Energy-Efficient Routing in Wireless Sensor Networks*

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Abstract

Efficient data collection is the core concept of implementing Industry4.0 on IoT platforms. This requires energy aware communication protocols for Wireless Sensor Networks (WSNs) where different functions, like sensing and processing on the IoT nodes is supported only by local battery power. Thus, energy aware network protocols, such as routing, became one of the fundamental challenges in IoT data collection schemes. In our research, we have developed a novel routing algorithm which aims at increasing the lifetime of the IoT network subject to pre-defined reliability constraints. Assuming that the data is split and transmitted in the form of packets, we seek the optimal paths over which packets can reach the Base Station (BS) with effective energy usage subject to the condition that the probability of successful packet arrival to the BS exceeds a pre-defined threshold (reliability parameter). As far as the radio propagation is concerned we use Rayleigh-fading in our model. The new algorithm will guarantee an increased longevity and information throughput of the network due to the efficient energy balancing in the IoT network. The performance of the new protocol has also been studied and confirmed by simulations.

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1 Introduction

Industry 4.0 is the newest stage of the fourth industrial revolutions, where the primary objective is digital data acquisition and performance enhancement of complex manufacturing processes by using the concept of "digital twins". This performance enhancement requires a number of different sensors and communication equipments to measure and transmit the information obtained about the underlying industrial process.

In most of the cases, connecting each sensor to a wired network proves to be physically infeasible, thus wireless IoT devices can provide an efficient solution for controlling the observed industrial process. The wireless nodes transmit the collected data in the form of packets to a Base Station (BS) where the complex processing of data and system evaluation is carried out. This also gives flexibility as additional sensors can easily be added to or redundant nodes can be removed from the network as needed. We refer to this combination of the sensor and an IoT device with wireless transceiver as a *node* in the forthcoming discussion.

Unfortunately, wireless devices need to be powered by built-in batteries which need to be recharged periodically, if possible. Under these circumstances, network longevity and energy efficiency becomes a driving force when one wants to maximize the throughput of IoT networks.

The power consumption of these devices can be divided into two main categories: the energy required to operate the sensor and the energy required to transmit data. The energy consumption of the sensor depends on several parameters, such as the consumption of the electrical components, the operation mode of the sensor and various parameters of the controlling electronics. In contrast, the energy required for reliable communication can be well defined and typically depends on the distance between the communicating nodes and the environmental noise and this energy used for communication is by far the most significant in energy consumption.

For this reason, it may often prove to be disadvantageous for a particular device to send its message directly to the BS due to the increased energy consumption of long distance communication. Instead, it may be useful to implement multi-hop packet transfers from the sender node to the BS via some relay nodes, thus in this paper, we develop a novel routing algorithm for packet transfer that ensure the extended lifetime of the network.

The rest of the paper is organized as follows. In Section 2 the related work is summarized. In Section 3 the model is defined. Section 4 introduces the two-hop and k-hop algorithms with numerical performance evaluation. The results of the algorithm are shown in Section 5. Section 6 concludes the paper and proposes further research directions.

2 Related Work

In the literature, several different algorithms have been proposed for efficient wireless communication in IoT networks.

LEACH [3] assigns nodes to be cluster heads periodically whose responsibilities are to collect the messages in their region. After compressing the received packets into a single message, every cluster head transmits its message to the base station, which is considered to be farther away from the nodes. If every node were to send their message directly to the base station, the energy required to transmit over the longer distances would quickly deplete every node. Collecting the messages in a region by the cluster heads have low energy requirements (because nodes are generally closer to each other), and this allows the node heads to compress multiple messages, decreasing the payload size. Due to these observations, the sensor network will stay alive longer in this scenario.

While the gathering and compressing of messages was a novel idea at the time, several new algorithms have been proposed with the aim of increasing the efficiency of LEACH. In [11], the authors suggest two modification to the original algorithm. In one algorithm, dubbed *energy-LEACH*, the cluster head selection algorithm was changed from the original random selection to selecting the nodes with the highest residual energy levels. Meanwhile, the other algorithm (called *multihop-LEACH*) changed the cluster head message routing: instead of directly sending the compressed message to the base station, the heads are allowed to send the message to other cluster heads. When implemented in simulations, both of these modifications showed better performance than the original LEACH algorithm.

