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 must be supported by local battery power. Thus, energy aware network protocols, such as routing, became one of fundamental challenges in IoT data collection schemes. In our research, we have developed novel routing algorithms which guarantee minimum energy consumption data transfer which is achieved subject to pre-defined reliability constraints. We assume that data is transmitted in the form of packets and the routing algorithm identifies the paths over which the packets can reach the Base Station (BS) with minimum transmission energy, while the probability of successful packet transmission still exceeds a pre-defined reliability parameter. In this way, the longevity and the information throughput of the network is maximized and the low energy transmissions will considerably extend the lifetime of the IoT nodes. In this paper we propose a solution that maximizes the lifetime of the nodes.

Keywords: IoT, WSN, energy-efficient, routing, WiFi

1 Introduction

Industry 4.0 is part of the fourth industrial revolution. One of the main focus of i4.0 is digital data acquisition and analysis of complex manufacturing processes, which requires a number of different sensors and communication equipment to measure and transmit the information about the process.

Since in many cases, connecting each sensor to a wired network would prove to be physically infeasible, wireless IoT devices can provide an efficient solution for controlling the sensor and transmit the collected data via a wireless network. This also gives flexibility, i.e. additional sensors can be easily added to or removed from the network as needed. This combination of the sensor and an IoT device with wireless transceiver will be called a *node* in the forthcoming discussion.

Unfortunately, wireless devices need to be powered by typically through a built-in batteries which needs to be recharged periodically. Under these circumstances, energy efficiency becomes a driving force when developing IoT communication protocols.

To save on transmission energy , it can often be disadvantageous for a particular device to send its message directly to the base station due to the energy consumption needed for reliable large distance communication. Instead, it may be useful to implement multi-hop packet transfers from the sender node to the BS via some relay nodes. In this paper we develop novel routing algorithms for packet transfer that ensures extended lifetime of the network.

The rest of the paper is organised as follows. In Section 2 the related work is summarised. In Section 3 the model is defined. Section 4 introduces the two-hop and multi-hop algorithms with numerical performance evaluation. Section 5 concludes the paper and proposes further research directions.

2 Related Work

In the literature, several different algorithms have been proposed for wireless efficient communication in wireless sensor networks. LEACH[1] assigns nodes to be cluster heads periodically whose responsibility are collecting the messages in their region. After compressing the received packets into a single message, every cluster head transmits it's message to the base station.

PEGASIS[2] creates a chain between the nodes close to each other. At every round, the measured values are aggregated and sent towards one particular node through the chain, which in turn transmits to the base station. This node changes every round.

The key difference between previous work and our research is that with our model, the lifetime of the network can be extended while high probability of successful packet delivery can be ensured.

3 Model

To investigate the different algorithms for routing, we first introduce the Rayleigh-fading model, which gives us a connection between the transmission energy and the probability of successfully packet transfer

$$g_{ij} = -d_{ij}^{\alpha} \frac{\theta \sigma_Z^2}{\ln P_{ij}} \quad (1)$$

where g_{ij} is the energy used in the transfer, d is the distance between the communicating nodes, α is the spatial dimension used in our models, θ and σ are parameters of the environment and communication, $\ln P_{ij}$ is the probability of successfully receiving the message between nodes i and j. This can be simplified to the following equation:

$$g_{ij} \ln P_{ij} = \omega_{ij} \quad (2)$$

where ω_{ij} is a constant dependent on the distance between the nodes and the parameters of the environment.

Let our wireless sensor network consist of N stationary nodes and a base station collecting the messages sent by the nodes. We place the nodes and the base station at random places for every simulation in a unit square. Each node starts with a given energy E, and transmit messages in a random order, given the constraint that the base station must receive it with a probability P_s. At any given time, only one message can be transmitted. We run the simulation until a node's energy level drops to zero, becoming a dead node. An example of this can be seen in figure 1.

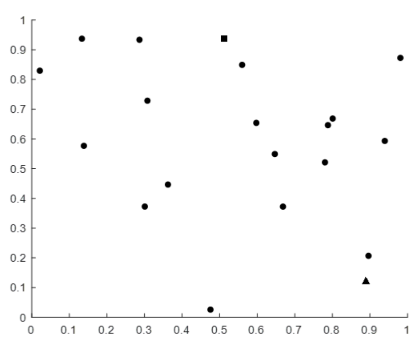

Figure 1: An example of one WSN. The square is the base station, while the triangle is a node currently sending a message.

Our proposed routing algorithms work on the principle that nodes with higher energy levels should participate more frequently in message routing.In order to achieve this, instead of minimizing the sum of the energies used in the transfer of a given message, we maximize the minimum remaining energy level after transferring a packet. This can be accomplished if and only if for every node the energy levels reach a common energy level after the transfer.

