO): TMPO [8] is a dynamic algorithm that considers movement and residual energy when forming a backbone. TMPO introduces the concept of gateways and doorways (which is adopted from clustering methods) to connect the dominating sets. There are several outstanding features of TMPO summarized in [8]. First, the formation of minimal dominating sets and CDS is free from any negotiation process, thus unnecessary overheads involved during the clusterhead election are avoided. Second, an identifier called node priority is calculated periodically, allowing the role of clusterhead to be rotated among nodes to extend the network lifetime. Third, the algorithm considers mobility and energy capacity of nodes when selecting clusterheads. Fourth, unlike other clustering methods that use gateways and clusterheads to form a connected cluster, TPMO introduces a new term called doorway.

There are two phases involved in the construction of a CDS as shown in Algorithm 5. The first phase is the clusterhead election process. It finds the clusterheads that can create a minimal dominating set in the network to minimize the size of the CDS. The selection of clusterheads is made according to the priority rule. A node becomes a clusterhead if it has the highest priority among its one-hop neighbors or among the one-hop neighbors of one of its one-hop neighborhood. The priority between candidate clusterhead nodes considers the identifier of the node's neighbor, present time and willingness value. The willingness value is assigned to each node u as a function of node mobility (s) and energy level (E_u). It is calculated as

$$W_u = 2^{\log_2(0.9E_u)\log_2(s_i+2)} \tag{3}$$

Based on the willingness value, node identifier and current time, the priority of the node is computed. The priority values of node u (u_{priority}) are changed periodically to provide random election of clusterheads and these values are unique. It is determined by

$$u_{\text{priority}} = \text{Hash}(\frac{t - u_{\text{off}}}{T} \oplus u) \times W_u \oplus u \tag{4}$$

where Hash represents a pseudo-random number generated in the range of 0 to 1, u_{off} is the time slot of node u and $\oplus$ is the bit-concatenation operation.

In the second phase, doorway and gateway nodes are elected and they connect the minimal dominating set generated in the previous phase to form a CDS. A doorway node is described as the node that can connect two clusterheads that are separated three hops away and there are no other clusterheads between them. The doorway must have the highest priority between the two clusterheads. The gateway node is defined as the highest priority node that can connect two clusterheads two hops aways or connect one clusterhead and one doorway separated

Algorithm 5 Construction of a CDS in TMPO algorithm

```
Require: Graph G(V, E)
Require: a set of relay nodes with the highest priority between two
  clusterheads that are 3hop away (3HRELAYSET)
Require: a set of relay nodes with the highest priority between two
  clusterheads that are 2hop away (2HRELAYSET)
Ensure: Connected Dominating Set (CDS) ∈ G(V, E)

procedure ELECTCLUSTERHEAD(G(V, E))                      ▷ Select Clusterheads
    CLUSTERHEAD ← ∅ ; CDS ← ∅
    u_priority ← Hash((t − u_off)/T ⊕ u) × W_u ⊕ u
    for all v ∈ N_1(u) and w ∈ N_2(u) do
        v_priority ← Hash((t − v_off)/T ⊕ v) × W_v ⊕ v   ▷ One-hop
        w_priority ← Hash((t − w_off)/T ⊕ w) × W_w ⊕ w   ▷ Two-hop
    end for
    if (u_priority > v_priority) or (u_priority > w_priority) then
        CLUSTERHEAD ← CLUSTERHEAD ∪ {u}
        CDS ← CDS ∪ {u}
    end if
end procedure

procedure FORMCDS(G(V, E))                               ▷ Form a CDS
    for u, v ∈ CLUSTERHEAD do
        if 3HRELAYSET ∩ CLUSTERHEAD = 0 then
            for x ∈ 3HRELAYSET do
                CDS ← CDS ∪ {x}                           ▷ Doorway node
            end for
        end if
        if 2HRELAYSET ∩ CLUSTERHEAD = 0 then
            for z ∈ 2HRELAYSET do
                CDS ← CDS ∪ {z}                           ▷ Gateway node
            end for
        end if
    end for
end procedure

procedure TMPO(G(V, E))                                  ▷ Main procedure
    ELECTCLUSTERHEAD(G(V, E))                            ▷ Phase 1 of TMPO
    FORMCDS(G(V, E))                                     ▷ Phase 2 of TMPO
end procedure
```

two hops away and there are no other clusterheads between them. After the election of gateway and doorway nodes, the CDS is formed.

D. Hybrid Approach

The hybrid approach is a topology control technique that uses some form of clustering in combination with other approaches such as power adjustment or power mode to achieve additional energy saving. The following section presents three such hybrid algorithms that aim to conserve energy.

1) SPAN: The SPAN [16] algorithm uses a hybrid of power mode and clustering approaches. It selects a subset of nodes to form a forwarding backbone using a CDS approach. The backbone is capable of forwarding packets, maintaining network connectivity and preserving network capacity. Based on local decisions, nodes in SPAN decide whether they should join or sleep in the forwarding backbone. Nodes in the forwarding backbone are called coordinator nodes while the remaining nodes in the network are called non-coordinator nodes. Non-coordinator nodes remain in a sleep mode to save power and periodically wake up to exchange traffic with coordinator nodes. One of the main features of SPAN is the use of the power saving features of 802.11 to improve routing throughput and packet delivery latency. Using SPAN on top of the 802.11 power saving mode allows packets sent to a sleep mode to be stored temporarily at its neighbor. The packets are later retrieved when the node wakes up, thus preventing packet loss.

SPAN is designed to meet the following four goals [16]. First, it elects a sufficient number of coordinators such that every node has at least one coordinator among its one-hop neighbors to guarantee the network connectivity. Second, it employs a load balancing technique that rotates the coordinators so that the coordinator task is fairly distributed among all nodes. Third, it creates a small CDS size. However, the CDS generated may not be a minimal CDS. Fourth, the selection of coordinators is done in a distributed manner using localized information gathered from neighbors.

The operation of SPAN is governed by two processes called coordinator election and coordinator withdrawal. These two processes are drawn in Figure 8. The information needed for a node to withdraw or elect itself as a coordinator is exchanged among neighbors via HELLO messages. During coordinator election, a non-coordinator node periodically checks whether it is being elected as a coordinator based on the coordinator eligibility rule. The rule states that a non-coordinator node will become a coordinator if it has two neighbors which cannot communicate directly or through intermediate coordinators. In the case of contention which happens when multiple nodes decide to become a coordinator at the same time, SPAN uses a random back-off delay to resolve the contention. This is done by setting a random delay and announces the contention to neighbors. When the delay is expired, nodes recheck the coordinator election by resending the coordinator announcement. If the eligibility rule is still valid, they become coordinators. Interestingly, SPAN incorporates both the energy level of nodes and the ability of nodes to connect additional pairs of nodes among their neighbors to address the energy conservation issue and fair load distribution in the network.

Coordinator withdrawal process allows the role of coordinator is rotated among nodes. If a coordinator has all neighbors that can communicate directly or covered by other coordinators, it withdraws from being a coordinator and becomes a tentative coordinator. It remains in this state for a certain duration of time, W_T before withdrawing its coordinator status. Results of SPAN indicate that it can preserve network connectivity, maintain capacity and provide significant energy savings. SPAN simulations show that the system lifetime with SPAN is more than a factor of two better than without SPAN.

2) CLUSTERPOW: The CLUSTERPOW [76] algorithm joins the clustering approach with the power control approach to gain network connectivity, network capacity and energy efficiency. The design of CLUSTERPOW is motivated by the limitation of COMPOW [51] in dealing with non-homogeneous node distributions. The choice of using a minimum common power level in COMPOW is not appropriate for non-homogeneous networks because the lowest common power level is determined by a faraway node. For illustration, consider node u in Figure 9 redrawn from [76]. All the nodes within the cluster $C1$ use the power level 1mW to communicate. When a node w joins the network, the rest of the nodes in cluster $C1$ are forced to use unnecessarily higher power

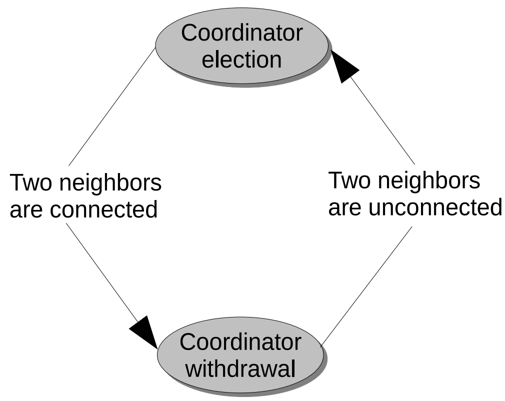

Fig. 8. The state diagram of the coordinator election and withdrawal processes in SPAN.