Another modification for LEACH, called LEACH-B [9] (shortened from LEACH-Balanced), extends the cluster head selection algorithm. The authors based their modification on another paper [2], where it has been shown that with the original LEACH algorithm, the highest efficiency can be reached when for every round, around 3-5% of the nodes are selected to be cluster heads. LEACH-B introduces another round for the cluster head selection with the aim of making the number of cluster heads equal to this ideal number. Through simulations, the authors showed that this modification significantly extended the lifetime of the system.

Looking at another popular WSN routing algorithm, PEGASIS [6] creates a chain between the nodes close to each other using a greedy algorithm. In each round, the measured values from the nodes are aggregated and sent towards one particular node (the *leader* node) through the chain, which in turn transmits to the base station. This transmitting node changes every round. This means that at the end of the round, the base station does not receive every message sent by the nodes, rather only an aggregation of every measured value. This makes it efficient, but limits the use cases, and makes it harder to compare to other routing strategies.

Several improvements have been proposed for the original PEGASIS algorithm as well. Clustering has been used to break up the single, long chain into multiple shorter part based on the distance to the base station [4]. Through simulations, the authors showed an improvement of 35% in energy efficiency. EEPB (Energy-Efficient PEGASIS Based protocol) [5] and IEEPB (Improved EEPB) algorithms modify the chain creation algorithm by imposing a constraint on the maximal link distance between nodes, and change the leader selection algorithm to account for the residual energy levels.

There are many other routing algorithms in the context of Wireless Sensor

Networks, LEACH is usually preferred due to its simplicity. While other algorithms perform better compared to LEACH, they generally introduce significant overhead to the clustering and network maintenance stages, making them unideal for low powered IoT devices. A survey has been conducted which compares most of the available WSN routing algorithm [10].

The key difference between the research reported above and our work is that our solution achieves energy-awareness and extends network lifetime subject to meeting a pre-defined quality of service criterion.

3   The model

In our model, we consider the network as a 2D graph. Each node is stationary, meaning that the distances between any two nodes remain constant in time, and each node has a current residual energy level calculated as the starting energy level minutes the energy used up forwarding the past packets. For modeling the radio propagation, we use the Rayleigh-fading model, which gives us the connection between the transmission energy g_{ij} and the probability of successful packet transfer P_{ij} for nodes i,j, based on [1] in a zero-interference network.

$$g_{ij} = -d_{ij}^2 \frac{\theta \sigma_Z^2}{\ln P_{ij}} \tag{1}$$

where d is the distance between the communicating nodes, θ and σ are the parameters of the environment and communication.

The equation above can be simplified to the following relationship, as the nodes are stationary:

$$g_{ij} \ln P_{ij} = \omega_{ij} \tag{2}$$

where $\omega_{ij} = -d_{ij}^2 \theta \sigma_Z^2$, is a constant dependent on the distance between the nodes and the parameters of the environment. Because θ and σ_Z^2 are positive values, ω_{ij} will have a negative value. Each packet transmission requires this energy from the the sending node, and in this paper we assume that the receiving node can receive the packet without any energy consumption (in the future work the reception energy will also be taken into account). In order to ensure a given reliability, we also define the probability P_s as the probability with which the base station must receive the message sent by a node.

Our proposed routing algorithm works on the principle that nodes with higher energy levels are supposed to participate more frequently in packet forwarding by being relay nodes. In this way low energy nodes are allowed to have short distance communication on low energy with other nodes and there is no need to send their packets directly to the BS. In order to achieve this, we introduce a new property into our model, called Minimal Path Residual Energy (*MPRE* for short). This is defined over a given path between nodes on which a message is transmitted. For a given path, MPRE is the energy level of the node which has the least energy remaining after the message transfer is successfully completed. We would like to

develop an algorithm which maximizes MPRE. This can be accomplished if the nodes participating in the packet transfer will have uniform remaining energies.

We prove this with a proof of contradiction: let us suppose that the energy levels after the routing are uniform, but the MPRE value is also maximized. Take the node with the most energy remaining. If this node was routing the message with more energy (without reaching the MPRE), the other nodes would be able to transmit the message with less energy usage to reach the same probability, increasing the value of MPRE. This contradicts our initial assumption, proving our statement.

