Analyzing energy efficiency of sensor networks deployed on the surface of a Solar System Body

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Following the exploration of Moon, the next step could be the exploration of Mars, since many man-made devices already sent measurement results from our closest planet. There is an interesting tendency that the private funding space researches are becoming more and more substantial next to state sponsored space programs. In the process of mapping a distant planet, cost efficiency is high priority since the available resources are limited. A cost-efficient method is using sensor networks to explore, which can be done on a lower budget compared to "single-probe" missions [1]. Human intervention is often not possible due to the great distances. Therefore, the usage of sensor networks can partly be a solution to the arising problems, since losing connection with the home base on Earth does not hinder the measurements [2]. Another advantage is that the failure of a device does not put the mission at jeopardy [3]. In our work, we assumed such a sensor network, which we examined from different points of view. Real Martian topographical data was used to create a Digital Elevation Model on which we studied different sensor movement algorithms. We analyzed the communication between sensors from the energy-efficiency aspect and we established an energy model to estimate the resource consumption of the sensors. A simulation program has been developed to examine our sensor network. In this simulation, we compared the efficiency of the algorithms and we investigated how the energy level of the sensors affect the time required to cover the measurement area.

Keywords—space exploration, sensors, energy efficiency

I. INTRODUCTION

There were many successful applications of wireless sensor networks on earth, for example; in healthcare, urban infrastructure development and agriculture [4]. They have important role in situations where human intervention is dangerous or not possible; like war zones or disaster areas.

In the next section, we provide an overview of wireless sensor networks. In section 3, we describe the network examined in this paper. Section 4 is about reviewing the simulation program we created. The results are presented in the section 5 and we draw conclusions in section 6.

II. OVERVIEW OF WIRELESS SENSOR NETWORKS

A. Overview

From a physical point of view, sensors make up a sensor network, however from a network perspective these units are called nodes. A typical sensor network has three components; source, data sinks and exit points. There are many configurations but in most cases the source is the sensor which takes the measurements and relays the results. The task of the data sinks is to collect and process the data gathered by the sources. Because of this they require more processing capability and memory, however they are part of the network so their communication is like the sources. The exit points can communicate with the satellite, so their task is to send the data processed by the data sinks to the satellite [5]. It is considered best practice to divide larger networks into smaller parts called clusters. This division can be based on the small physical distance between a set of sensors or their place in the logical topology in the network.

B. Grouping of wireless sensor networks

1) Based on communication: Single-Hop and Multi-hop

As their name suggests, the difference between the two groups is in the flow of information. In single-hop networks, the source sends the information directly to the data-sink. In multi-hop networks the information goes through multiple participants before it reaches the data-sink [6].

2) Based on topology: Single-hop star, Multi-hop mesh, Two-tier hierarchical cluster

In wireless networks the simplest topology is the Single-hop star, when all nodes are directly connected to the exit point and there is no connection between the nodes themselves. The simplicity of this topology makes designing these networks easier. Great disadvantage is the lack of robustness and the limited expandability. To cover larger areas, multi-hop communication is necessary, which is used by the multi-hop mesh and the two-tier hierarchical cluster topologies. The former can be considered a single cluster, while the latter consists multiple clusters. Each cluster has a cluster head, which receives the data from the nodes [7].

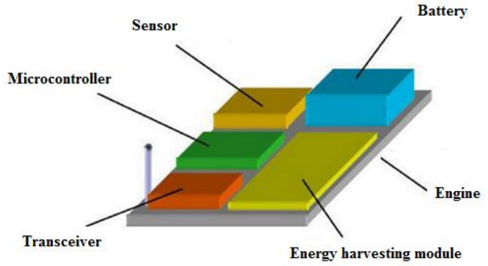
3) Based on the event which triggers data relay: time-triggered, event-triggered, request-triggered

In the time-triggered case, the nodes send the data in predetermined time intervals, while in the event-triggered case the occurrence of some sort of event triggers the data relay. In a request-triggered network the nodes send data only when the data-sink asks for it.

