A Comparison of Energy Efficient Hierarchical Chain-based Routing Protocols in Wireless Sensor Networks

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***Abstract*—Wireless Sensor Networks (WSN) are highly distributed networks of small sensing devices that can be deployed in a vast number of locations and for many purposes. Advances in hardware technology have allowed devices to become smaller and smaller, and as these nodes are not connected to a wired power source, energy conservation is a pressing issue. There are many areas to consider when thinking of energy conservation, but this paper will focus on energy efficient routing and data propagation protocols. Many categories of routing protocols exist, but we look specifically at hierarchical chain based protocols. The two main protocols in this area are LEACH and PEGASIS, and each has been around for many years. This paper will survey and discuss three new protocols that try to build off of and improve upon LEACH and PEGASIS.**

I. Introduction

Wireless Sensor Networks (WSN) are groups of connected wireless nodes that perform some unified task together. WSNs are, by definition, wireless, and therefore have very limited battery life. Many other network types have wired connections to a power source, so special consideration to energy efficiency isn't always a top priority. In a WSN, you have to deal with all the other issues that come from a network of connected devices, with the added constraint of being as energy efficient as possible in order to extend the lifetime of the network.

Interest in wireless sensor networks has been regaining traction lately, which leads many to believe that the idea of a WSN is relatively new, but that is hardly the case. One of the first examples of a functional WSN was developed in the 1970s and was used by the military and defense industries. WSNs were used during the Vietnam War to help detect enemies in the jungle, but one of the main drawbacks of the system was that each node consumed too much energy which severely restricted the effectiveness of the system [1].

Today, the most common use of a WSN is monitoring [1]. WSNs are often equipped with a myriad of high quality sensors that can be used for scenarios including detection of enemy intrusion for the military, as well as monitoring air pollution, or monitoring water pressure in a water tank. The real world applications of wireless sensor networks is almost literally limitless. If there is something that can be detected by a sensor, then a WSN could be deployed to track and monitor it. In addition, WSNs can help to track things in previously unreachable physically. Examples of this include inside rotating machinery, in areas hazardous to human health, as well as spots that are physically out of reach, such as at the top of redwood trees in California [1].

When looking at the energy consumption in a wireless sensor network, the three main culprits of energy usage are the sensing, data processing, and communication activities. In order to have a successful and energy efficient system, all three areas need to be addressed, but this paper will focus on the communication activity. Communication of the nodes in a WSN is done through use of data propagation, or routing protocols (from here forth simply referred to as protocols). Significant gains in the lifetime of a network can be achieved through design and development of protocols that use the least amount of energy possible. The main task of a protocol is to find the "lowest energy path from source to destination" as well as find the best way to extend the network's lifetime [1].

There are four different categories of protocols for wireless sensor networks: Network Structure protocols, Communication Model protocols, Topology Based Protocols, and Reliable Routing Protocols. Each category of protocol has its own characteristics and each are used in different scenarios. Each of these categories can also be broken down further, into specific types of each protocol class. Network Structure protocols can be either flat or hierarchical, Communication Model protocols are either query-based, coherent and non-coherent, or negotiation based. Topology based protocols are broken down into location-based or mobile agent based, and Reliable Routing protocols include Qos-based or multipath-based. This paper will focus specifically on Network Structure protocols [1] [2].

As discussed above, network structure protocols are comprised of flat and hierarchical protocols. In flat protocols, all the nodes in the network play the same role, which imposes very minimal overheard. In hierarchical protocols—which is what this paper is concerned with—a structure is imposed on the network. The nodes are organized into clusters and each cluster is comprised of a cluster head and several simple nodes. The basic structure of a hierarchical protocol is shown in

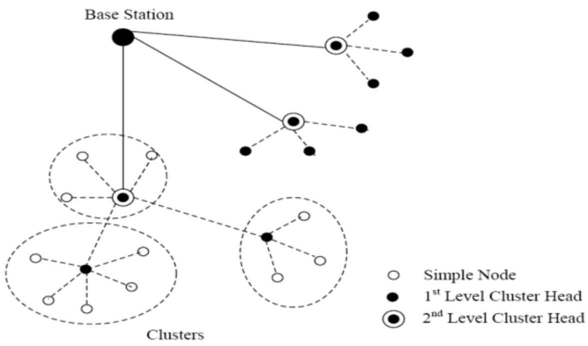


Figure 1. Hierarchical network structure [2]

figure 1. The cluster heads are responsible for coordinating activities within its own cluster, aggregating data from all the nodes, as well as forwarding information between clusters and the base station [1] [2].