4   The proposed algorithm

Based on the observation above, the objective of our algorithm is to make the residual energy of the nodes participating in the packet transfer as uniform as possible, while still satisfying the reliability constraint (guaranteeing that the packet will reach the BS with a pre-defined probability). We investigate the following routing strategies:

- *Direct sending*, i.e. the source node sends the packet directly to the base station without using an intermediate node. This is the simplest strategy which serves as a baseline.

- *2-hop* strategy, when an intermediary node may be used for sending the message to the base station.

- *K-hop* strategy, in which case at most k-1 intermediate nodes form the path for packet transfer.

The strategies are described by the next sections.

4.1   Two-hop routing

For the sake of simplicity, let us first assume that a single packet is forwarded to the BS over a two-hop path, and at time instant k a sender node denoted by index s sends this packet to the BS via a relay node denoted by index l. Knowing that after the transmission, both nodes must arrive at the same energy level, and that the successful transfer probability is P_s is given, we can write the following equation (where c is the common energy level after the transmission, c_s is the starting energy level of the source node and c_l is starting energy level of the relay node):

$$\frac{\omega_{s,l}}{c_s - c} + \frac{\omega_{s,BS}}{c_l - c} \geq \ln\left(P_s\right) \tag{3}$$

Arranging the equation for c will get us the following quadratic formula:

$$c^2 A + cB + C = 0 \tag{4}$$

where

$$A = \ln(P_s) \tag{5}$$

$$B = \omega_{s,l} + \omega_{l,BS} - (c_s + c_l) \ln(P_s) \tag{6}$$

$$C = c_s c_l \ln(P_s) - \omega_{s,l} c_l - \omega_{l,BS} c_s \tag{7}$$

where ω_{ij} is defined in the following way (from Section 3): $\omega_{ij} = -d_{ij}^2 \theta \sigma_Z^2$. Taking into account the constraints on the variables ($c >= 0$, $\omega < 0$), only one solution is possible:

$$c = \frac{-B + \sqrt{B^2 - 4AC}}{2A} \tag{8}$$

If $c < 0$, then the needed energy for the communication is higher than the nodes can provide, and so the packet can not be sent with the given confidence. Our strategy requires us to find an intermediary node which maximises the common energy level c. This can be done by calculating the resulting common energy level c for every possible intermediary node, and using the one with the maximum value to route the message through.

The algorithmic complexity of this strategy is $O(|V|)$.

4.2   K-hop routing

Calculating the solution for k-hop routing requires significantly more calculations. We have to calculate the optimal common energy level for a given set of the intermediary nodes, which requires finding the roots of a k-degree complete polynomial which satisfies the constraints, then we also have to check different paths containing k hops to find the one with the highest PMRE. Because of this computational complexity we rather develop an approximate solution for the problem.

This approximation can be broken up into two main parts. First, for a given node energy distribution vector c, let us find the highest probability with which a message can be sent between a chosen source node and the base station. Formally, this can be written in the following way:

$$\max_g \sum_{j=0}^m \frac{\omega_{j,j+1}}{g_{j,j+1}} \tag{9}$$

Since ω must be a negative number, we can see that for a given path, the maximum transmission probability can be reached if $g_{l_j l_{j+1}} = c_j$, meaning that every node along the path is using their remaining energy to send the message. Since we know the energy level of every node before the transmission occurs, we can calculate $\gamma_{j,j+1} \equiv \frac{\omega_{j,j+1}}{g_{j,j+1}}$, making the problem:

$$\max \sum_{j=0}^m \gamma_{j,j+1} = \min \sum_{j=0}^m -\gamma_{j,j+1} \tag{10}$$

which makes this problem equivalent to finding the shortest path in a graph with at most k edges, in which an edge between node j and $j+1$ have a weight of $-\gamma_{j,j+1}$.

This can be solved using the Bellman–Ford algorithm, and stopping after the kth iteration, which has the worst case complexity of $O(k \mid V \mid^2)$.

