IMPACT OF LEADER SELECTION STRATEGIES ON THE PEGASIS DATA GATHERING PROTOCOL FOR WIRELESS SENSOR NETWORKS

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ABSTRACT
The Power Efficient-Gathering in Sensor Information Systems (PEGASIS) protocol is one of the classical data gathering protocols for wireless sensor networks. PEGASIS works by forming a chain of the sensor nodes starting from the node farthest away to the sink. Data from either end of the chain gathers towards the leader node, selected for each round of data gathering, through a hop-by-hop transfer and aggregation process. The leader node transmits the aggregated data to the sink node. In this paper, we investigate the impact of the following leader node selection strategies for every round: Random (randomly selected node), Shuffle (a node is selected as leader only once in N rounds in a network of N nodes), High-energy (node with the highest energy), 2-block and 4-block (the network is divided into 2 or 4 blocks and the leader node is the highest energy node in the randomly chosen block of a round). We study the PEGASIS protocol for both TDMA and CDMA systems. For each combination of network topology (square, circular and rectangular) and sink location (center, origin and outside the network field), we identify the leader selection strategy that yields the longest network lifetime (up to 5% node failures) and the minimum energy*delay per round.

Keywords: Wireless Sensor Networks, Data Gathering, Leader Selection, Energy, Chain.

1 INTRODUCTION
A wireless sensor network is a network of smart sensors that collect data about the ambient environment and propagate the collected data to one or more control centers called sinks. The end user accesses the data through the sink. Sensor nodes are constrained with limited battery charge, transmission range (to save energy), computing and memory capacity. Also, a sensor network has limited bandwidth and nodes within the transmission range of each other share the communication medium. The sink is normally fixed and is located far away from the sensor network field. Because of all the above constraints, direct communication from each of the sensor nodes to the sink cannot be a viable solution from both the energy and bandwidth point of view. There would also be interference if several signals are simultaneously transmitted over long distance.

All of the above observations motivate the need for data gathering protocols that can be effectively and efficiently run at the sensor nodes to combine the data and send only the aggregated data (that is a representative of the data collected from all the sensor nodes) to the sink. Throughout this paper, we use the terms ‘data aggregation’ and ‘data gathering’ interchangeably. They mean the same. Data gathering algorithms typically run in several rounds, wherein for each round, data from each of the sensor nodes are collected and aggregated, and then forwarded to the sink. Among the various data aggregation protocols proposed in the literature, the well-known protocols are the LEACH (Low-Energy Adaptive Clustering Hierarchy) [1] and the PEGASIS (Power-Efficient Gathering in Sensor Information Systems) [2][3] protocols.

In LEACH, a certain percentage of the sensor nodes are elected as cluster heads for each round of communication. Each cluster head forms a cluster around it and a sensor node chooses to join the cluster whose cluster head is closest to it. If P is the percentage of nodes that can be cluster heads, LEACH ensures that a sensor node is elected as cluster head exactly once within every 1/P rounds of data communication. PEGASIS forms a single chain of sensor nodes, starting from the node farthest to the sink and the same chain is used for all the rounds of data communication. The chain of sensor nodes is formed using a greedy-heuristic based on the distance between the sensor nodes. For every round of data communication, a sensor node is uniformly-randomly elected as the leader of the chain and data from either end of the chain gets forwarded towards the leader node. PEGASIS incurs a huge delay, especially for Time Division Multiple Access (TDMA) systems [4], as data moves across the chain.
complete chain of sensor nodes, one node at a time, before transmitted to the sink. For CDMA (Code Division Multiple Access) systems [5], PEGASIS has been later improved using a chain-based binary scheme to minimize the delay and the energy*delay metrics. The energy*delay metric best captures the tradeoff between energy and delay. In the chain-based binary scheme for PEGASIS [3], a round of data communication is accomplished using $\log N$ levels, where $N$ is the number of nodes in the network. For a data gathering round, each node transmits to a close neighbor in a given level of the hierarchy. Nodes that receive data at a given level are the only nodes that move to the next level. At the top level, there will be only one node that will remain the leader and it will transmit the aggregated message to the sink. Communication takes place only one level at a time and all the communication within a level can occur simultaneously using unique CDMA codes assigned for each node.