Deployment of a hierarchical protocol comes with both positives and negatives. A hierarchical protocol has the potential to significantly reduce energy consumption, extend network lifetime, they boast high delivery ratios, and are easily scalable. The tradeoffs come from the fact that cluster heads and nodes physically close to the base station will use energy much more quickly than simple nodes, and disconnectivity is also an issue. In a hierarchical protocol, is a cluster head goes down, due to loss of energy or other reasons, then an entire section of the network is now unreachable. These positives and negatives need to be balanced when discussing implementation of a protocol. Two seminal protocols in the hierarchical area are LEACH and PEGASIS, discussed in [3] and [4] respectively. These two protocols are described in section II, and are the basis of the protocols discussed in sections III, IV, and V. Section VI will compare the three new protocols and conclude the paper.

II. Background

A. Low-energy Adaptive Clustering Hierarchy: LEACH

The first protocol that revolutionized hierarchical protocols was the Low-energy Adaptive Clustering Hierarchy, or LEACH, protocol. LEACH is an example of a hierarchical protocol, and follows the same basic structure as discussed in the introduction of the paper. LEACH will form clusters of nodes, and most of the nodes in the network will transmit their data to a cluster head, which will then aggregate the data and send it off to the base station. There are a few main differences between LEACH and just a standard hierarchical system. LEACH revolutionized the area though its mechanism for selecting the cluster head and forming

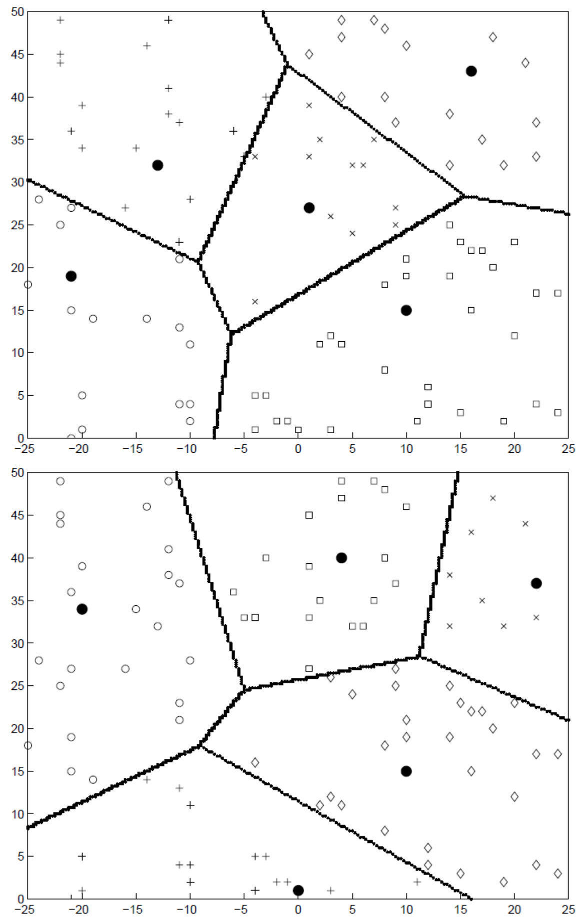


Figure 2. LEACH cluster formation [3]

the clusters. The LEACH protocol is split up into two phases: the setup, and the steady state phase.

The setup phase of LEACH is where the clusters are organized and the cluster heads are chosen [3]. LEACH is unique in that each node determines locally whether or not it will become a cluster head for a given round. This means that LEACH requires no global knowledge of the network, which reduces complexity and overhead. During the setup phase, each node decides whether or not it will become a cluster head. If a node becomes a cluster head, then it cannot be a cluster head again for *P* rounds, where *P* is a certain percentage specified before execution. Therefore, each node has a probability of 1/*P* of becoming a cluster head in any given round. This creates the dynamic of rotating cluster heads.