With this, we can approximate the optimal common energy level for k-hop routing the following way. Instead of every node sending with its remaining energy, let us choose a common energy level c_{common}, and the aim is that every node participating in the transmission reaches this energy level after the transmission. This gives us the energy for every node with which they can participate in the transmission: $g_{j,j+1}(k) = c_j - c_{common}$, from which the previously presented approach gives us the maximum transmission probability.

Looking at the relation between the chosen common energy level and the maximum transmission probability, we can intuitively see that if we lower the energy level, the transmission probability rises since nodes can use more energy in the transmission. Because of this, we can use binary search over the interval $(0, c_s)$ for the common energy level where the maximum transmission probability reaches the given $\ln(P_s)$. This gives us an approximate solution for the optimal common energy level with complexity $O(\mid V \mid^2 \ln \frac{c_s}{\delta c_{common}})$, where δc_{common} is the maximum guaranteed absolute error between the optimal and approximated solution.

The presented approach will give us an approximate solution for the k-hop routing strategy.

5 Numerical results

To evaluate the performance of our energy efficient algorithm, we used the following simulation environment: Our wireless sensor network consists of N stationary nodes and a BS collecting the messages sent by the nodes. The location of the nodes are chosen randomly in a unit square. An example of a random network can be seen on Figure 1.

We have chosen the number of nodes to represent 3 different sizes:

1. 10 nodes for a *small* network

2. 100 nodes for a *medium* network

3. 1000 nodes for a *large* network

Every node starts with the same initial energy. The parameters of the Rayleigh-fading model were chosen to mimic real-life circumstances. We have chosen the probability value for successful message transfer to be 95%.

In every step of the simulation, the source node is selected randomly, which transmits a message towards the base station subject to the given probability criterion. We repeat this procedure until a node depletes its energy, and count the messages received by the base station.

To make comparisons between LEACH and other strategies, the simulation consists of separate rounds. In every round, every node in the network must send one message to the base station. For LEACH, this is the original algorithm, meaning no modification is needed. For our energy-efficient algorithm, the order of nodes
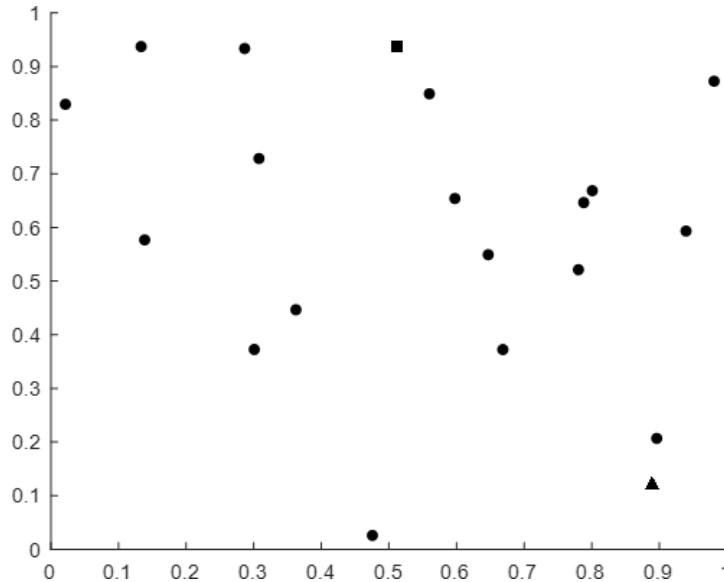
Figure 1: An example of one WSN. The square is the base station, while the triangle is a node currently sending a message.

sending their message is randomized in a given round. Like previously, we run as many rounds as possible before one node depletes its energy, and count the messages received by the base station.

We implemented the LEACH algorithm as discussed in the original paper [3]. We have chosen the probability for a node to become a cluster head each round to be 15%.

The simulation environment and proposed strategies were implemented in MAT-LAB. During our research we have not found sources for the exact values of the θ and σ_Z^2 environmental parameters. However, these parameters have no impact on the relative performance of one strategy compared to another. Looking at equation 1, we can see that increasing the product of these parameters by a ratio of x would increase the required energy as well, meaning that on average, the sent message count would also decrease by this ratio as well when sending with the same transfer probability. In our simulations, we have estimated the product of θ and σ_Z^2 to be 2.14 based on the transmission parameters of the nrf24l01 chip, but this will be refined in future work. We have generated a hundred different random network topologies, and for each topology we have run the simulation ten times. We average the results over these runs.