III. The Examined Sensor Network

A. Structure of the network

In our sensor network we differentiate two different kind of devices. One of them is the node, which makes measurements and processes the information extracted from the survey. This device is capable of movement and it can also forward the processed data. Every node has a probability of measurement value, which determines if the node measures or moves onward in the given simulation step. In our simulation, we set this step to a 6-minute time interval. The nodes have limited energy. The other device is the base station, there is only one of this in our network. In our paper, we did not examine the energy-relations of this unit, we assumed its energy to be undepletable. The base station is also capable of movement; however, it does not take any measurements. The task of this device is to forward the data gathered by the nodes to the satellite in orbit around the planet.



1. Figure – Structure of a node

B. Energy model

Energy provisioning is critical in space exploration, due to the long-term measurements the devices need to take. When modeling a sensor network we must pay great attention to the examination of the energy-relations, because if a node runs out of energy it cannot take further measurements. To achieve this, in the design we must take into consideration the proper energy intake and storage. In our simulation, we used 2000 mAh battery, which means 43200 Joule energy [8]. Energy storages are often used due to the matters discussed above, supplemented by some sort of energy harvesting solution, which means using the environment to produce energy. In most cases replacing the batteries is not possible, so it is necessary to find an alternative source of energy. The most commonly used renewable energy sources are solar, wind, water, mechanical and thermal, however under the Martian circumstances their uses are limited. We only considered the energy gathered by the solar cells in our simulation [9]. The energy collected from outer sources means new challenges in the design of low consumption wireless sensors, due to the small size of these sensors.

We beared this factors in mind, while creating different energy models for the movement, measurement, data processing and communication.

In our simulation, we used the data of a simple engine [10] to move the nodes. Two state has been created; a standing and a moving state. The energy required for the moving was calculated from the multiplication of the rated voltage with the current without load. In our paper, we dismissed any outer factors, like drag.

According to their measurement probability, the nodes take measurements in intervals. In this case the do not move. In our simulation, we used the data of a temperature sensor [11]. We created two different states; one when the temperature sensor is turned off, the other is when it is turned on. To change states, some energy is required, which is calculated by:

$$e_{sensor-change} = \frac{1}{2} * T_{init-end} * (P_{init} + P_{end})$$

formula. In this formula $T_{init-end}$ represents the time needed for the state change, while P_{init} and P_{end} are the start and end state's power.

Following the measurement, the next step is the data processing, which is done with a microcontroller [12]. Here we created a sleeping state to reduce our energy expenses.

After processing the measured data, the nodes forward them to the base station. We used the data of a transmitter-receiver unit to calculate this [13].

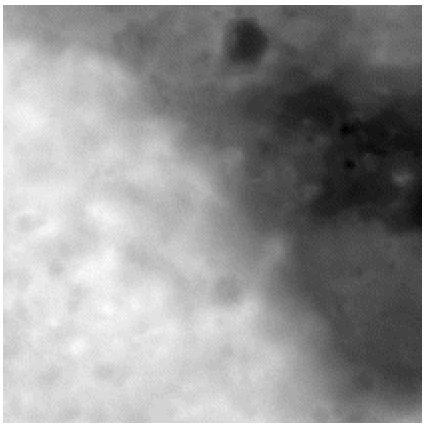
IV. The Simulation Program

A. Utilization of maps

There are several satellites in Mars orbit, which can take high resolution images. One of these units is the Mars Reconnaissance Orbiter with a device called HiRISE (High Resolution Imaging Science Experiment) [14] aboard. The pictures taken by the device and the relief map generated from the pictures are accessible to the public, through the internet [15], so we could use these. From the many obtainable pictures, we chose one taken of the Gale crater [16]. The Curiosity Mars rover landed in this area in 2012 [17]. The rover is still operational. From the map, we cut out an area of one square kilometer.

B. Creation of the digital elevation model

We modified the relief map created by the HiRISE project to a grayscale picture. Our program reads the RGB (Red, Green, Blue) values of the picture mentioned above and it constructs the digital elevation model. The (255,255,255)-white color code represents the lowest point, while the (0,0,0)-black stands for the highest point. In order to properly calculate elevation data, another parameter was necessary, which defines the elevation change represented by one unit difference in the color value on a pixel. The resolution of the used map is 1 meter/pixel. Between the highest and the lowest point the elevation difference is 280,5 meters.