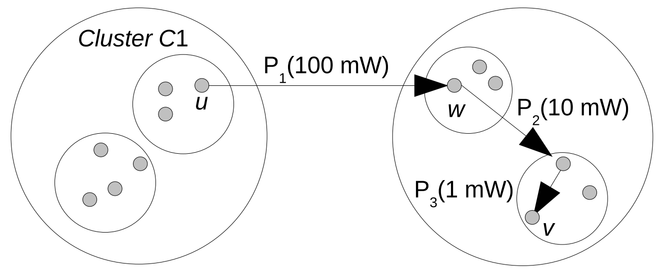

Fig. 9. The CLUSTERPOW multihop routing using a smaller power creates a non-homogeneous network.

level of 100mW to communicate with node w. As a result, the minimum common power level is set to a much higher level. As a solution, CLUSTERPOW offers a joint topology control and routing solution that selects an optimum minimum power level for each cluster. CLUSTERPOW provides implicit clustering which means that the small transmit power level chosen automatically creates clusters. Consequently it has no clusterheads or gateways.

Similarly to COMPOW, CLUSTERPOW requires each node to keep separate routing tables, one for each power level constructed using exchanged HELLO messages. It also employs parallel modularity at the network layer by running multiple routing daemons as in COMPOW. When node u has a message to send to node v, it computes the lowest transmit power level P such that the destination is reachable in multiple hops by using the power levels smaller than P. This process is executed at the source, and at every intermediate node along the route from the source to the destination. For example, the network in Figure 9 has three levels of clustering corresponding to power levels of 1mW, 10mW and 100mW. To transmit from node u to node v, a power level of 100mW is used at each hop until the packet gets to the 10mW cluster. Then 10mW is used at each hop and the transmit power is lowered down to 1mW as the packet gets closer to the destination.

3) Low-Energy Adaptive Clustering Hierarchy (LEACH): LEACH was introduced in [28] to reduce energy consumption by means of clustering, data aggregation, load balancing and TDMA/CDMA. LEACH integrates the clustering approach and power mode approach to prolong network lifetime. In WSNs, a considerable amount of energy is involved when all nodes participate in data transmission over long distance. The use of clustering can minimize the energy spent by limiting the number of nodes that participate in long distance transmissions. In clustering, only clusterhead nodes can transmit data to the base station. To reduce the number of data transmissions, LEACH assigns data aggregation and fusion tasks to the clusterhead nodes. LEACH uses a load balancing mechanism that periodically rotates the role of clusterhead nodes. Fair and uniform election of clusterhead nodes are also used to ensure that nodes die randomly. LEACH uses TDMA to reduce intra-cluster communications which solves collision, hidden problems, overhearing and idle listening. This is achieved by switching-off the radios of non-clusterhead nodes when they are not in use. LEACH uses CDMA to overcome the collisions among clusterhead nodes competing for simultaneous data transmissions to the base stations.

The operation of LEACH is divided into rounds with each round consisting of two phases. Algorithm 6 shows the two phases. The set-up phase is responsible for cluster formation while the steady-state phase is responsible for data forwarding operations to the base station. The set-up phase begins with clusterhead election. The clusterhead election is rotated in each round to provide uniform load distribution and extend node's lifetime. Clusterheads are elected randomly according to two criteria. The criteria are based on the suggested percentage of clusterheads (decided a priori) and the number of times the node has been a clusterhead. Each node u chooses a random number, RN between 0 and 1. If the number is less than the threshold value, Th, it becomes a clusterhead for the round. The Th is computed as

$$Th(u) = \begin{cases} \frac{P}{1-P(r\frac{1}{P})} & \text{if } n \in G \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

where P is the desired percentage of clusterhead, r is the current round and G is the set of non-clusterheads in the last $\frac{1}{P}$ rounds. Therefore, the chances of a node becoming a clusterhead are low if it has been selected as a clusterhead in the previous round. The elected clusterhead nodes then broadcast their election to the rest of the nodes in the network by sending an INVITE message. The non-clusterhead nodes that receive the INVITE message will then measure the signal strength received to choose a cluster. The nodes will join the cluster with the largest signal strength value and inform the clusterhead nodes of their decision. This information is required by the clusterhead nodes to create a TDMA schedule for each member in the cluster.

In the steady-state phase, nodes that are scheduled for data transmission will begin their data transmission to the clusterhead node. The nodes that are not scheduled for transmission will switch to sleep mode to conserve power. The data received by the clusterhead nodes are aggregated or fused to compress the size before being sent to the base station. After a certain time, the next round starts again and the two phases are repeated.

Algorithm 6 The LEACH algorithm

Require: Graph $G(V, E)$
Ensure: Cluster $(C) \in G(V, E)$

```
procedure SETUPCLUSTER(G(V,E))                    ▷ Form clusters
    C ← ∅ ; CH(u) ← ∅
    RXSS ← ∅        ▷ Store the received signal strength of clusterheads
    for all u ∈ V do
        RN(u) ← RN[0 : 1]                 ▷ Choose a random number
        if RN(u) < Th(u) then
            C ← C ∪ {u}
            CH(u) ← CH(u) ∪ {u}       ▷ Selected as a clusterhead
        end if
    end for
    for all v ∈ N(CH) do
        RXSS(v) ← RXSS(v) ∪ {SSI(CH)}   ▷ SSI, received signal strength of clusterhead
        for all SSI(w), SSI(x) ∈ RXSS(v) do
            if SSI(w) > SSI(x) then
                CH(v) ← CH(v) ∪ {w}
            else
                CH(v) ← CH(v) ∪ {x}
            end if
        end for
    end for
end procedure

procedure STEADYSTATE(G(V,E))
    if u scheduled for transmission then
        transmit and aggregate data
    else
        transit to sleep mode
    end if
end procedure

procedure LEACH(G(V,E))                          ▷ Main procedure
    SETUPCLUSTER(G(V,E))                       ▷ Phase 1 of LEACH
    STEADYSTATE(G(V,E))                        ▷ Phase 2 of LEACH
end procedure
```

E. Comparative Evaluation of 2D Distributed Topology Control Algorithms

So far we have discussed twelve 2D algorithms and classified them into four categories. For a better understanding on the performance of different algorithms from an energy efficiency perspective, we provide a cost comparison based on the design criteria presented in Appendix A. Direct comparisons among algorithms are not possible since different criteria are used by the authors to evaluate the energy efficiency performance of the algorithms, thus poses a difficulty for finding a common ground to evaluate them. It is worth noting that a quantitative comparison of these algorithms is unfeasible on account of a lack of information given by the authors. Table I summarizes the cost comparison of their characteristics.

In the following section, we provide a discussion on each algorithm in the four categories. To provide an overall comparison of these algorithms, we summarize the advantages and disadvantages of these algorithms in Table II. In addition, we review the network lifetime definition used by each algorithm and highlight the strengths and weaknesses of these definitions.

1) Power Adjustment Approach: In this section, we present a discussion of the power adjustment algorithms, highlighting their advantages and disadvantages as well as the network lifetime definition used.

