Increasing lifetime in grid wireless sensor networks through routing algorithm and data aggregation techniques

Dragoş I. Săcăleanu, Dragoş M. Ofrim, Rodica Stoian, Vasile Lăzărescu

Abstract— The major problem for Wireless Sensor Networks (WSN) is the limited energy supply of the sensors. The research in this area is focused on making smaller sensors with low power consumption. Some of the most common techniques in prolonging the lifetime of the sensor network are data compression, routing algorithms, data aggregation, scheduling and synchronization. In this paper, an adaptive routing algorithm (ARA) suited especially for grid WSN is presented. The algorithm takes into account the residual energy of the sensor nodes and configures the paths in order to maximize the network lifetime. It also presented data aggregations techniques based on temporal and spatial correlation characteristic to for monitoring and data acquisition sensor networks. Tests were performed on an OmNET++ simulating platform, comparing ARA with already existing algorithms for grid WSN and highlighting the advantages of using the routing algorithm together with the data aggregation technique. Additionally, a test to determine the most energy effective place of the sink in the network and a comparison between square and hexagonal topology for WSN are performed.

Keywords - data aggregation, energy saving, grid wireless sensor network, routing algorithm

I. Introduction

DUE to the flexibility of the system, wireless sensor networks (WSN) offers a great diversity of applications that can be implemented with their help. WSN consists of tens, hundreds or thousands of autonomous devices that are capable of sensing, processing and communicating. The limited transmission range allows for such networks to be able of self-organize into multi-hop wireless systems. In most cases, a WSN is organized into clusters where a node gathers data from its neighbors. This cluster head then transmits all the data to a higher cluster head until all the information from the network reaches the sink.

Technology developments have made it so that a sensor node can reach the size of millimeters. This generally includes a sensor, a microcontroller, a communication module and a power source. Since in most cases the modules are placed in locations where a wireless system is imposed, the power source is a battery. The design goal is to make a wireless sensor network in a manner that the energy consumption is minimized, to increase the network lifetime.

A sensor node consumes energy during sensing, processing and transmission. During communication, the sensor node consumes the greater amount of energy, with values ranging between 60% [1] and 80% [2], while during sensing and processing operations, it consumes only 20%-40%. The goal of much research in this field is to minimize the quantity of transmitted data through different methods that involve processing, in order to reduce the spent energy for communication. Some of the most common methods are: data compression, routing protocols, data aggregation, scheduling, synchronization and others.

In order to apply these methods, it is highly recommended to take into consideration the type of application for which the system is intended. For example, in monitoring cases where the sensors transmit their data periodically to the sink, some data redundancy might be registered. This can be removed with the help of data aggregation based on temporal correlation in data sensed by individual sensors over time and spatial correlation in data sensed by sensors which are physically close to each other.

Also depending on the type of application, the nodes can be placed in a random order or in a grid layout with fixed distances between nodes. Some random layouts can be organized in clusters over a geographical region and a cluster grid can be obtained. In typical grid wireless sensor networks the sensors are placed manually in an array configuration. Another grid configuration could also be considered in the case of a sensor network where the sensors are depleted on a hexagonal lattice. In these situations the nodes have to be reliable because a certain region depends on the data only

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offered by them. The routing protocol has to take into consideration the remaining energy of the nodes in order to balance the data traffic in the network and increase its lifetime.

II. Related Work

Increasing lifetime in WSN is a continuous theme of intensive research. Many methods are exploited and implemented in order to minimize the nodes energy consumption.

One of the most efficient methods is data compression. A multitude of compression algorithms can be implemented in WSN. An important algorithm is the Adaptive Huffman [3] which can be used and modified in different ways. In [4] the authors present a Dynamic Huffman algorithm suited for changing statistics of highly correlated data.

Data aggregation is a technique used in minimizing the amount of bits transmitted. In [5] some techniques for data aggregation that do not use any explicit structures are proposed. The spatial and temporal convergence is exploited (requires packets to meet at the same node at the same time). Most of the work in data aggregation is based on query. In [6] a new distributed algorithm for query processing in WSN is provided. Some similarities are used with the tinyDB [7], a database used for WSN.

In general, a lossy process of data characterizes the data aggregation function. In [8] approximate data aggregation is considered with precision guarantees. Data impreciseness is measured by the quantitative difference between an approximate value and the exact value.

Another technique for increasing the lifetime of WSN is presented in [9]. An adaptive scheduling algorithm is evaluated. The work combines the topology and routing improvements with management, synchronization and scheduling techniques.

Increasing network lifetime it is also possible with an appropriate routing scheme. For cluster configuration of the WSN some algorithms where proposed, [10], [11] to reduce the energy consumption. In [12] a hierarchical structure is adopted and multi hop before clustering is produced. Another location based routing protocol that takes advantage of the cluster topology is proposed in [13].