The steady state phase of LEACH is where each node that is not a cluster head chooses what cluster it will belong to. This is done simply by proximity to a cluster. After the clusters are created, the cluster head will create a schedule for each node in its cluster to transmit its data. While a node is not transmitting, it will power off until its time slice to preserve energy. After all the nodes in the cluster are finished sending their data, the cluster head aggregates all the data and sends it off to

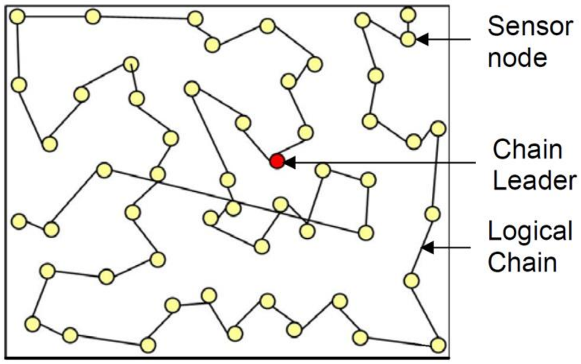


Figure 3. PEGASIS Chain formation [4]

the base station. Figure 2 shows two different rounds of LEACH and how the cluster head changes, and the actual clusters themselves change as well. The bolded black dots represent nodes that are the cluster head, and the dividing lines show the boundary of each cluster.

LEACH introduces a few main advantages. The first advantage is that each node and the base station do not require global knowledge of the network. This reduces overhead and complexity. Secondly, because of the rotation of the cluster heads, nodes will die randomly. In a standard hierarchical structure the cluster heads will always die before normal nodes. This aspect of LEACH extends network lifetime significantly. Finally, use of the LEACH protocol results in an 8x reduction of energy usage versus standard hierarchical protocols.

B. Power-Efficient Gathering in Sensor Information Systems: PEGASIS

Two years after LEACH the Power-Efficient Gathering in Sensor Information Systems, PEGASIS, protocol was introduced. PEGASIS was developed as an extension of the LEACH protocol, and with LEACH became one of the most important protocol advancements in this area.

PEGASIS introduced one main difference to LEACH. In PEGASIS, instead of clusters, a chain is formed that connects the entire network. Similar to LEACH, within a chain, a random node is chosen each round to send data to the base station. Figure 3 shows an example chain formation. PEGASIS contains two phases, the construction and the data fusion phase [4].

The construction phase of PEGASIS is where the chain is created. The creation of the chain assumes that all nodes have global knowledge of the network and forms the chain using a greedy approach. The chain will start at a single node and it will connect with its closest neighbor that is not already part of the chain. Therefore, each node that isn't the start or end of the chain is connected to two other nodes. If at any point any node dies, however, the entire chain will have to be reconstructed.

The data fusion phase of PEGASIS is where the chain

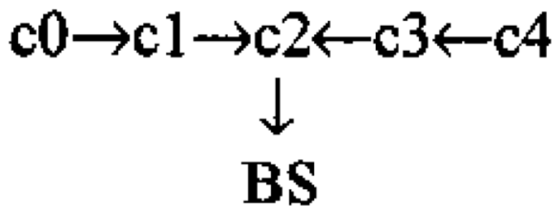


Figure 4. Chain function in PEGASIS, c2 is the chain leader [4]

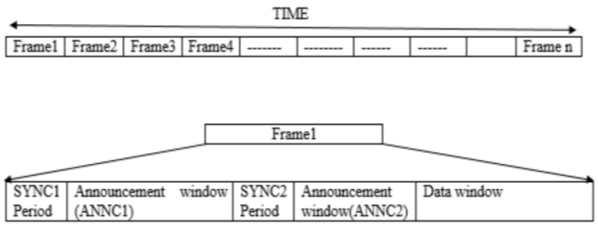
leader is chosen as well as where data aggregation and transmission occurs. Each round, a different node is chosen to be the chain leader, and the responsibility of the chain leader is to send all the data to the base station. In the data fusion phase of PEGASIS, the aggregation of data occurs in each node. Starting at both ends of the chain, each node will send its data to its neighbor, who will aggregate the data then continue sending down the chain until it gets to the chain leader. The chain leader will take the data from both sides of the chain, aggregate it, and send it off to the base station. This process is shown in figure 4 [4].