One of the key findings of Minimum Energy Communication Network (MECN) is the strong connectivity of the enclosure graph [62]. In the worst case condition every node is able to maintain communication links with all the nodes inside its enclosure [62]. MECN also generates a sparse network, which means that the number of links increases linearly with the number of nodes in the network. The impacts of the sparse network are the reduction in the level of interference and improvement in the energy conservation. However, there are several assumptions made in the MECN algorithm. The assumption that all nodes know their exact location in the deployment region by means of a global positioning system (GPS) is impractical. This is due to the message overhead incurred for updating location information and also installing additional hardware. MECN also assumes that each node can communicate with all its neighbors and neglects the obstacles that usually exist in the deployment region between two nodes. Another downside of MECN is its reliance on an explicit propagation model to compute the relay region and enclosure graph [66]. For example, in order to determine the lowest energy route, nodes need to compute all the possible routes based on the actual transmit power level. Therefore realistic radio propagation conditions must be used when computing the optimum topology. One main challenge reported in [62] is to limit the search region such that the algorithm terminates. When nodes are highly mobile, the computation of relay nodes and the enclosure region can be expensive (time complexity) and it can drain the energy of nodes. The time complexity of MECN given in [68] is $O(V^3)$, where V is the number of neighbors of a node. Even though the message overhead of MECN is not provided, we believe a considerable message overhead is also introduced during the second phase, in which MECN relies on global information to compute the best topology. MECN is designed for static or slowly changing networks. Nevertheless, because of its localized property it is also appropriate for mobile networks but possibly at the expense of a relatively high message overhead.

Small Minimum Energy Communication Network (SMECN) uses the same network and energy models as MECN [62]. Thus it exhibits all the advantages and disadvantages of MECN for common features. SMECN outperforms MECN in terms of power efficiency and time efficiency due to its smaller generated subgraph. The time complexity of SMECN is $O(V^2)$ [68]. It converges faster than MECN because the subgraph constructed has a fewer number of links that can also result in lower link maintenance costs and achieve a significant energy saving [40]. It is observed that during neighbor search, the choice of transmit power is influenced by network density. For instance, a lower transmission power is sufficient to enclose a dense network whereas a much higher transmission power is needed to enclose a sparse network. This suggests that SMECN may not be a power efficient solution for sparse networks where the maximum transmission power is frequently used. In such cases, the battery of nodes can quickly drain and shorten the network lifetime. This limitation has been addressed in [68].

COMPOW has a modular structure that allows topology

TABLE I
COST COMPARISON OF 2D DISTRIBUTED TOPOLOGY CONTROL ALGORITHMS. IN THE TABLE, n REPRESENTS THE TOTAL NUMBER OF NODES, V IS THE NUMBER OF NEIGHBORS, P IS THE NUMBER OF TRANSMIT POWER LEVELS, AND Δ IS THE MAXIMUM DEGREE IN THE GRAPH.

Algorithms	Localized	Time Complexity	Message Complexity	Space Complexity	Connectivity	Mobility
MECN	Yes	$O(V^3)$	Not provided	$O(V^2)$	High	Low
SMECN	Yes	$O(V^2)$	Not provided	Not provided	High	Low
COMPOW	No	Not provided	$O(Pn)$	Not provided	Low	Low
GAF	No	Not provided	$O(V)$	Not provided	Low	Low
STEM	Yes	Not provided	Not provided	Not provided	Low	No
ASCENT	Yes	Not provided	Not provided	Not provided	Low	No
PACDS	Yes	$O(\Delta^2)$	$O(n\Delta)$	Not provided	High	Low
ECDS	Yes	$O(n)$	$O(n)$	Not provided	High	No
TMPO	Yes	Not provided	Not provided	Not provided	High	High
SPAN	Yes	$O(n)$	$O(n)$	Not provided	Low	Low
CLUSTERPOW	No	Not provided	$O(Pn)$	Not provided	Low	Low
LEACH	Yes	$O(n)$	$O(n)$	Not provided	Low	Low

TABLE II
ADVANTAGES AND DISADVANTAGES OF 2D DISTRIBUTED TOPOLOGY CONTROL ALGORITHMS.

Category	Algorithm	Advantage(s)	Disadvantage(s)
Power Adjustment	MECN	Strong connectivity	Needs location information (GPS) system to build topology
	SMECN	Strong connectivity. More power and time efficient than MECN	Needs location information(GPS) to build topology
	COMPOW	Practical-based topology control. Built on a wireless testbed	High message overhead for computing multiple power levels
Power Mode	GAF	Low communication overhead	Relies on location information system to compute the grid and allocate nodes into the grid
	STEM	Energy efficient for event-triggered applications	Trade-off energy savings with setup latency
	ASCENT	Self-reconfigurable and adaptive to react to applications' dynamic events	Possibly fast energy depletion among active nodes due to uneven load distribution
Clustering	PACDS	Simple and quick to calculate the connected dominating set and location service-free	Not suitable for high mobility
	ECDS	Node's energy residual considered in the construction of connected dominating set	High message overhead
	TMPO	Stable topology and load balancing features. Appropriate for high mobility networks	High message overhead and computationally intensive
Hybrid	SPAN	Location service-free and exploits the advantage of power saving 802.11 for routing	Nodes have to periodically wake-up and listen for traffic advertisements
	CLUSTERPOW	Easy maintenance of clusters and possible implementation on a wireless card	Significant message overhead for computing multiple power levels
	LEACH	Offers a variety energy efficient mechanisms	Complicated tasks performed by clusterheads and not scalable

control to be plugged into any proactive routing protocol, thus making it flexible. However there are several shortcomings of COMPOW. The first shortcoming is its significant message overhead. Each node runs six different power levels and exchanges significant link state information with other nodes to set the optimum power level. This process creates extra message overhead, which may exhaust the nodes' energy reserve and shorten the nodes' lifetime. The decision on setting the optimum power level is also made based on the global information provided by various routing tables running multiple power levels. As a result, it incurs a considerable message overhead to maintain and update the network topology. In the worst case scenario COMPOW's message overhead is $O(Pn)$ [71], where P is the number of power levels used by nodes while n is the total number of nodes in the network. Obviously, a significant message overhead is required if nodes run more power levels. In practical situations P can reach as high as 10 as reported in [64]. The second shortcoming of COMPOW is apparent in a non-homogeneous network whereby nodes are required to converge to a much higher common power level set by a new node joining the network that resides faraway from the majority of the nodes. As a result, a higher transmit power is used to maintain the network graph thus, defeating the purpose of minimizing power consumption through the use of a minimum common power level.

2) Evaluations based on the Network Lifetime Definitions.: Among the three power adjustment algorithms, only SMECN provides the network lifetime definition, whereas MECN and COMPOW do not specify any network lifetime definition.

The aim of MECN is to maximize the battery lifetime of the network by finding the routes that consume the lowest energy. Depending on the accuracy of the radio model, the total energy consumption for transmitting packets using these routes might be greater than anticipated. In MECN, the radio model used only considers the energy spent by the transmitters and neglects the energy dissipation of the receivers. According to the work in [28], under conditions of short transmission distances and/or high energy consuming radio electronics, the total energy consumption of MECN might be greater than for algorithms that use direct transmission to the base station.

SMECN uses the number of nodes remaining alive over some duration of time for its definition for the network lifetime. A simulation was conducted to compare the network lifetime performance of SMECN over MECN. The result shows that SMECN has more alive nodes than MECN [40]. However, the measured lifetime based on this definition alone is not accurate because it cannot represent the criticality of nodes. Since SMECN chooses the path that has the minimum energy routes, each node tends to send messages to the base station via the same route through its closest neighbors. The nodes along this route are the critical ones in which, without a proper care, SMECN can overuse the energy of the critical nodes and shorten the lifetime of the network.

Another important metric to be considered in the network lifetime definition is the connectivity of the network to the base station. In certain applications such as data monitoring, the failure to transmit data to the base station is used to describe the end of the network lifetime, even though the number of alive nodes is significantly. In SMECN, the connectivity to the base station is defined by the number of alive nodes remaining connected to the base station. SMECN uses this definition to describe the ability of the network to communicate with the base station. Incorporating the failure to transmit data to the base station with this definition would provide a more extensive definition of the network lifetime. For example, consider a scenario in which the number of alive nodes is low but the network can still provide a useful task of transmitting data to the base station. In this case, the network should be considered as still alive and the use of both definitions is able to capture this scenario.

3) Power Mode Approach: In this section, we present a discussion of the power mode algorithms by highlighting their advantages and disadvantages as well as the network lifetime definition used.