Through several research articles [2][3][6][7], it has been shown that, for both TDMA and CDMA systems, PEGASIS yields a larger node lifetime and a lower energy consumption per round compared to LEACH. The lifetime of the nodes achieved with PEGASIS is $1.5 - 2$ times more than that incurred with LEACH, whereas the energy consumed per round for LEACH is $2 - 3$ times more than that incurred for PEGASIS. We conjecture that the performance of PEGASIS (as vindicated by our simulation results presented in the later sections of the paper) very much depends on the choice of the leader node selected for a round. Even though the choice of uniform-randomly selection is aimed towards being fair to all sensor nodes, it cannot guarantee that a sensor node that has just served as the leader node for a round is not again selected as the leader before every other node in the network has served as leader nodes. More importantly, it important to consider the available energy at a node while deciding the choice for the leader node of a round. A sensor node located far away from the sink may lose more energy to transmit the data to the sink, compared to a sensor node located closer to the sink. Basically, all sensor nodes cannot be given equal chance to serve as the leader node.

In this paper, we investigate the impact of the following leader node selection strategies: Random (leader of a round is selected randomly), Shuffle (a node is selected as leader only once in N rounds in a network of N nodes), High-energy (the node with the highest energy is selected as the leader of the round), 2-block and 4-block (the network is divided into two blocks or four blocks and for each round a random block is selected; the node with the highest energy in the selected block is the leader of the round). The Random and Shuffle strategies do not consider the available energy at the nodes before making the leadership decision. These two strategies will thus serve as the basis case to demonstrate the node lifetime obtained when we attempt to give equal chance to all the sensor nodes to serve as the leader. The High-energy, 2-block and 4-block strategies are energy-aware strategies that consider the energy available at the nodes before deciding on the leader node. For each of these five leader selection strategies, we study the performance of PEGASIS for both TDMA and CDMA systems in square, circular and rectangular network topologies and for three different sink locations (center, origin and outside the network field). For each combination of network topology and sink location, we identify the leader selection strategy that yields the largest network lifetime and the minimum energy*delay.

The rest of the paper is organized as follows: Section 2 briefly reviews the PEGASIS protocol and its chain-based binary scheme for CDMA systems. Section 3 introduces the five leader selection strategies explored in this research. Section 4 illustrates the simulation results obtained for different network topologies and sink locations. Section 5 presents the results obtained for each combination of network topology and sink location and identifies the leader selection strategy that yields larger network lifetime and lower energy*delay. Section 6 concludes the paper.

2 REVIEW OF THE PEGASIS PROTOCOL

The PEGASIS (Power-Efficient Gathering in Sensor Information Systems) protocol [2] forms a chain of the sensor nodes and uses this chain as the basis for data aggregation. The chain is formed using a greedy approach, starting from the node farthest to the sink. The nearest node to this node is put as the next node in the chain. This procedure is continued until all the nodes are included in the chain. A node can be in the chain at only one position.

![Figure 1: Example for PEGASIS Chain](image_url)

During each round, a leader node is randomly selected. The leader node is responsible for forwarding the aggregated data to the sink. Once the leader node is selected and notified by the sink node, each node in both sides of the chain (with respect to the leader node), receives and transmits the aggregated data to the next node in the chain, until the data reaches the leader node. For example, consider the chain formed in Figure 1 for a 10-node
network. The index of the nodes in the chain is different from the identification numbers for the nodes (i.e., the node ID). If node 3 at chain index 6 is selected as the leader node, the flow of data would be in the following order: \( c_0 \rightarrow c_7 \rightarrow c_1 \rightarrow c_2 \rightarrow c_3 \rightarrow c_4 \rightarrow c_5 \rightarrow c_6 \rightarrow c_7 \rightarrow c_8 \rightarrow c_9 \). PEGASIS can lead to significant delays in data aggregation because of the waiting time at the leader node to receive data from both sides of the chain.