For our first set of simulations, we are only comparing the 2-hop, 3-hop, 4-hop and 5-hop strategies to each other.

As can be seen on Figure 2, under these circumstances, the two-hop routing performed better than either the direct routing or the k numbered strategies (*$k > 2$).
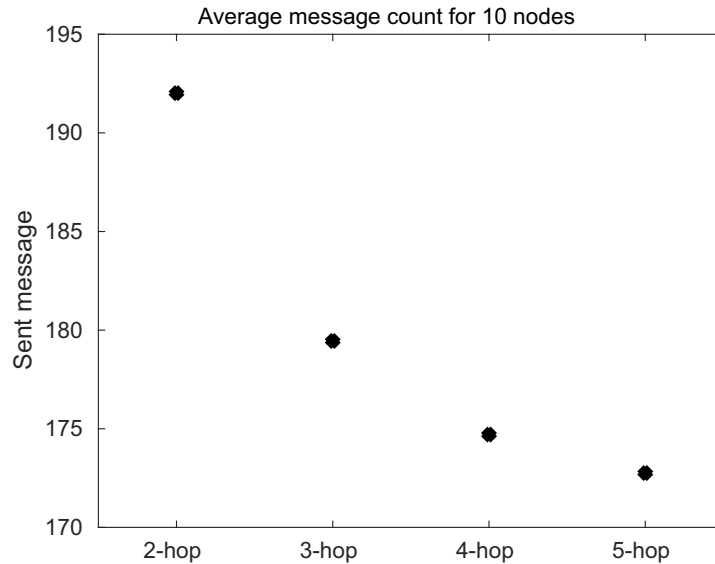
Figure 2: Result for small network

Compared with the direct routing, the two-hop strategy can make use of an intermediary node, so nodes farther away or with lower energy are able to conserve their energies. This is in contrast with the results of higher k numbered strategies, where the extended use of more intermediary nodes leads to shorter lifetime. Examining the energy levels after each message, we concluded that while the remaining energy levels are indeed higher compared to the two-hop strategy, the use of multiple nodes results in an overall higher energy usage which depletes the network faster.

To give a simple example of this effect, let us suppose that we have a network with ten nodes, each having 4 unit of energy. After choosing a random source node, we run the different strategies on this network, and we find that for two-hop, the optimal solution is sending the message through one intermediary node to the base station with 4 units of energy, while with 4-hop, the optimal solution is sending the message through 4 nodes with 3 unit of energy. In this case, two-hop used 8 units of energy, while 4-hop used a total of 12 energy unit. This results in higher overall energy usage for 4-hop, draining it faster.

For the medium sized network with 100 nodes, 2-hop still performed better with regards to the average message count seen on Figure 3. However, 3-hop is closer to the 2-hop result, under performing only by 4%.

For our final simulation, we ran the network with 1000 nodes. In this case, Figure 4 shows that 3-hop strategy outperformed the 2-hop routing by around 3%.