GAF connectivity is very much influenced by the network density and the accuracy of the nodes' radio model. In dense networks, the connectivity and routing fidelity are guaranteed by the existence of multiple communication paths. But in sparse networks the connectivity and routing fidelity are low if no active node is present in a grid. GAF is a location-based algorithm. It depends heavily on the availability of global location information to form virtual grids and associate nodes with the grids. Although the information provided by the global location information is highly accurate, the use of the global location information places a burden on the networks that have limited resources. The network lifetime also increases proportionally with the node density. The network lifetime extension is more significant in a dense network because of the large amount of energy saving achieved by powering down many redundant nodes that participate in routing. In contrast, the network lifetime saving may not be apparent in a sparse network. GAF promises small communication overhead. Each node broadcasts only one message during the discovery and active states. The message overhead of GAF is $O(V)$, where V represents the number of neighbors of each node.

STEM exploits the node redundancy to gain energy saving in the network. Similarly to GAF, the energy saving achieved by a dense network is much higher than the energy saving achieved by a sparse network. This is due to the property that dense networks have more redundant nodes that can be rigorously switched to sleep mode. STEM assumes that nodes in the network mostly reside in the monitoring state and they have infrequent data forwarding activities. This assumption implies that STEM is an application-specific algorithm, thus STEM is energy efficient for sensor nodes that have an occasional data transfer which is triggered by an event. STEM requires the radios of the receiver nodes and the subsequent nodes along the communication paths prior to data transfer. These nodes must also wait for an acknowledgment from the receiver nodes. Hence, there is a probability of nodes experiencing delay which could lead to a data latency issue. The advantage of STEM is that nodes rely on local information to decide their wake-up time. The decision to switch to sleep mode is also made locally whereby nodes immediately turn off their radios after transferring data. A significant energy saving is also gained when nodes spend the majority of their time in this mode. But regular periodic switching between the sleep and active states to listen for incoming packets typically consumes a significant amount of energy. In STEM, the energy consumption associated with this switching process is not specified. In addition, the time, space and message overheads for setting up and transferring data are not mentioned. The connectivity of STEM is defined by the average number of neighbors M which is given by

$$M = \frac{nR^2\pi}{L^2} \tag{6}$$

where n is the total number of nodes in the network, R is the transmission range of nodes and L is the length of the square field. Strong connectivity is possible for a dense network deployed in a small region.

ASCENT exploits the redundancy of node density to prolong network lifetime like GAF and STEM. This means that the energy saving is significant when nodes are densely deployed in the network. The advantages of ASCENT lie in its flexibility and adaptive mechanisms that allow parameters to be tuned to cater for the requirements of applications. But setting the parameters to accurately reflect the requirements of applications is not a simple task, which can make ASCENT impractical. The parameters involved are the neighbor threshold (NT) value, the loss threshold (LT) value, the sleep timer T_t value, the passive timer T_p value and the sleep timer T_s value. The (NT) value can be adjusted to optimize the network connectivity. By setting (NT) to a much lower value the average degree will be lower thus resulting in low connectivity in the network. The low connectivity can partition the network when the energy of active nodes is depleted. The (LT) parameter specifies the maximum amount of data losses that a network can withstand. When the data loss rate exceeds the (LT) value, nodes in the passive state will be switched to the active state to participate in data forwarding. Setting the (LT) value is based on the application of the network. For example, networks that are highly mobile tend to experience high data losses whereas networks that are used for environmental monitoring such as bushfire event are likely to have low data losses. The T_t, T_p and T_s values define the amount of time a node stays in the test, passive and sleep states, respectively. The choices of T_t, T_p and T_s values trade-off the energy saving with the decision quality. For example, setting the T_p to a larger value means that nodes will have a sufficient time to collect data loss information from their neighbors to make further decision, thus contributing to the high accuracy of ASCENT but at the expense of high energy consumption associated with turning on more nodes' radios. A larger values of T_s results in improved energy saving but less nodes in the passive state. These nodes are used to backup the active nodes, joining them when the connectivity of the network is low. Consider the case when the connectivity of the network is very low due to the depletion of energy in the active nodes and there are no nodes in the passive state. The network may experience partitioning if the active nodes are the only links connecting to other nodes. The time, message and space complexity of ASCENT are not provided.

4) Evaluations based on the Network Lifetime Definitions.: In the power mode approach, the definition of the network lifetime is not given in STEM and ASCENT. GAF on the other hand provides the network lifetime definition.

GAF uses two metrics to define the network lifetime. The first metric measures the network lifetime as the fraction of survived nodes as a function of time. This network lifetime metric is used to analyze the performance of GAF under both low mobility (1 m/s) and high mobility (20 m/s) patterns. GAF considers a range of pause times to indicate node movements. The shorter pause time represents moving nodes whereas the longer pause time represents no node movement. GAF shows that nodes with shorter pause times result in better network lifetimes than nodes with longer pause times. This is because the moving nodes possibly move into grids with other nodes allowing them to share the load.

The second metric employed to define the network lifetime is the time t until the monitored packet delivery ratio drops dramatically. This definition measures how long the network can successfully deliver packets until the ratio drops below a certain threshold value. It measures the ability of GAF to connect to the base station.

GAF uses both metrics to define the network lifetime because the use of either the first or second metric alone is not sufficiently accurate to represent the network lifetime. Consider the case of using the fraction of alive nodes to define the network lifetime. Since the network lifetime of GAF is closely related to the density of the network, thus under a dense network the small fraction of alive nodes can deliver the traffic without affecting routing fidelity, whereas in a sparse network the routing might be disrupted. The second metric on the other hand requires one to define an appropriate packet delivery ratio. However, the method to set the ratio and identifying the best packet delivery ratio are not mentioned in GAF.

5) Clustering Approach: In this section, we present a discussion of the clustering algorithms, highlighting their advantages and disadvantages as well as the network lifetime definition used.

Power Aware Connected Dominating Set (PACDS) uses a simple marking process to calculate a CDS. This process provides a quick and simple way to build the network backbone. PACDS requires one round of message exchanges for the marking process and one more round for the pruning process. Thus, PACDS can be completed in a constant number of rounds. The authors [34] claimed that the time complexity to calculate the CDS is $O(\Delta^2)$, where Δ is the maximum node degree in the graph. The message complexity is given by $O(n\Delta)$, where n is the total number of vertices or nodes in the graph [34]. However, these claims are refuted in [77], in which the time and message complexity of PACDS maybe higher. According to [77], in the pruning process, a node u may need to examine as many as $O(\Delta^2)$ pairs of neighbors. Also, for each pair of neighbors, as much as $O(\Delta)$ time may be taken to find out whether such a pair of neighbors together dominates all other neighbors of u. Hence, the time complexity of PACDS could possibly be as high as $O(\Delta^3)$. The estimated message complexity of PACDS is actually $O(m)$ where m is the number of edges in the unit-disk graph, as each edge contributes to two messages in the first stage [77]. The number of edges m can be as many as $O(n^2)$. In PACDS, each time a topology changes a backbone is reconstructed to update the changes. Frequent topology changes triggered by highly mobile nodes can waste the energy resources in the network. Therefore, PACDS is only appropriate for static and low mobility networks.

Energy Efficient Connected Dominating Set (ECDS) employs local information to achieve a desired global property. The result in [34] shows that nodes in ECDS can survive longer than in PACDS. The authors [88] show that the message complexity of the ECDS algorithm is $O(n)$ because in the worst condition each node sends out one message during each phase. The time complexity of ECDS is also $O(n)$, which is estimated from the construction of the MIS. But the message complexity in ECDS is possibly higher than reported in [88]. This is due to the frequent exchange of messages during the search of the MIS and connector nodes. Therefore, the ECDS algorithm may not be appropriate for dynamic networks. In the second phase, the decision to choose a connector node is made according to a weight metric. Hence, MIS nodes need to compare the weight of their neighbors and consult with other nodes before appointing a connector. This process may impose a high message overhead. The connectivity of the network is guaranteed as long as the CDS remained connected. The authors of ECDS have proven the correctness of ECDS in constructing a CDS.