PEGASIS introduces a few advantages to the LEACH protocol. In PEGASIS nodes will only communicate with its closest neighbors. Because each node is only connected to two other nodes it greatly reduces the number of transmissions compared to LEACH. PEGASIS also eliminates the overhead of cluster formation and cluster head selection that is required in LEACH. The random selection of chain leader will level out data consumption throughout the network, similar to random cluster head selection in LEACH. Use of PEGASIS results in a network lifetime twice as long as LEACH [4].

III. Optimized Energy Efficient LEACH: OE-LEACH

The Optimized Energy Efficient LEACH, or OE-LEACH protocol is a hierarchical protocol that builds directly off of LEACH, but with one main change. The main deviation from LEACH comes from how the time slice is divided amongst cluster members. In original LEACH, each cluster head gives a time slice to each cluster member for them to transmit their data to the head. OE-LEACH sees this as an issue, because there is a substantial amount of time wasted using the original method. Time is wasted, for example, if a node does not have anything to send or will not use their entire slice [5].

OE-LEACH, instead splits up its time into frames, and each frame is made up of five distinct sections, this is shown in figure 5a. Each frame consists of a SYNC1 period, Announcement window (ANNC1), SYNC2 period, and a second announcement window (ANNC2). In the SYNC1 period, cluster members are allowed to randomly select a time slot that it will use, this is shown



5a) OE-LEACH frame format [5]

Figure 5. OE-LEACH time frames and slot selection

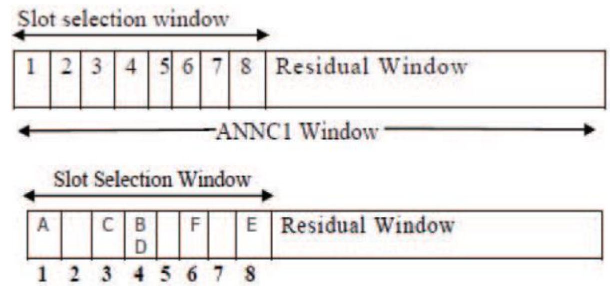
in figure 5b. After the nodes have selected their slot, ANNC1 begins and acknowledgements are send to nodes who have successfully chosen a slot. If there is a collision in slot selection, then no acknowledgement is given. Any slots that remain open are then broadcast again and in the SYNC2 period nodes that do not have a slot select a new option from the remaining available slots. ANNC2 then begins and it follows the same procedure as ANNC1. After this has finished, then any open slots are given to nodes that need more time to transmit data. Shown in figure 6, open time slots are given to neighbors who request them, and there are no wasted time slots. OE-LEACH helps to save energy by avoiding wasted time slots. As in the original LEACH, when a node is not transmitting data it is turned off to save power. In OE-LEACH if a node is finished transmitting data or has none to transmit it will never turn on because it will never be given a time slot. Additionally, giving open timeslots to nodes with lots of data to send shortens the number of frames needed to send all the data, again giving significant energy savings.

The results of using OE-LEACH are significant, and is shown in figure 7. In OE-LEACH the first node dies on average after round 1839, which is three times as long as LEACH, in which the first node dies after an average of 600 rounds. The last node dies in OE-LEACH after an average of 4300 rounds against an average of 2200 rounds for LEACH [5].

IV. PEGASIS with Ant Colony Algorithm: PEGAnt

The PEGASIS with Ant Colony algorithm, or PEGAnt, is based directly off of the original PEGASIS protocol. PEGAnt differs from PEGASIS in two key area: chain formation and leader selection.