2. Figure – Relief map of the examined area

The program read the map and it created a grid model to store the data in. We chose this model mainly because of its simplicity. The grid is constructed as follows: there is an elevation value assigned to every point of the map, it is a two-dimensional array. The arrays columns and rows represent the X and Y coordinates. The values stored in the array are the elevation values.

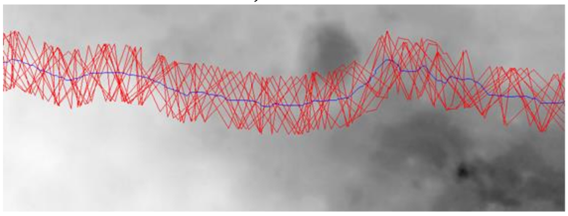
C. *Movement of the nodes*

In our sensor network the nodes are capable of movement. The simulation is terminated once all the Nodes leave the surveyed area, whilst moving on a predetermined path set for them. We implemented three algorithms to set the path of the nodes. Random-bouncing, base station-following and random-bouncing around the base station.

When the nodes follow the random-bouncing algorithm, they start from one side of the map and they set a random coordinate from the upper or lower side of the area as goal. When they reach the upper or lower end of the map, they set a new path from the other end of the map randomly (they “bounce back”). This goal is set in a way, that the node always moves forward, in other word they don’t “bounce backwards”. The results presented in this paper were acquired using this moving algorithm.

We have only one base station on our design, so losing it would mean that our network wouldn’t be able to forward the gathered data. We must minimize every risk factor, which threatens this unit to maximize the chance of a successful mission. The repositioning of a device on the surface of a distant planet holds many risks, because the terrain is unknown and there is very limited human intervention if there is any at all. Our base station following algorithm sets the path of the base station in a way that the device tries to avoid movements which requires change in elevation. We used the Dijkstra [18] algorithm to achieve that. From the grid model, we created a weighted graph in which we could run the Dijkstra pathfinding. The vertices of the graph correspond to the coordinates of the digital elevation model. The weighted edges are calculated from the distance of the neighboring coordinates and from the height difference. The nodes move parallel to the base station.

Combining the first two algorithms mentioned above, we created a third one, when the path of the base station determines a zone in the map and inside this zone the nodes move like the random-bounce method. In this algorithm, the goal is to cover only a part of the map, so the “bouncing” of the nodes is triggered by reaching the end of the zone we intend to cover. We can see the path of the nodes, marked with red and the base station, marked with blue on the 3rd figure.

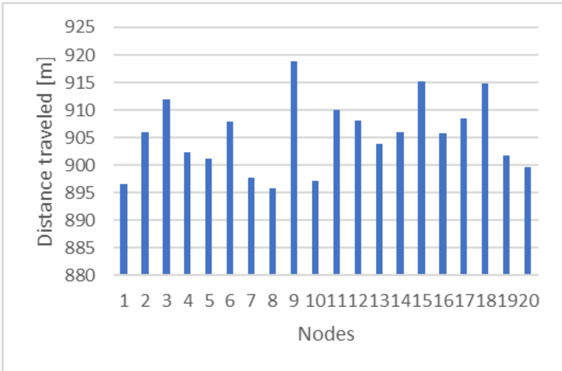


3. Figure – Random-bouncing around the base station movement

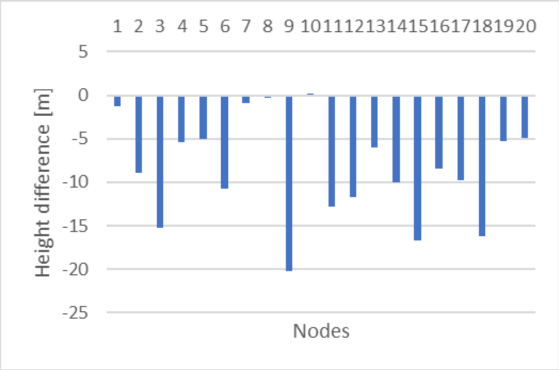
V. RESULTS

A. *Effect of the terrain*

The movement is the operation, which has the most substantial effect on energy consumption, so the different paths the nodes take has different influence on the energy-relations. We couldn’t ignore the height difference in the paths of the nodes, because we used a three-dimensional map in our simulation. The nodes movement is not only horizontal, but they move according to the terrain; if a node moves from a higher point to a lower point, it consumes less energy, while in the reversed situation it consumes more. We calculated the height difference in every simulation step because it affected the energy the node required to move and we summed up the elevation differences.