TMPO offers several advantages. First, TMPO performs a local computation on the minimal dominating set (MDS) based on two-hop neighbor information. Second, it uses a priority parameter that considers the node movement and energy level. As a result, the node with a higher energy level and low mobility has a greater chance of becoming a clusterhead. The priority parameter is used to achieve a stable topology. An unstable network that requires frequent topology constructions is computationally expensive. Different mobility environments have been used to test the stability of the topology constructed by TMPO. Therefore, TMPO is suitable for low and high mobility networks. Third, the clusterhead election is also rotated after some period of time to distribute the load fairly. The performance analysis of TMPO shows that it has better load balancing capability and higher topology maintenance stability against other heuristics. The willingness value in TMPO is used to control the network connectivity. The clusterheads that are highly mobile are likely to be disconnected from their neighbors. In order to avoid the network partitioning, TMPO adjusts the willingness value to a much lower value to remove the clusterheads from the dominating sets. The disadvantage of TMPO is the difficulty in managing the hierarchical structure of the network. TMPO requires at most 3-hop away neighbor information to find doorway and gateway nodes. Any changes in the role of clusterhead, host, doorway or gateway will require nodes to propagate changes to their neighbors, resulting in a delay for updating the topology changes.

6) Evaluations based on the Network Lifetime Definitions.: Most of the three clustering algorithms include the network lifetime in their studies, except the TMPO algorithm.

PACDS measures the network lifetime as the time until the first node in the network runs out of energy and fails. This definition does not account for the connectivity to the base station. If the first node to fail is a backbone node, then there is a possibility that the backbone has to be reconstructed. If the first node to fail is a node outside the backbone, then the network can still operate. This definition might be appropriate for a network consisting of nodes that are equally important and failure of one node is unacceptable.

ECDS defines the network lifetime as the number of periods that the network can survive until it can no longer construct a CDS. In other words, the network fails because it can no longer construct a backbone. This network lifetime definition can describe the successful delivery of messages to the base station as long as the backbone exists. However, in harsh environments where nodes often fail, this definition could over estimate the network lifetime. This is because ECDS may not be quick enough to respond to the dynamic changes in the environments, leading to an extended lifetime. Importantly, frequent re-computation of the backbone can consume a significant amount of energy which contributes to the energy drain on the backbone nodes.

7) Hybrid Approach: In this section, we discuss the hybrid algorithms, highlighting their advantages and disadvantages as well as the network lifetime definitions.

SPAN combines the clustering approach with the power mode approach to allow idle non-CDS nodes to switch to sleep mode, thus conserving energy consumption and simplifying the switching mode operation. The sleeping nodes are also able to receive packets because SPAN runs on top of 802.11 ad hoc power saving mode. Thus, SPAN minimizes packet losses and packet retransmissions. However, the power saving mode feature can limit SPAN's ability to save energy if nodes frequently switch from sleep mode to active mode to listen for traffic advertisements. The message complexity of SPAN is $O(n)$ since each node exchanges one message during the coordinator announcement or coordinator withdrawal [39]. The time complexity of SPAN is $O(n)$ in the worst case because SPAN needs to consider n total number of nodes in the network for constructing the CDS backbone [39]. SPAN has to piggyback HELLO information onto the broadcast updates, thus it is dependent on the routing protocol. SPAN is practical because it does not require any location information system to determine the position of nodes. In SPAN, the location information is provided by the GOD module of ns through the exchange of HELLO messages. However, the location given by the GOD module is less accurate than the location given by a location information system. In SPAN, each node needs to keep a maximum of 3-hop neighborhood information for coordinator announcement and withdrawal processes. Maintaining and updating the 3-hop information may impose a significant message overhead. The connectivity of SPAN is low since it is governed by the rules used during the coordinator announcement and withdrawal.

CLUSTERPOW is not tightly coupled to a specific routing protocol and therefore it can be used with any routing protocol. Since CLUSTERPOW is an extension of COMPOW, it can be used in a homogeneous network by setting the common power to a minimum value. CLUSTERPOW does not have any leader or gateway and the clusters are automatically generated when the power level is chosen. This attribute simplifies the cluster formation process as nodes do not need to elect clusterheads or gateways. In this way, the energy resources consumed for electing the clusterhead nodes and building the clusters can be saved. The architecture of CLUSTERPOW is similar to COMPOW hence, its message overhead is determined by the number of power levels used in the network. In the worst case scenario CLUSTERPOW's overhead is $O(Pn)$, where P is the number of power levels used by nodes while n is the total number of nodes in the network. CLUSTERPOW depends on global information in deciding on the minimum power level needed for routing because each node has to consult the master routing table. The master routing table is formed by taking an input from different routing tables. The message overhead for building and maintaining the multiple power routing levels is significantly high. The advantage of CLUSTERPOW is that it's, design has been tested on CISCO wireless cards and its correctness has been verified. Even though the authors experienced a technical problem when changing the transmit power level, they manage to test it on laptops. Thus, the practical implementation of CLUSTERPOW is proven.

LEACH's advantages are energy efficiency and network lifetime extension. LEACH is a localized algorithm that allows each node to gather information from its neighbors to form clusters. Each node sends out one message during cluster set-up, thus the message and time complexity of LEACH are low. The message and time complexity of LEACH are $O(n)$, where n is the total number of nodes in the network [39]. Unlike other clustering or hybrid approaches, LEACH uses data aggregation to compress the size of messages before sending them to the base station. This reduces the energy involved in transmitting a large amount of data over long distances. However, there are several drawbacks of LEACH. First, LEACH executes many tasks. Therefore, the operation of LEACH is quite complicated. Each clusterhead node is assigned for data aggregation, TDMA scheduling and data forwarding tasks. These demanding tasks can drain the energy of the clusterhead nodes and shorten the lifetime of the nodes. Second, the clusterhead nodes use long distance transmission to send data directly to the base station. In other words, LEACH has a scalability issue in which it does not exploit the multihop communication between two clusters that can contribute to energy saving and network scalability. The scalability issue of LEACH has been addressed in HEED [87], in which HEED proposed inter-cluster routing between clusterhead nodes to support multihop communication with the base station. Third, LEACH assumes that all nodes have data to transmit whereas in practice this assumption maybe untrue, hence energy is wasted. Fourth, LEACH selects clusterhead nodes randomly according to criteria that consider the number of times nodes become a clusterhead and a predetermined percentage of clusterheads. These criteria do not account for the remaining energy capacity at each node and it is possible that a node with a lower energy level is selected as a clusterhead node. In LEACH, clusterhead nodes are burdened with various tasks, thus appointing a lower energy node to become a clusterhead can shorten the network lifetime as it has insufficient energy to perform the tasks. Finally, even though the use of TDMA-based scheduling can avoid multiple retransmissions, it is not easy to synchronize nodes.

8) Evaluations based on the Network Lifetime Definitions.: In the hybrid approach, the network lifetime is defined in PACDS and LEACH but not in the CLUSTERPOW.

The network lifetime in SPAN is defined by the fraction of the CDS nodes that remained alive as a function of time. But the appropriate figure detailing the number of nodes that must remained alive to support the operation of the network is not provided. This definition might be reasonable if the fraction of the alive CDS nodes can provide the connectivity to the base station. In a particular application such as routing, the dominating set constructed in SPAN must remained connected. Therefore, the fraction of the CDS nodes that remained alive must be connected otherwise the routing is disrupted.

In LEACH, the number of sensors still alive is used to measure the network lifetime. LEACH also measures the number of rounds from the first node to the last node dying. Each node is assigned a certain energy threshold. The system lifetime of LEACH is shown to be higher than other algorithms regardless of the energy thresholds assigned to the nodes. Even though LEACH can prolong the network lifetime, it is not known whether the remaining nodes in the network can form a backbone or not. If the backbone cannot be constructed, data cannot be transmitted to the base station. Nevertheless, LEACH shows that nodes die in a random fashion which indicates a fair load distribution in the network. This characteristic is desirable for monitoring applications in which the network can cover every region of interest, as each region has at least one node to monitor the area.