4 Proposed algorithms

Based on this observation, the objective of our algorithms is to bring the energy level of the nodes involved in a packet transfer to the highest common energy level while still satisfying the reliability constraint (guaranteeing that the packet will reach the BS with a pre-defined probability). We propose the following routing algorithms:

- *Direct sending*, i.e. the source node sends the packet directly to the base station without using an intermediate node. This is the simplest algorithm which serve as a baseline algorithm.
- *K-hop* algorithm, in which case at most k-1 intermediate node form the path for packet transfer.
- *Multi-hop* algorithm is a special case of k-hop, where we do not set the number of nodes prior to the routing algorithm (i.e. any number of intermediate nodes can be used in a path).

It can easily be demonstrated that calculating the optimal solution for two-hop routing results in a quadratic equation to be solved for every possible intermediary node. In contrast, calculating the solution for k-hop and multi-hop routing requires significantly more calculations. First we have to calculate the unique solution for a given permutation, which requires finding the root of an (k-1)-degree complete polynomial which satisfies the constraints. After that we must check every permutation of nodes for the optimal solution, making the complexity at least $O \mid V \mid!$ Because of this, we opted to use an approximation.

Instead of solving the optimal common energy level problem, let us first find for a given energy distribution which guarantees that a packet can be send form the source node to the BS with the highest probability. Formally, this can be written as follows, using equation 3:

$$\max_{g} \sum_{j=0}^{m} \frac{\omega_{j,j+1}}{g_{j,j+1}} \tag{3}$$

Since ω must be a negative number, we can see that for a given path, the maximum transmission probability can be reached if $g_{l_j l_{j+1}} = c_j(k)$, 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:

$$\max \sum_{j=0}^{m} \gamma_{j,j+1} = \min \sum_{j=0}^{m} -\gamma_{j,j+1} \tag{4}$$

which makes this problem equivalent to finding the shortest path in a graph with the edges having weight $-\gamma_{j,j+1}$. This can easily be solved using the Bellman-Ford algorithm for directed graphs, which has a worst case complexity of $O(\mid V \mid\mid E \mid) = O(\mid V \mid^3)$.

With this solution, we can approximate the optimal common energy level for multi-hop routing. Instead of every node sending with it's remaining energy, let us choose a common energy level c, which every node participating in the transmission must reach. This gives us the energy for every node with which they can participate in the transmission: $g_{j,j+1} = c_j(k) - c$, 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 $(0, c_s(k))$ for the common energy level where the maximum transmission probability reaches the given success probability. This gives us an approximate solution with complexity $O(| V |^3 \ln \frac{c_{max}}{\delta c})$, where c_{max} is the starting energy level of the nodes and δc is the maximum absolute error between the energy levels of the optimal and approximated solution.

The proposed algorithms were implemented in MATLAB, and simulation were run with it. We have changed the placement of the nodes and the order of the messages being sent between simulations, and measured the number of messages being sent before the first node run out of energy. The results can be seen in table 1.

Table 1: Number of messages before first dead node.

	Minimum			Average			Maximum		
Node count	Direct	2-hop	Multi	Direct	2-hop	Multi	Direct	2-hop	Multi
10	26	76	75	112.2	160.32	152.09	289	416	398
20	78	220	136	212.39	350.79	281.53	536	761	608
50	156	590	314	428.7	987.3	656.3	1392	1896	1443
100	308	1256	650	760.2	1980.2	1178.9	1673	3622	2287

It can be seen that under every circumstance, two-hop routing performed better than either direct or multi-hop routing. Comparing to direct routing, two-hop can make use of an intermediary node, so nodes farther away or with lower energy are able to conserve energy. This is in contrast to the results of multi-hop routing, where the 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 algorithm, the use of multiple nodes result in an overall higher energy usage which depletes the network faster.

5 Conclusion and future works

In this paper we have developed different routing algorithms for energy aware IoT data communication. As the performance analysis have revealed the 2-hop routing performed the best for every case. In the future, we would like to examine the k-hop algorithm for k larger than 2. Another future development may relate to the network topology. I these results were measured with randomly placed nodes. In the future, we would like to consider the special network topologies including indoor transmission, as well as different packet sending frequencies , when optimising the routing algorithm. The model developed 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 future cars).

6 Acknowledgement

This work was supported by the BME-Artificial Intelligence FIKP grant of EMMI (BME FIKP-MI/SC) and by the János Bolyai Research Fellowship of the Hungarian Academy of Sciences.

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