**Figure 2: Example for Chain-based Binary Scheme of PEGASIS**

Improved Chain-based Binary Scheme of PEGASIS: This scheme [3] works primarily for CDMA systems [5] where there can be simultaneous communication between any pair of nodes if each node is assigned unique CDMA code and each node knows the CDMA code for communication with every other node. The chain formed using the greedy distance-based heuristic is still used as the basis for data aggregation. A round of data aggregation and transmission is comprised of \( \log N \) levels, where \( N \) is the number of nodes in the network. Each node transmits the data to a close neighbor in a given level of the hierarchy. Nodes that receive data at a given level are the only nodes that rise to the next level. In order to lower the delay, data is aggregated simultaneously using as many pairs as possible at each level. Figure 2 shows an example of data aggregation at different levels for a 10-node chain. Here, node at chain index 3 is chosen as the leader of the round and data gets aggregated towards this node, which is responsible for transmission to the sink.

3 STRATEGIES FOR LEADER NODE SELECTION

We now introduce the five leader node selection strategies explored in this paper.

3.1 Random Selection

The leader node for a round is uniform-randomly selected among all the nodes in the chain. The advantage with the random selection strategy is that once node failures start occurring due to exhaustion of energy, the node failures will be uniformly distributed throughout the network and not concentrated in any particular area of the network, thus reducing the chances of creating a void in the network. However, the random selection strategy may not be the best approach if we try to maximize the lifetime of every sensor node in the network. A node located away from the sink would lose more energy to transmit a data packet to the sink, compared to a node located closer to the sink. Also, as a node can become the leader for any round, if there are \( N \) nodes in the chain, there is no guarantee that a node is not selected as a leader more than once within \( N \) rounds.

3.2 Shuffle Selection

The Shuffle selection strategy is similar to the Random selection strategy in many respects. The main difference is that in an \( N \) node network, for every \( N \) rounds of data communication, a node is selected as the leader exactly once. Initially, the chain of sensor nodes \( C_{\text{initial}} \) is constructed using the greedy-distance based heuristic employed by PEGASIS. A copy of \( C_{\text{initial}} \), referred as \( C_{\text{shuffle}} \), is made and is randomly shuffled. The node at index \( i \) in the shuffled chain \( C_{\text{shuffle}} \) is selected as the leader node for the \( i \)th round of a data gathering cycle of \( N \) rounds. Note that \( C_{\text{shuffle}} \) is used only for selecting the leader node for a round. Once the leader node for a round is selected, the chain \( C_{\text{initial}} \) is used for data forwarding and aggregation. At the end of a cycle of \( N \) rounds, the chain \( C_{\text{shuffle}} \) is again shuffled and the above procedure is repeated.

3.3 High-energy Node Selection

In this strategy, for every round of data communication, the node with the highest energy during that instant is chosen as the leader of the round. This strategy is aimed towards maximizing the lifetime of the nodes in the network. However, as nodes closer to the sink are more likely to be selected as leaders compared to nodes farther away from the sink, once node failures starts to happen, this strategy is vulnerable of creating a void in the network. The block approach proposed in Sections 3.4 and 3.5 balances this tradeoff between random node selection and high-energy node selection.

3.4 2-Block Approach for Node Selection

The whole network region is divided into two equal, non-overlapping, contiguous blocks. For every round of data gathering, one of the two blocks is randomly chosen and the node with the highest available energy within the chosen block is selected as the leader node of the round. By randomly selecting a block, the chances of creating a void within a region of the network are reduced and by selecting the node with the highest energy in the randomly chosen block, the 2-block strategy aims to maximize the lifetime of the nodes in both the blocks.
Overall, the strategy aims to reduce the chances of creating a void within either of the two blocks of the network. However, for larger block sizes, there is still a non-negligible chance of void created in regions towards the sink.