IV. Three-Dimensional (3D) Distributed Topology Control Algorithms

In WSNs, the important characteristics that make the networks attractive for a broad range of applications are self-organization, flexibility and large-scale deployment. The most recent and interesting but yet challenging applications of WSNs are underwater monitoring and exploration [1], [9], [15], [27], [38], [56], [57], [75], [83]. An underwater acoustic sensor network (UW-ASN) consists of acoustic sensors and underwater vehicles that are deployed to perform environmental monitoring, undersea explorations, disaster prevention and surveillance [2]. These underwater sensors are distributed at different depths in the ocean, and require 3D rather than 2D modeling. The topology control algorithms designed for 2D networks are inappropriate to model the UW-ASNs. Moreover, the challenges of underwater applications [2] and the characteristics of the underwater acoustic communication channels which have limited capacity and high propagation delays [60], [2] may impose a unique design requirement on topology control techniques. Further discussion on the complexity of deploying the 3D networks and extending the existing designs to 3D networks can be found in [55].

A. Energy Efficient 3D Topology Control Algorithms

In UW-ASNs, energy scarcity remains one of the major challenges due to the difficulty of recharging the battery underwater, hence energy conservation is very critical. Since our focus is on energy conservation mechanisms, this section will review the energy efficient topology control algorithms designed for 3D networks. Although the problem of energy conservation has been widely addressed in 2D networks, there are not fully addressed in 3D networks. So far there is limited work on 3D networks that discusses the energy efficiency issue. For this reason, we are unable to classify the energy efficient 3D algorithms accordingly. Other research in 3D WSNs focus on the aspects of routing [31], [63], fault-tolerant [7], [80], coverage [30], [74], connectivity [5] and localization [17], [73] .

1) Sensor Topology Control (STCA): The energy conservation approaches used in STCA [4] are to put redundant nodes into sleep mode and minimize the number of active nodes participating in data forwarding and sensing activities. STCA's approach is similar to the approach in [14], [67], [85] except that it is extended to 3D networks. In order to find the active nodes, STCA partitions the 3D network into virtual cells so that each node can be allocated to its respective cell through the use of cell id. The cell id provides each node with a knowledge about its neighbors in the same cell that are within its transmission range. In STCA, the network lifetime can be extended by electing only one node to be active and switching-off the redundant nodes if there are at least two nodes in the cell. It is worth noting that STCA does not propose any leader election algorithm. Instead it uses the existing 2D leader election algorithm [45] to elect the active nodes.

There are three aims of STCA. The first aim is to find the best method to partition the network into cells in three-dimensions that results in a small number of active nodes without affecting the network connectivity. The second aim is to discover the minimum sensing range that guarantees the network coverage. The third aim is to design a fast, efficient and distributed algorithm to partition the network into cells and allocate nodes to each cell.

In order to partition the 3D network into virtual cells, STCA explored four possible shapes to model the 3D space. The four shapes are cubic, hexagonal prism, rhombic dodecahedron and truncated octahedron tessellations. The key finding of STCA is that partitioning the 3D networks into truncated octahedron cells yields the smallest number of active nodes. However, the minimum sensing range of the octahedron cells that ensures full coverage is slightly larger than the sensing range of the other three shapes which is 0.542326 times the transmission radius. The use of topology control algorithm in this work is to determine the respective cell for each node with the condition that the location of the node and its information sink are known. To choose the appropriate cell, each node has to find the cell whose center has the minimum euclidean distance to the node. This is done by computing the distance from all possible eight centers of the cells.

The network lifetime is measured by the inverse of the number of nodes in the cells. Thus, the shape with the lowest number of nodes has the largest network lifetime. Obviously, the network lifetime of the truncated octahedron is the highest compared to the network lifetime of the cubic, hexagonal prism and rhombic dodecahedron shapes.

2) Adaptive Yao Graph with Platonic Solid (APYG): The APYG algorithm [37] is an extension of the Yao graph [43] proposed for building an energy efficient topology for three-dimensional WSNs. APYG calculates the minimum transmit power by considering both the effects of path loss and signal interference. In practice, the minimum transmit power will be affected by both.

In APYG, node u partitions the 3D space into k equal cones using a regular k-hedron and chooses the neighbors that require the least transmit power to reach in each cone. The least transmit power is the link cost used for building the topology. It considers the signal interference effects that may exist between a pair of nodes. Initially, using the maximum transmit power $\mathrm{P_{TX(max)}}$ node u broadcasts a HELLO message containing information about its location and signal power threshold $\mathrm{P_{S-TH}}$ (in dBm) as

$$\mathrm{P_{S-TH}} = 10\log(\mathrm{S_I}(\mathrm{P_I}+\mathrm{P_N})) \tag{7}$$

where $\mathrm{S_I}$ is the signal to interference plus noise ratio (SINR) for a successful reception, $\mathrm{P_I}$ is the interference power and $\mathrm{P_N}$ is the noise power (both in mW). $\mathrm{P_I}$ can be measured by reading the received signal strength indicator (RSSI) of the radio. When node u receives a response from its neighbor node v, it measures the received signal power P_S and then estimates the path loss $\mathrm{PL}(u,v)$ using

$$\mathrm{PL}(u,v) = \mathrm{P_{TX(max)}} - \mathrm{P_S} \tag{8}$$

and minimum transmit power $\mathrm{P_{TX(min)}}$ using

$$\mathrm{P_{TX(min)}}(u,v) = \mathrm{PL}(u,v) + \mathrm{P_{S\text{-}TH}}(v) \tag{9}$$

Node u then selects the node with the minimum transmit power in each cone and broadcasts the selection to all its neighbors.

APYG has the ability to adjust the topology during periods of interference, which is illustrated in Figure 10. This is possible because each node updates the interference power periodically and rebroadcasts the P_{S-TH} value when the received signal is degrading. In Figure 10, initially node a is selected as the closest neighbor of u. When node a experiences interference effects, node u will increase the signal power threshold and send the updated threshold value to its neighbors. It will then select a new node c that has the minimum transmit power. In this example although node b is closer to node u, node c is chosen over node b because the path loss of edge(u,b) is larger than the path loss of edge(u,c).

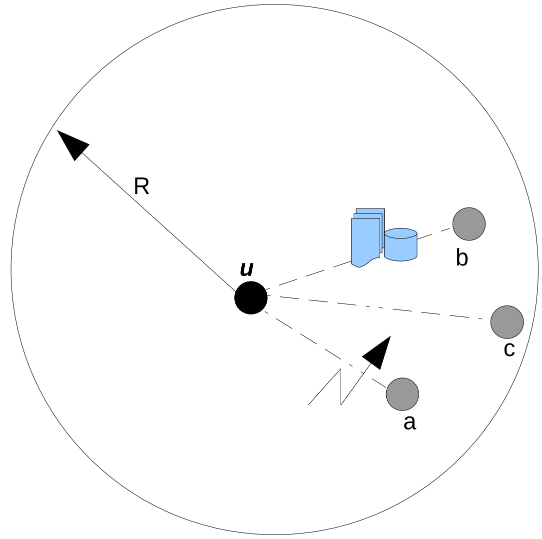

Fig. 10. APYG reconfigures the topology when node a, the closest neighbor of node u detects an interference. Node c is now selected as the closest neighbor of node u.

APYG uniquely defines two types of neighbor sets. A default edge set consisting of unidirectional edges and symmetric edge set consisting of bidirectional edges. The symmetric edge set is used to remove unstable edges under the influence of interference for routing purposes. In the worst case, unidirectional edges are used temporarily if nodes that are connected using bidirectional edges are partitioned.

3) Fixed Yao Graph (FiYG) and Flexible Yao Graph (FlYG): Wang et al. [81] proposed two algorithms that are also an extension of the Yao graph. The Yao graph was chosen because it can guarantee a bounded node degree. In both algorithms, node u will choose the node with the shortest edge among its neighbors in every cone to reduce the energy consumed during transmission. There are two types of 3D space partitioning algorithms proposed by the authors, fixed partitioning (FiYG) and flexible partitioning (FlYG) as shown in Figure 11.