Chain formation in PEGAnt is done through use of an ant colony algorithm. This algorithm is based off of the behavior of ants choosing a path to food. Ants choose a path to food based on the pheromone levels of a path. If a path has a higher concentration of pheromones, that means more ants are traveling along that path, so the other ants in the colony will start to take that path, because it is presumably better [6]. The way the ant colony algorithm work in PEGAnt is greedy chain formation is run starting from *k* number of random nodes in the network. If we assume *k* = 5, then 5 random nodes are chosen as the beginning of 5 different chains. The resulting chains from each of the 5 starting points are then analyzed. If a particular connection between two nodes is used in many of the chains from the k greedy chains, then the artificial "pheromone" level of that edge is raised. On subsequent runs of the ant colony algorithm paths will be chosen more frequently if the artificial pheromone level of a path is higher. Therefore, after each iteration of the ant colony algorithm a better and better final path is chosen [6]. Results of the ant colony approach to chain creation is shown in figure 8. It is clear that the connections



5b) OE-LEACH SYNC1 slot selection [5]

TABLE I. Cluster Head Routing Table

Slot Number	1	2	3	4	5	6	7	8
Node	A	B	C		D	F		E

TABLE II. Extension Of Data Slots By Neighbor Nodes

Slot Number	1	2	3	4	5	6	7	8
Node	A	B	C		D	F		E

TABLE III. Routing Table After Extension

Slot Number	1	2	3	4	5	6	7	8
Node	A	B	C	C	D	F	E	E

Figure 6. OE-LEACH time slots [5]

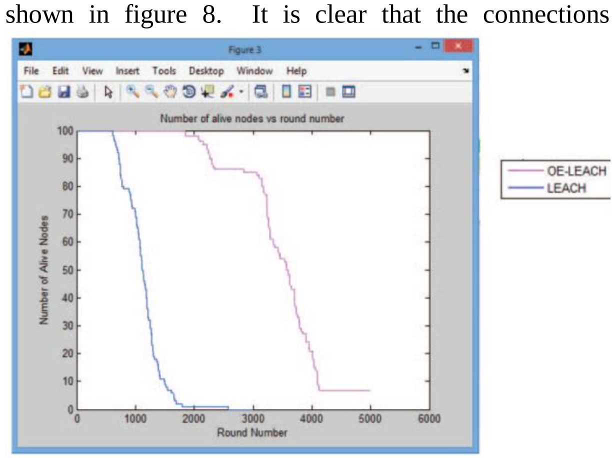


Figure 7. Number of alive nodes in each round in OE-LEACH [5]

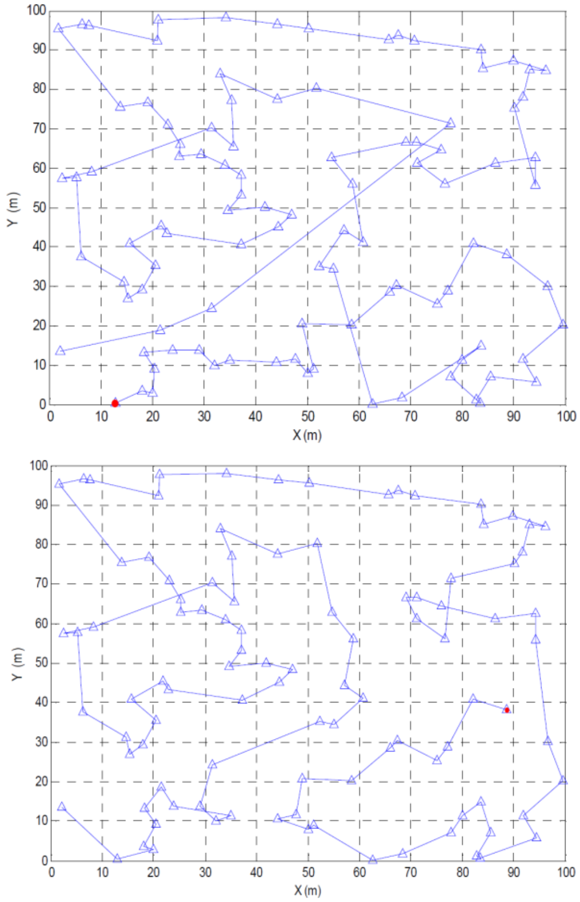


Figure 8. Chain creation with PEGASIS (top), and PEGAnt (bottom) [6]

between nodes are overall shorter than original PEGASIS, and the distance of the entire network connections is reduced from 14,576 to 9,199 in PEGAnt [6].