3.5 4-Block Approach for Node Selection

The 4-block approach for node selection is similar to the 2-block approach. The difference is that the whole network region is divided into four equal, non-overlapping, contiguous blocks. For every round of data gathering, one of the four blocks is randomly chosen and the node with the highest available energy within the chosen block is selected. For a given network field, due to the relatively smaller block sizes, the chances of creating a void within a block in a 4-block approach are low compared to the 2-block approach. Figures 3 and 4 illustrate how the 2-blocks and 4-blocks were created for the different network topologies considered in this paper. The total area of the network in all the cases is 10,000m².

4 SIMULATION ENVIRONMENT AND METRICS

We conducted all of our simulations in a discrete-event simulator developed in Java. Such a simulator has also been previously used [6][7] to successfully report simulation results in sensor networks. Simulations of the PEGASIS protocol were run for both TDMA and CDMA systems. The area of the network field is 10,000m² and we chose three different network topologies that have this same area: a square field of dimensions 100m x 100m, a rectangular field of dimensions 1000m x 10m and a circular field of radius 56.4m. For each network field, simulations were conducted for three different sink locations (one sink location per simulation): (i) the sink is located outside the network field at (50, 300), (ii) the sink is located at the center of the network field at (50, 50) and (iii) the sink is located at the origin (0, 0). The different simulation scenarios are summarized in Figure 5.

The number of nodes used in each of the simulations is 100. Each sensor node is assumed to be capable of conducting transmission power control: i.e. the sensor node will be able to adjust its transmission range depending on the distance to the receiver node. For CDMA systems, each sensor node has a unique CDMA code and it is assumed to be known to all of the other sensor nodes. The initial energy supplied to each node in all of our simulations is 1J. We had also conducted simulations with initial energy of 2J and 3J. The results for node lifetime obtained in these scenarios are basically double and triple the values obtained for 1J. The size of the data packet is 2000 bits. We assume that an aggregating node fuses its own data with the data collected from its peer node in the chain and sends a data packet of the same size to the next node in the chain. In other words, the size of the data packets does not increase with data aggregation.
4.1 Energy Consumption Model

We use the following first order radio model [8] that has been also previously used (e.g., [2][3][6][7]) to model energy consumption. According to this model, the energy expended by a radio to run the transmitter or receiver circuitry is $E_{\text{elec}} = 50 \text{ nJ/bit}$ and $\epsilon_{\text{amp}} = 100 \text{ pJ/bit/m}^2$ for the transmitter amplifier. The radios are turned off when a node wants to avoid receiving unintended transmissions. An $r^2$ energy loss model is used to compute the transmission costs. The energy lost in transmitting a k-bit message over a distance d is given by: $E_{\text{TX}}(k, d) = E_{\text{elec}} \ast k + \epsilon_{\text{amp}} \ast k \ast d^2$. The energy lost in receiving a k-bit message is $E_{\text{RX}}(k) = E_{\text{elec}} \ast k$. The cost of fusion is 5 nJ/bit/message.

4.2 Performance Metrics

The performance metrics measured are the following: (i) Network lifetime and (ii) Energy * delay per round. For a given sink node location and network topology, the simulation results presented in Figures 6 through 9 are average values obtained for five different trials under each of the 18 different simulation scenarios presented in Figure 5.

The network lifetime is measured as the number of successful rounds of data aggregation that have been completed at the time of failure of 1%, 2%, 3%, 4% and 5% of the nodes in the network. As we start our simulations with 100 nodes, our definition of network lifetime translates to measuring the number of rounds of successful data aggregation at the time of the 1st, 2nd, 3rd, 4th and the 5th node failures.