Looking at the results of different network with regards to the network size, we can conclude that as the network size increases, higher numbered k algorithm will become more efficient.
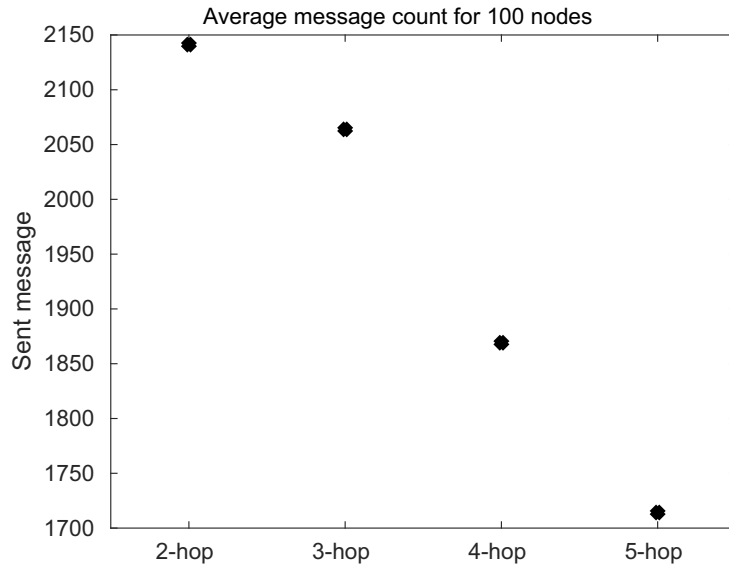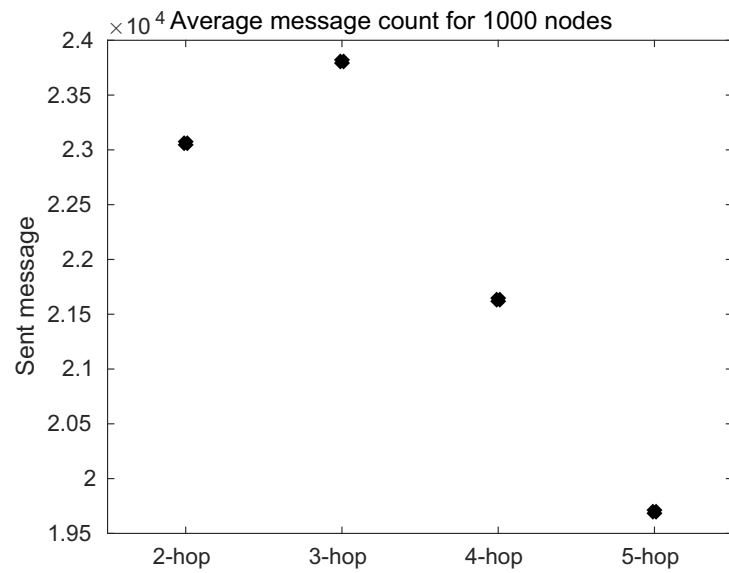
Figure 3: Result for medium network

Figure 4: Result for large network

For our next set of runs, we compare LEACH with the proposed strategies as well as with direct sending.

As can be seen on Figure 5, LEACH under performs even when compared to direct sending. This can be explained by the fact that originally, LEACH was proposed for networks where the base station is farther away from the nodes. Also, LEACH is typically run until every node in the network dies, while we are focusing on the first dead node.

Looking at the energy-efficient strategies, we can see slightly higher results compared to the previous simulations. This is because of the way we run the simulations with LEACH: due to the presence of rounds, the selected nodes are more evenly spread out around the network (due to the fact that in every round, every node will be selected exactly once for message sending). This spreads out the energy differences more evenly, increasing the longetivity of the network.

Looking at the results for medium networks in Figure 6, we can see the same results as with the small network.

In the result for large networks seen on Figure 7, the other strategies still outperform LEACH by a huge margin. Another interesting point that can be seen is that in this case, 2-hop still performed better compared to 3-hop, while in the previous runs, 3-hop outperformed 2-hop in large networks.
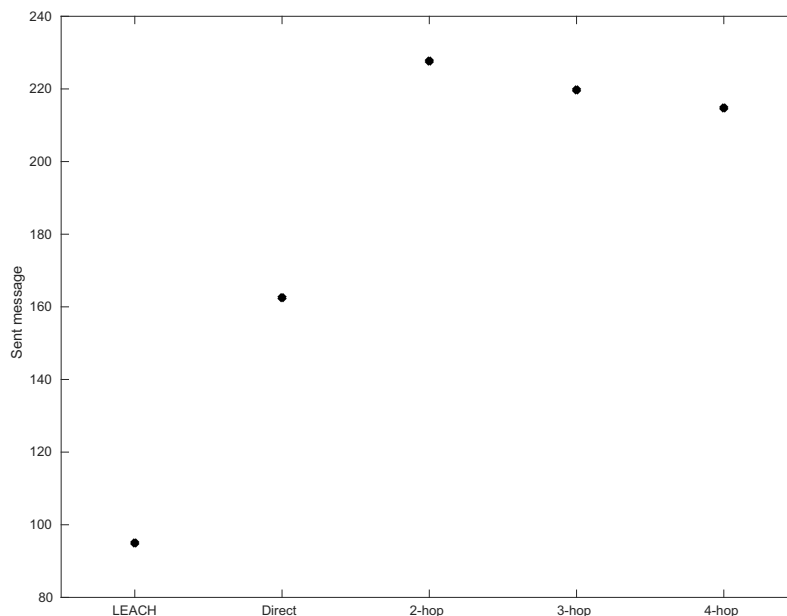