The second optimization introduced in PEGAnt is a change in leader selection. In PEGASIS, the chain leader is chosen randomly, which aims to evenly distribute energy consumption throughout the network, because the chain leader uses more energy than a standard node. In PEGAnt, the leader is chosen based on energy level. The node with the highest remaining energy level is chosen as the leader for any given round. This means that all nodes are kept at approximately the same energy level. Therefore, all of the nodes die at approximately the same time in PEGAnt. This leads to a total network lifetime similar to PEGASIS, but the lifetime average of each individual node is significantly longer in PEGAnt. These results are shown in figure 9 [6].

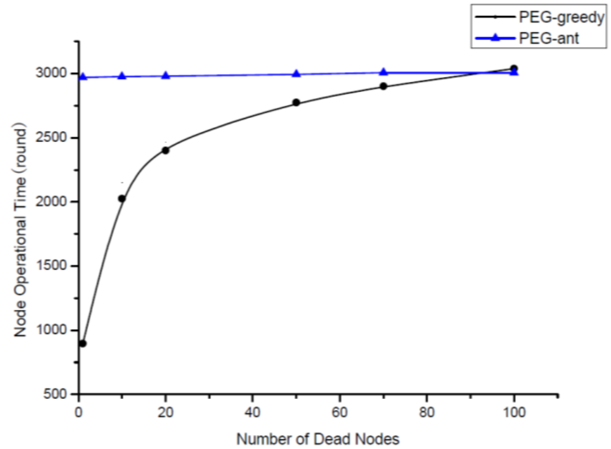


Figure 9. PEGAnt node lifetime [6]

V. SECTOR-CHAIN BASED CLUSTERING: SCBC

Sector-Chain Based Clustering, or SCBC, is a protocol that uses aspects of both LEACH and PEGASIS in an attempt to reduce energy consumption and increase network lifetime. SCBC is split up into two distinct phases, the setup phase, and the data transmission phase [7].

The setup phase is concerned with partitioning the network into sectors, as well as the chain formation and chain leader selection within each sector. SCBC partitions the physical area of the network into *k* "sectors" based on node distribution in the physical area. Each sector forms a chain with the other nodes in the sector, and then each sector acts as a cluster. If you partition the sensing area into 5 sectors, then each sector creates its own chain with its own chain leader.

The data transmissions phase handles sending data through the chains and ultimately to the base station. Data propagation through the chains is done in the same fashion as PEGASIS and then the leader of each of the 5 chains sends its data to the base station [7].

An example network created by SCBC is shown in figure 10. The base station will partition the area into *k* sectors, in this case 5, while trying to have the nodes evenly distributed between the sectors. The chains are formed in each sector using a greedy approach, and the chain leader of each sector is chosen randomly each round. This chain formation and leader choosing is the same as PEGASIS, and the splitting of the nodes into sectors is based off of cluster formation in LEACH.

The results of SCBC show significant improvement in number of alive nodes per round, as well as energy consumption. These results are shown in Figure 11. Simulations run of SCBC shows network lifetime improves 70% over PEGASIS [7].