The energy consumed per round is the sum of the energy lost at all the nodes for transmission, reception and fusion of the data. For TDMA systems, the delay per round would be the number of nodes in the network. For CDMA systems, the delay per round would be the number of levels of simultaneous data aggregation and it is theoretically equal to the logarithm (to the base 2) of the number of nodes in the network. The energy*delay per round best captures the tradeoff between energy consumed and the delay incurred per round. Lower values of the energy*delay per round are preferred. For simplicity, the energy consumed per round and the delay per round (and hence the energy*delay per round) are measured until the time of first node failure.
5 SIMULATION RESULTS

5.1 Impact of Sink Node Location

A quick look at the values of network lifetime illustrated in Figures 6 through 8 indicates that the magnitude of the network lifetime is the greatest when the sink is located at the center of the network and it is the least when the sink is located outside the network field. This observation holds good for each of the leader node selection strategies and for both TDMA and CDMA systems. The observation can be justified from the fact that more energy is lost at a leader node to transmit the data to a far away sink node than to a sink node that is located within the network field (i.e., at the center of the network) or at the boundary of the network field (i.e., at the origin of the network).

5.2 TDMA vs. CDMA Systems

The network lifetime values, observed as a result of node failures, are larger for TDMA systems than that observed for CDMA systems. This is due to the higher energy consumed per round incurred by the PEGASIS protocol for CDMA systems compared to that obtained for TDMA systems. In a CDMA system, as the level of data aggregation increases, nodes are more likely to forward data to peer nodes located far away. For each combination of sink location and network topology, the difference in the magnitude of the network lifetime obtained for TDMA and CDMA systems increases with increase in the number of node failures.

For a given network topology, when the sink is located outside the network field, the maximum difference between the network lifetime for TDMA and CDMA systems occurs when we use the Random and Shuffle node selection strategies. On the other hand, when the sink is located at the center or the origin of the network field, the maximum difference between the network lifetime for TDMA and CDMA systems occurs when we use the energy-aware High-energy, 2-block and 4-block strategies.

5.3 Impact of Network Topology

Magnitude-wise, for a given system (TDMA or CDMA), sink location and leader node selection strategy, the network lifetime obtained with both the square and circular network topologies are almost the same. A slightly larger network lifetime is obtained under circular network topologies, but the difference in magnitude is within 5%. Network lifetime values
obtained under the rectangular network topology are significantly low compared to those obtained for the square and circular network topologies. This could be attributed to the predominantly one-dimensional structure of the network field in the case of the rectangular topology studied in this paper.

5.4 Sink Location: Outside the Network Field

When the sink is located outside the network field, the Random and Shuffle selection strategies perform very poor. For both TDMA and CDMA systems, the energy-aware High-energy and the Block-based strategies yield a relatively 20-35% larger network lifetime for square and circular network topologies and 100-250% larger network lifetime for rectangular network topologies. The High-energy strategy slightly outperforms the Block-based approaches, and the difference in the magnitude of network lifetime is within 10%. The better performance of the energy-aware leader selection strategies, compared to the Random and Shuffle selection strategies can be attributed to the prudent consideration of the available energy levels of the nodes before letting the nodes to transmit over a longer distance.

5.5 Sink Location: Center of the Network Field

When the sink is located at the center of the network field, for both TDMA and CDMA systems, the Random and Shuffle leader selection strategies yield a larger network lifetime compared to the energy-aware leader selection strategies, for both square and circular network topologies. As the sink is actually located in the center of the network field for both the square and circular network topologies, it is essential to guarantee fairness of node usage as illustrated by the performance under the Shuffle leader selection strategy. The Shuffle leader selection strategy yields about 5-15% larger lifetime compared to the other strategies. Among the energy-aware leader selection strategies, the 4-block strategy yields a larger network lifetime – sometimes close enough to that of the Shuffle strategy. This is because the 4-block leader selection strategy attempts to achieve fairness in region selection in addition to considering the available energy level of the nodes within the selected block.