In fixed partitioning all nodes will have the same partitions. Fixed Yao graph (FiYG) partitions the transmission range into 32 non-intersected cones. Each node has the same transmission range and is aware of the location of its neighbors. In Figure 11a, each node first divides its region into 8 divisions by three orthogonal planes (xy-plane, yz-plane and zx-plane). It then further divides each of these divisions into 4 cones using three planes c_1, c_2 and c_3. Nodes c_1, c_2 and c_3 are the center points of arc yz, zx and yx respectively. In each of the 32 cones, node u will select the closest node to form a graph and in the case of a tie, node ID is used to break the tie. However, the final graph formed has an infinite spanning ratio when the angle inside the cone is $\pi/3$. To resolve this problem,

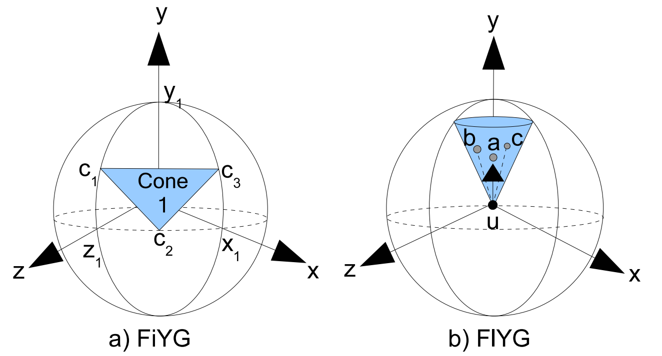

Fig. 11. Examples of 3D Yao graphs. a) FiYG divides the sphere into either 32 or 56 fixed cones b) FlYG forms a cone around node u drawing links to each neighbors a, b and c. The shortest edge ua is chosen in the cone and the position of the cone is determined by the location of neighbors resulting in a non-fixed cone.

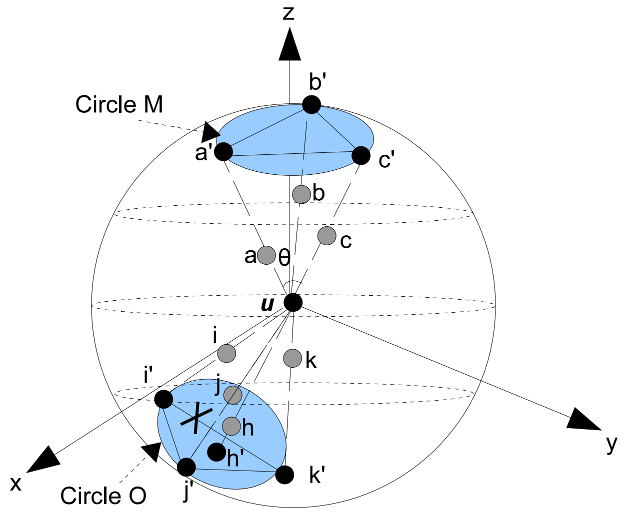

Fig. 12. The spherical Delaunay triangulation (SDT) is shown in Circle M. Node u projects all its neighbors on the spherical surface forming a cone and finds the SDT. Circle O does not satisfy the SDT empty circle property since the triangle is not empty due to the existence of node h'. Thus nodes in Circle O are not connected.

the authors partition the 3D space into a much smaller cone. Instead of dividing the 8 divisions into 4 cones, they divide them into 7 cones, thus producing 56 cones in total.

In flexible partitioning, nodes may have different partitions as shown in Figure 11b. There are three algorithms proposed for flexible partitioning, in which identical cones with a top angle θ are used to divide the 3D space. The location of the cones is determined by the location of the neighbors. The angle θ can be adjusted to be smaller than $\pi/3$ in algorithm 2 and $2\pi/3$ in algorithm 1 and algorithm 2. The first algorithm forms a 3D cone for each edge connecting node u to all its neighbors and selects the shortest link of all cones. The second algorithm however does not form a 3D cone for each link connecting node u to all its neighbors. Instead it initializes all links uv to be unprocessed. These will be later mark as processed. In the second algorithm, initially node u forms the 3D cone for the unprocessed links, then finds the shortest link in the cone and finally marks all links in the cone as processed links. This process is then repeated for unprocessed links only. The third algorithm on the other hand sorts the link lengths in ascending order. Similar to the second algorithm, all links are initially unprocessed. Algorithm 3 defines a 3D cone for the link, adds the link and marks all other links in the cone as processed.

4) 3D Spherical Delaunay Triangulation (3DSDT): 3DST [25] uses the spherical Delaunay triangulation (SDT) to identify the largest empty cone around a node in 3D networks and this idea is adopted from [55]. 3DST finds the largest surface area generated from SDT such that node u has at least one neighbor in a 3D cone when the angle of the cone is greater than $2\pi/3$.

There are two phases involved in the construction of 3DST. The first phase is responsible for finding the relative locations of node u's neighbors assuming that node u is transmitting at the maximum power level. The relative locations of neighbors are determined using the multi-dimensional scaling (MDS) technique. MDS represents the nodes as a point in a multi-dimensional space and arranges them in such a way that two similar nodes are represented by two points that are closer to each other, and two dissimilar nodes are represented by two points that are further apart [25].

The second phase is responsible for constructing the topology using the SDT technique. SDT identifies that two nodes on the surface of a sphere are connected if there exists an empty circle through the two nodes. The circle is said to be empty when a triangle is typically drawn on the spherical circle is empty, meaning that there is no node inside the triangle. As long as the circle is empty (so is the triangle) the graph is connected. In Figure 12 this property is met in the Circle M in which the triangle is formed by the three points a', b' and c'. The Circle O is not the SDT circle because node h' is located in the triangle. In this figure the spherical cap $Cap(a', b', c')$ is cut-off by a plane that passes through three non-linear points a', b' and c' which are located on the surface of a sphere. These three points a', b' and c' are the projection of nodes a, b and c (neighbors of node u) onto the surface of the spherical ball centered at u with radius R (which is a function of power level P). The projection draws the edges between node u and all its neighbors node v until they intersect with the spherical surface. The spherical Delaunay triangulation is then applied on the spherical surface such that the spherical triangles are found. The 3DSDT technique proves that the largest spherical area created by the 3D cone using the spherical Delaunay triangulation can guarantee the connectivity if the angle of the cone is greater than $2\pi/3$ around a node that is transmitting with power level P.

B. Comparative Evaluation of 3D Distributed Topology Control Algorithms

We have thus far discussed four algorithms for 3D networks. Because of the lack of performance metrics evaluated in the papers [25], [81], [37], [4], we can only make a comparison based on the time complexity. The cost comparison and their features are summarized in Table III. Most of the 3D algorithms presented in this paper use the Yao graph to model the networks. The Yao graph is chosen because it has a bounded node degree defined by the number of k cones.

Another advantage of the Yao graph is that it requires less computation under node mobility if the cones are fixed [37]. In case of node mobility only the neighbors of the moving node in the cone are affected and reconfigured. However, in FiYG [81] this is not the case because the formation of cones is flexible creating unfixed cones. Thus, FiYG may have a higher time complexity due to excessive recomputations of cones when neighboring nodes move. STCA [4] also has fixed cones and the node degree is bounded by the number of cells, therefore it can adjust well to node mobility. All 3D algorithms in this paper require 1-hop neighbor information to form the topology [80]. Under topology changes, the network can be easily reconfigured at a low expense.

The topology in 3DSDT [25] has bidirectional and connected properties. The connectivity of 3DSDT is bounded by the angle of the cone as long as the angle around a node is greater than $2\pi/3$. The authors claim that the time complexity of 3DSDT is $O(d \log d)$ where d is the node degree of a node. The time complexity of 3DSDT is much lower than for the algorithm in [7] which is $(O(d^3 \log d))$. The node degree of 3DSDT has been proven to be bounded by 15, calculated using the percolation theory of critical average node degree for network connectivity. In the case of topology changes due to node failure or mobility, 3DSDT requires every node to compute the spherical triangle. Therefore the construction of 3SDT is highly expensive [80], [37].

APYG [37] considers the effect of interference in the network and uses a realistic radio model. Many existing topology control techniques adjust the transmission power of nodes (thus varying the transmission range) to reduce energy such that the network lifetime is prolonged. In practice, the transmission range of nodes is very much affected by the multipath and shadowing effects. APYG on the other hand takes into account the interference by measuring the SINR value at each node and alerts the neighbors to the existence of the interference.

V. Concluding Remarks and Open Issues

In WSNs, nodes operate with a limited battery source and they cease operating once their battery depletes. Therefore, a network's lifetime is strongly dependent on battery lifetime. It is for this reason that power conservation and power management become the main focus in the design of topology control algorithms. A common approach to address the power issue is to develop energy efficient algorithms that optimize the use of the energy supply. In this article we have discussed, in particular, the topology control algorithms that are specifically designed for energy conservation in 2D and 3D network configurations.