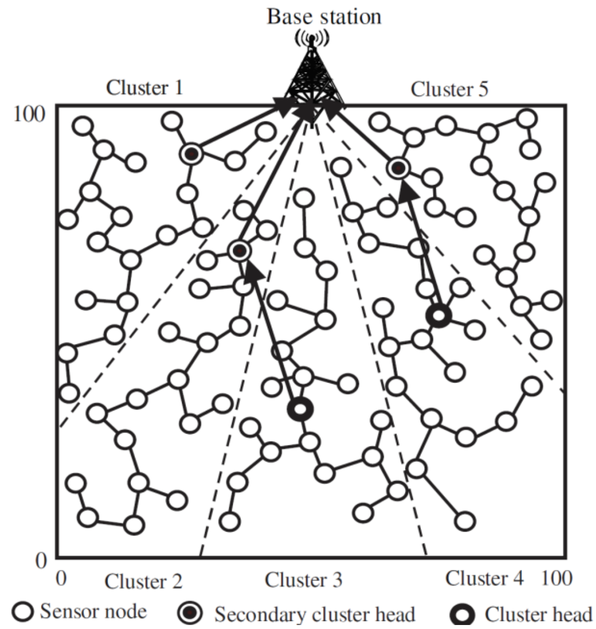


Figure 10. SCBS network structure [7]

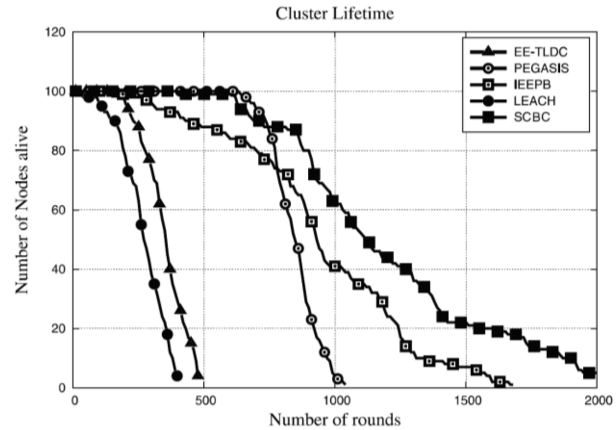
VI. Comparisons

LEACH and PEGASIS were trailblazing protocols in their day, and continue to influence the state of the art in WSN data propagation today. Three new protocols based off of LEACH and PEGASIS were looked at in this paper, and each has strengths and weaknesses.

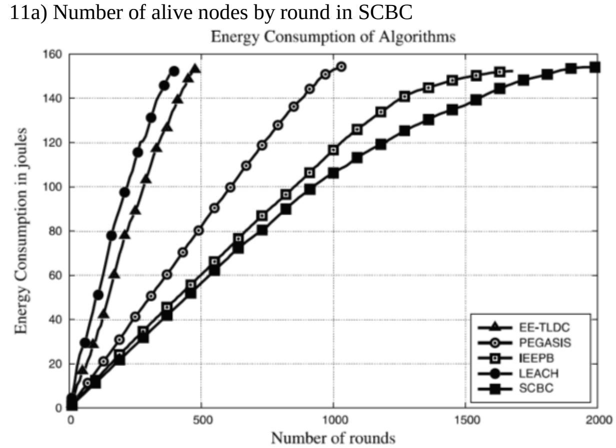
OE-LEACH offers significantly improved performance over LEACH, but does so at the cost of additional complexity and overhead. In LEACH, the splitting up of time slices is straight forward and done quickly, OE-LEACH adds a new layer to the time slice aspect of this protocol. This improves lifetime of the network, but increases implementation difficulty significantly.

PEGAnt gives improved performance over PEGASIS, but introduces complexity and overhead to a protocol that originally boasts simplicity. The running of the ant colony algorithm adds complexity and time requirements before the network can be live. This is mitigated, however, through the leader selection that occurs in PEGAnt. In PEGASIS, the chain has to be reconfigured every time a node dies. If this had to be done with the ant colony algorithm, then it would be implausible due to time restrictions. PEGAnt, however, selects its leader so that all of the nodes die at the same time, which means that after the original chain is constructed it will not have to be constructed again.

SCBC introduced a protocol that is based on both LEACH and PEGASIS. It partitions the nodes into sectors based on physical node placement, which is reminiscent of cluster formation in LEACH. It then forms chains in each sector, comparable to PEGASIS. SCBC outperforms both LEACH and PEGASIS based on energy consumption and network lifetime.



11a) Number of alive nodes by round in SCBC



11b) Energy consumption of SCBC against common protocols

Figure 11. Performance of SCBC [7]

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