For rectangular network topologies, especially for TDMA systems, the energy-aware leader selection strategies yield significantly larger network lifetime compared to the Random and Shuffle leader
5.6 Sink Location: Origin of the Network Field

When the sink is located at the origin of the network field, we observe the High-energy and Shuffle selection strategies to respectively yield a relatively larger network lifetime for TDMA and CDMA systems. However, for both square and circular network topologies, the difference in the network lifetime observed among the various leader selection strategies is within 5% (i.e., all the five leader selection strategies perform almost equally well). For rectangular network topology and TDMA system, the energy-aware leader selection strategies perform better and yield a relatively larger lifetime. On the other hand, for rectangular network topology and CDMA system, all the five leader selection strategies yield a relatively lower lifetime (compared to that obtained for TDMA systems), with the Random and Shuffle strategies yielding a slightly larger network lifetime.

5.7 Energy * Delay per Round

Figures 9.1 through 9.6 illustrate that the energy*delay per round is the lowest when the sink is located at the center of the network field and it is the maximum when the sink is located outside the network field. This observation holds good for each of the leader node selection strategies and for both TDMA and CDMA systems. For a given leader node election strategy and sink location, the energy consumed per round for CDMA systems is 14% - 27% more than that obtained for TDMA systems for square and circular network topologies and is 32% - 137% more than that obtained for TDMA systems for rectangular network topologies. However, the delay incurred in TDMA systems is roughly about 12 – 12.5 times more than that incurred for CDMA systems. As a result, the energy*delay per round incurred for TDMA systems is significantly larger (as large as by a factor of 10) than that obtained for CDMA systems.

For both square and circular network topologies, the difference in the energy consumed per round
among the leader node selection strategies is within 5%. As a result, the difference in the energy*delay per round among the leader node selection strategies is also within 5%. This observation holds good for both TDMA and CDMA systems. However, for the rectangular network topology, the energy-aware leader selection strategies (especially the 2-block and 4-block strategies) yield significantly lower energy consumption per round compared to the Random and Shuffle selection strategies. As a result, the energy-aware leader selection strategies (High-energy, 2-block and 4-block strategies) yield a lower energy*delay product, as low as half the value obtained for Random and Shuffle selection strategies.

Table 1: Leader Node Selection Strategies Yielding the Largest Network Lifetime (up to 5% Node Failures)

<table>
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<tr>
<th>Scenario</th>
<th>Random</th>
<th>Shuffle</th>
<th>High-energy</th>
<th>2-Block</th>
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6 CONCLUSIONS

The overall contribution of this paper is the identification of the leader node selection strategies that would yield a larger network lifetime and lower energy*delay product for the PEGASIS protocol. The leader node selection strategies considered are: Random, Shuffle and energy-aware strategies such as High-energy node selection, 2-block and 4-block strategies.

To obtain the maximum network lifetime, the energy-aware selection strategies should be considered when the sink is located outside the network field for any network topology. Also, the energy-aware selection strategies should be considered for rectangular topologies with respect to any sink location. For square and circular topologies, when the sink is located at the center of the network field, the Random and Shuffle strategies should be preferred; whereas, when the sink is located at the origin of the network field, all the five leader selection strategies yield network lifetime values that are very close and the difference is only within 5%. The leader node selection strategies that yield the largest network lifetime (5% node failures) for each of the different scenarios considered are highlighted in Table 1.

With respect to the energy*delay per round, we observe that for both the square and circular network topologies and for both TDMA and CDMA systems, all the five leader node selection strategies yield very close energy*delay values; the difference is only within 5%. However, for rectangular network topologies, especially for TDMA systems, the energy-aware leader selection strategies (especially the 2-block and 4-block strategies) yield a relatively lower energy*delay value.

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8 REFERENCES

Wireless Networks, Las Vegas, USA, July 2009.