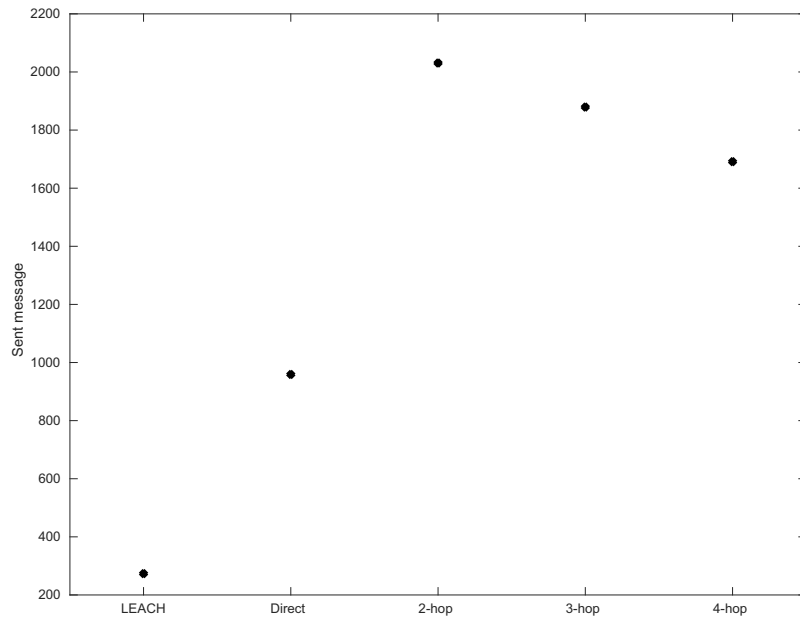Figure 5: Result for small network with LEACH
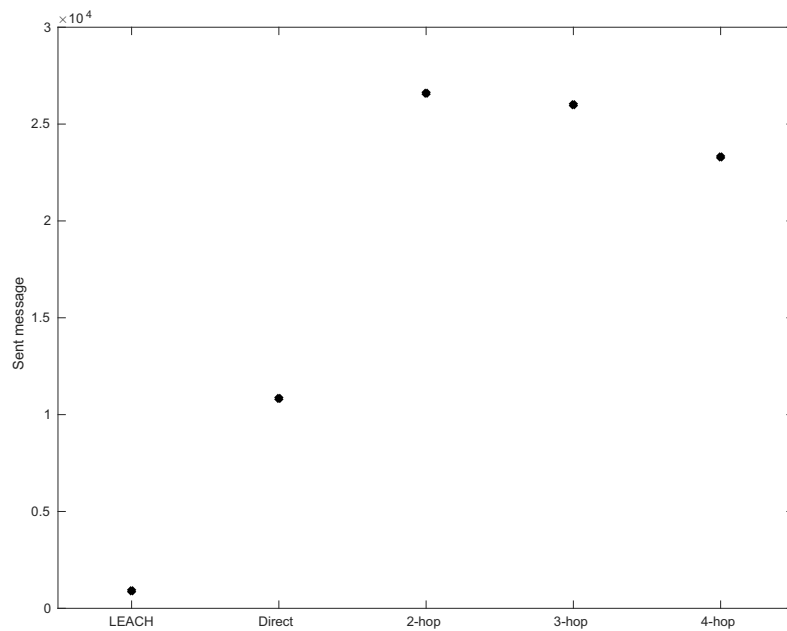
Figure 6: Result for medium network with LEACH

Figure 7: Result for large network with LEACH

6 Conclusion and future works

In this paper we have developed a novel routing algorithm for energy aware IoT data communication where the successful packet transfer from the nodes to BS is guaranteed with a given level of reliability. As the performance analysis have revealed, 2-hop performed well for any network size, while 3-hop outperformed 2-hop in a large network.