Although considerable research effort has been devoted to topology control problems, there are many issues that are yet to be addressed. Based on the outcomes of our work, we derive and list the potential open issues that need further investigation.

1) **Hybrid Approach**. The future topology control techniques should explore the hybrid approach to develop a simple and energy efficient topology control solution. By integrating the power mode, power adjustment and clustering approaches, we can exploit the advantages of each approach. For instance, the techniques that combine clustering and power adjustment can utilize the advantage of the clustering approach to simplify the network and use the ability of the power adjustment to solve the optimal transmission power. The clustering approach can also be used with the power mode approach to reduce the energy consumption spent in idle mode. The power adjustment and power mode approaches can be jointly adopted to find the optimal transmission range for each node. In addition, the radio of the redundant nodes can be switched-off to gain more power saving. To the best of our knowledge, none of the existing topology control algorithms integrates power adjustment, power mode and clustering approaches.
2) **Realistic Energy Models**. It was observed that various radio models had been used by topology control algorithms to compute a topology. For example, the power adjustment approach such as MECN considers only the total energy consumption in transmitters and ignores the total energy consumption in receivers. As a result, the topology constructed may not be energy efficient if different radio characteristics are employed. A practical topology control should use a realistic energy model.
3) **Network Lifetime Definition**. Network lifetime is the main metric used to evaluate the performance of networks. We observed that various definitions of network lifetime are used in topology control. We showed that in some situations, the definition used to describe the life of the network is not sufficient and/or accurate. We believe that the network lifetime should be defined to meet the requirement of applications. Unfortunately, a target application of the algorithms is rarely discussed.
4) **Signal Interference Effect**. In topology control, the common energy saving methods used are by controlling the transmission power, turning-off nodes in idle mode or selecting a subset of nodes responsible for backbone formation. However, the effects of signal interference can increase the energy consumption and shorten the network lifetime. Future topology control technique should study the impact of the signal interference on the network lifetime.
5) **Mobility**. Many topology control algorithms presented in this paper were not designed to deal with mobility. In fact, none of these algorithms exploit the advantage of mobility to improve network lifetime. For example, mobile nodes (agents) can be used in the clustering approach to share the loads with clusterhead nodes to extend the clusterhead's life and prolong the network longevity. Future topology control should also explore various mobility patterns to create a stable topology that is resilient to the mobility effect.
6) **Three-Dimensional (3D) Wireless Sensor Networks**. The popularity of underwater WSNs and the complexity of the networks have opened up more opportunities for researchers to address the many design challenges in 3D networks. In real life, wireless sensor networks are more likely to be deployed in 3D space rather than 2D space

TABLE III
COST COMPARISON OF 3D DISTRIBUTED TOPOLOGY CONTROL ALGORITHMS (d REPRESENTS THE NODE DEGREE).

Algorithms	**Graph Model**	**3D Shape**	**Time Complexity**
STCA	Unit Ball Graph	Truncated octahedron	Not provided
APYG	Yao Graph	Dodecahedron	Not provided
FiYG	Yao Graph	3D cone	Not provided
FlYG	Yao Graph	3D cone	Not provided
3DSDT	SDT	3D cone	$O(d \log d)$

such as within multiple floor buildings or underwater. In 3D WSNs, energy remains as one of the major challenges because sensor nodes operate with a limited energy supply which cannot be recharged. Moreover, the topology of the 3D networks is much more complex than the one in 2D networks. For example, the node degree of 3D networks is much higher than the node degree of 2D networks, hence the 3D networks require high message and time complexities for constructing the topology. In this situation, an energy efficient management technique is required to avoid fast energy depletion and maximize the battery's life.

APPENDIX
DESIGN GUIDELINES

This section provides criteria to aid in the design of topology control algorithms that aim for energy saving and network lifetime extension. We briefly explain each of them below.

1) **Distributed Construction**: Existing topology control algorithms can be computed using either a centralized or distributed approach. Of these two approaches, distributed topology control algorithms provide the best option for achieving energy efficiency. In contrast, a centralized computation is not preferred due to its unacceptable communication overhead involved in information gathering, especially in a network consisting of a large number of sensor nodes. In addition, centralized algorithms require one or more nodes with additional resource capabilities to act as a centralized administrator to form a global network topology, whereas sensor networks typically lack a centralized administration.
2) **Localized Computation**: Apart from being distributed, a topology should be constructed based on local information gathered from immediate neighbors without relying on global information provided by a centralized system. Localized algorithms should not make decisions based on global information because gathering such information can incur a high communication overhead and introduce delays. Gathering global information is not energy efficient for sensor networks that are known to have a dynamic topology which is caused by node mobility or node failure. Localized algorithms can quickly gather information locally from their neighbors and efficiently recompute the network to update topology changes. Thus, they are the best option for achieving energy efficiency. This feature has been mentioned in [66], [82] as an important criterion for designing a topology control algorithm.
3) **Use Bidirectional Links**: A communication graph G in a sensor network is said to exhibit bidirectional links if node A is able to send messages to node B as well as receiving messages from B with no interference. This property is also known as symmetrical communication. There are several reasons why a topology must be constructed using bidirectional links. In topology control, the use of power adjustment technique may create unidirectional links since nodes use different transmission ranges. The existence of the hidden terminal problem [72] may also generate some links that are unidirectional. Unidirectional links can affect network connectivity. Thus, bidirectional links are needed to preserve connectivity as well as supporting data acknowledgment and dissemination in the network. From the routing perspective, many routing protocols such as ad hoc on-demand distance vector (AODV) [54] and dynamic source routing (DSR) [35] rely on bidirectional links for efficient routing. Bidirectional links are also needed in the medium access control mechanism at MAC layer as in IEEE 802.11 [32]. Communication between two nodes at the MAC layer is assumed based on bidirectional links.
   The disadvantages of unidirectional links have been investigated in [46], [59]. Prakash [59] studied the impact of unidirectional links on the AODV and DSR routing protocols. The result of this work indicates that the usage of unidirectional links in routing protocols caused higher communication and storage overheads in the order of $O(V^2)$. The overheads also increased the energy consumption and may affect the network lifetime.
4) **Low Message Complexity**: Each node in a network must have sufficient information before making topology control decisions. This information is provided through message exchanges with neighbors. The maximum number of messages to be broadcast by each node in the worst case is called the message complexity. Message complexity is also known as message overhead or communication overhead. The larger the number of message exchanges, the larger the amount of time spent on acquiring these messages and hence the more complex the topology algorithms. Extensive message exchanges will consume a significant amount of energy that may shorten the node's lifetime. Hence, a topology control algorithm that requires a small number of message exchanges with its neighbors is favored.
5) **Low Time Complexity**: Time complexity measures the

amount of time an algorithm needs to be run in order to make topology control decisions. In other words, time complexity indicates the speed of a given algorithm in the worst case. Typically, a simple algorithm requires less time to run. In sensor networks when nodes frequently move and/or fail, several recomputations of topology are needed to update these rapid changes in the network. Topology control algorithms that run slowly may not have sufficient time to update the changes in the network. Therefore, an energy efficient algorithm should have a reasonable speed to cater for the scalability and dynamic nature of networks.

6) **Strong Connectivity**: The connectivity feature is required to support data communications in a network. The network is connected if there is a path connecting two nodes directly or through multiple hops. A network generated by a topology control algorithm often has fewer links than the network generated using maximum transmit power because topology control removes redundant links in the network. It is important for topology control algorithms to preserve connectivity after the removal of the redundant links.
7) **Consider Node Mobility**: Node mobility can affect the performance of topology control algorithms. In the presence of node mobility, topology control algorithms require frequent message exchanges to continuously update topology changes. This could entail significant message overheads and increase energy consumption. Topology control algorithms should be explicitly designed to account for node mobility. This is crucial as node movement in sensor networks is common. They should avoid centralized approaches as these approaches require a considerable message overhead to recompute the topology under moderate and high mobility. A simple topology control algorithm that exchanges few messages with neighbors requires little maintenance in the presence of mobility, thus it is more practical.

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