4. Figure- Distance traveled by each node

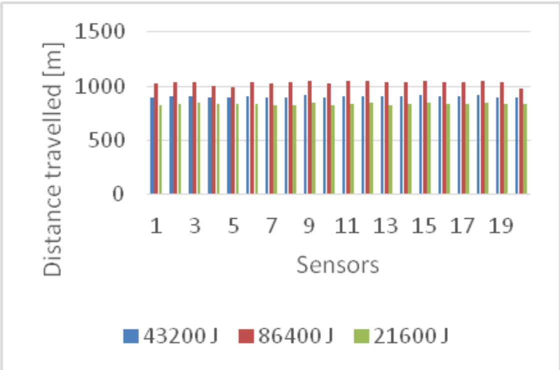


5. Figure – Elevation change, the nodes took during the simulation

As expected; those nodes could move further, which moved downward on a slope for most of their paths. It can be observed that the nodes with less downward movement consumed more energy, that is the reason they traveled less distance.

B. *Effect of the battery*

In this examination, we were trying to find out, how the size of the battery affects the operation of the nodes. In the different scenarios, we used the following battery sizes; 43200 J, 86400 J, 21600 J.



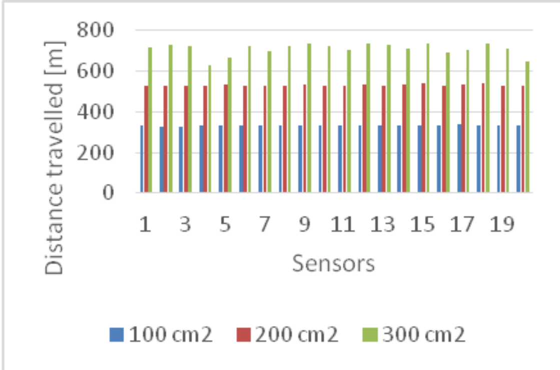
6. Figure – Distances traveled with different battery sizes

It is a noteworthy observation that despite the fact we doubled the battery size, the traveled distance only grew by 9-15,5%. In the scenario where we reduced the battery size by half, the nodes traveled 7-8% less distance. The reason behind this result is that the movement of the nodes consumed much more energy than the solar energy could cover. During the simulation, discarding the starting period the energy level of the nodes were low. The conclusion we can draw from this is that the longer we run the simulation, the less effect has the battery size on the traveled distance.

In larger network when we talk about thousands of nodes, it should be considered to reduce the size of the batteries, seeing we can achieve similar results with less financial investment. The smaller battery size means smaller nodes, so we can send more of them in the cargo hold of the spacecraft to the distant planet. The reduced battery sizes also mean less mass, so we can save on the fuel cost of the rocket.

C. *Effect of the solar cell*

The nodes only have one source of energy, therefore the only way to increase the energy revenue is to expand the surface of the solar cell.



7. Figure – Distances travelled with different solar cell sizes

It can be observed that if we double the size of the solar cells, the nodes traveled approximately 60% greater distances. On average the nodes made 110% further, when they had triple size solar cells. Of course, the size of the solar cells cannot be increased infinitely. The nodes operate both day and night resultantly, for them to move at night also, it is not enough to expand the solar cell, but we would have to increase the battery size. It must also be taken into consideration, that due to the small size of the sensors, the solar cells have a limited expandability.

VI. CONCLUSION

In a wireless sensor network operating on the surface of the Mars, to make effective use of the devices we must consider the energy relations. In our paper, we reviewed the architecture of the wireless sensor networks and some of the grouping possibilities. We created a simulation model, in which we examined the factors influencing the energy consumption. The replacement of the batteries in the devices is not possible due to the absence of human intervention, so it is necessary to use energy efficient methods.

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