As can be seen, LEACH performed poor due to multiple reasons, such as in our environment, the base station was placed near the other nodes, while LEACH was proposed with the base station being placed farther away. Also, the original LEACH does not take into account the current energy levels of the nodes, for a low energy node to become cluster head instantly depletes that node. Since we are running the simulations until the first node goes flat (i.e. runs out of battery power) , this also results in lower performance. We also plan on making comparisons with other, improved versions of LEACH such as E-LEACH [8] and ME-LEACH [7], where the residual energy is taken into account for cluster head selection.

Our planned future work will take into account the network topology, as well. The results given above were achieved with randomly placed nodes but we can further tailor them if the network topology is known in advance. In the future, we would like to consider special network topologies including indoor transmission, as well as different packet sending frequencies, when optimizing the routing algorithm. The model can be further expanded by introducing barriers between nodes (such as buildings). We plan to apply the findings of our research in the wireless sensor network deployed at ZalaZone (being a test environment for autonomous vehicles).

References

[1] Haenggi, M. On routing in random rayleigh fading networks. *IEEE Transactions on Wireless Communications*, 4(4):1553–1562, 2005. DOI: `10.1109/TWC.2005.850376`.

[2] Heinzelman, W. B., Chandrakasan, A. P., and Balakrishnan, H. An application-specific protocol architecture for wireless microsensor networks. *IEEE Transactions on Wireless Communications*, 1(4):660–670, 2002. DOI: `10.1109/TWC.2002.804190`.

[3] Heinzelman, W. R., Chandrakasan, A., and Balakrishnan, H. Energy-efficient communication protocol for wireless microsensor networks. In *Proceedings of the 33rd Annual Hawaii International Conference on System Sciences*, pages 10 pp. vol.2–, 2000. DOI: `10.1109/HICSS.2000.926982`.

[4] Jung, S., Han, Y., and Chung, T. The concentric clustering scheme for efficient energy consumption in the pegasis. In *The 9th International Conference on Advanced Communication Technology*, volume 1, pages 260–265, 2007. DOI: `10.1109/ICACT.2007.358351`.

[5] Li, T., Ruan, F., Fan, Z., Wang, J., and Kim, J. An improved pegasis protocol for wireless sensor network. In *2015 3rd International Conference on Computer and Computing Science (COMCOMS)*, pages 16–19, 2015. DOI: `10.1109/COMCOMS.2015.20`.

[6] Lindsey, S. and Raghavendra, C. S. Pegasis: Power-efficient gathering in sensor information systems. In *Proceedings, IEEE Aerospace Conference*, volume 3, pages 3–3, 2002. DOI: `10.1109/AERO.2002.1035242`.

[7] M. Abdurohman, Y. Supriadi and Fahmi, F. Z. A modified e-leach routing protocol for improving the lifetime of a wireless sensor network. *Information Processing Systems*, 16:845–858, 2020. DOI: `10.3745/JIPS.03.0142`.

[8] Patel, H. B. and Jinwala, D. C. E-leach: Improving the leach protocol for privacy preservation in secure data aggregation in wireless sensor networks. In *2014 9th International Conference on Industrial and Information Systems (ICIIS)*, pages 1–5, 2014. DOI: `10.1109/ICIINFS.2014.7036607`.

[9] Tong, M. and Tang, M. Leach-b: An improved leach protocol for wireless sensor network. In *2010 6th International Conference on Wireless Communications Networking and Mobile Computing (WiCOM)*, pages 1–4, 2010. DOI: `10.1109/WICOM.2010.5601113`.

[10] Watteyne, T., Molinaro, A., Richichi, M. G., and Dohler, M. From manet to ietf roll standardization: A paradigm shift in wsn routing protocols. *IEEE Communications Surveys Tutorials*, 13(4):688–707, 2011. DOI: `10.1109/SURV.2011.082710.00092`.

[11] Xiangning, F. and Yulin, S. Improvement on leach protocol of wireless sensor network. In *2007 International Conference on Sensor Technologies and Applications (SENSORCOMM 2007)*, pages 260–264, 2007. DOI: `10.1109/SENSORCOMM.2007.4394931`.