Many random depletion schemes of wireless sensors are reduced and partitioned into grid layouts. In [14] the authors propose a direct grid topology from the source node to the sink node. The sensor network is divided into grid subnets where the transmitter node is selected according to its dependencies on a certain cost parameter that includes the distance to the location of the ideal grid node and the residual power. In [15] a non-uniform grid-based coordinated routing design is presented. Here, different types of partitioned square shaped grids that divide the sensor network are used. A load balancing with respect to the residual energy is also implemented.

In [16] a hexagonal grid topology is proposed. This is tested for a geographic adaptive fidelity (GAF) protocol. For this configuration improved results for packet delivery ratio and throughput were obtained by keeping energy consumption almost the same as GAF for array grid. Some studies are made on a classic grid topology where the nodes are arranged on an array layout and all of them participate to route data. In [17] a comparison between four routing algorithms for grid topologies is presented. A similar topology is proposed in this paper but the data is transmitted accordingly with the residual energy of the nodes. The routes are structured on an adaptive format, considering the leveling of energy spent. The influence on the network lifetime of the sink position in a grid WSN is also studied. In addition, by taking into account a certain degree of spatial and temporal correlation, a data aggregation technique was proposed in order to increase the network lifetime.

The rest of the paper is organized as follows: Section 3 presents an adaptive routing algorithm (ARA). Section 4 refers to data aggregation impact on a sensor network and the implemented model. In Section 5 are presented experimental results. ARA is compared with a tree based routing algorithm and data aggregation techniques are implemented and simulated on ARA. Also, the importance of the sink place in a sensor network is revealed and a comparison between different grid networks topologies is performed. Experimental data are simulated on OmNET++ platform. Section 5 concludes this paper and presents ideas for future work.

III. Adaptive Routing Algorithm

In [9], [10] routing algorithms for networks with random deployed sensors grouped in grid layouts are presented. We are interested to study a deployment of the wireless sensor nodes in a situation where the nodes respect the places of an array. They are placed manually at certain locations where the distance between two neighboring nodes is the same (*d*). The sensor network has a *M*X*N* dimension and is similar with the one presented in Fig. 1.

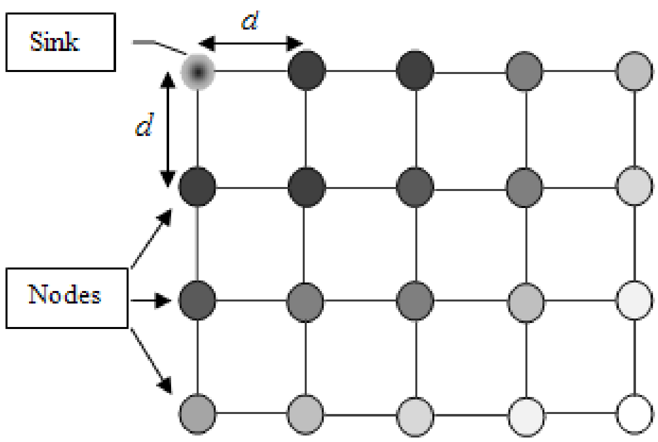


Fig. 1 Grid network with a 5X4 dimension
- A darker node means a more used one.

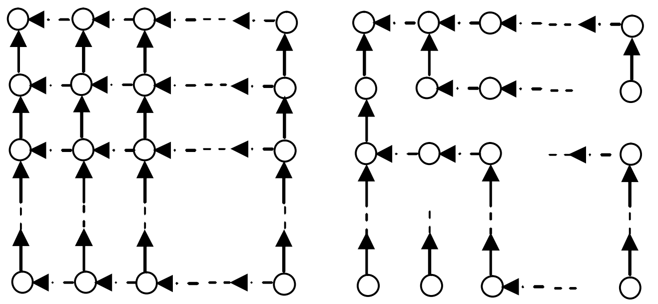
Each sensor is identified by its bi-dimensional coordinates, (*i*, *j*), where *i* represents the horizontal index of the sensor with values between 0, *M*-1 and *j* represents the vertical index of the sensor taking values between 0, *N*-1. For the simplicity of the presentation we choose to select the network sink at the point (0,0). The sink also acts like a sensor and it has unlimited energy. Each node placed in the interior of the grid has 4 neighbors: two high neighbors, node $(i, j + 1)$ and node $(i + 1, j)$, and two low neighbors, node $(i - 1, j)$ and node $(i, j - 1)$. The nodes located on the edge of the grid can have two or three neighbors. A node can transmit only through the smallest paths, to his low neighbors. This way the nodes closer to the sink are more used because they transmit all the data from behind. In Fig. 1 a darker node means a more used one. We can observe that the nodes are darker once they get closer to the sink.

A. The ideal routing model for grid

In a WSN grid the nodes closer to the sink spent the most amount of energy. It is considered that the network lifetime is the same with the lifetime of the first node that dies. Assuming ideal conditions where all the data packets have equal sizes and the transmission is without error, in order to balance the data traffic and to maximize the lifetime of the network, the nodes that have two options in transmitting will choose alternate destination. This way disappears the extra load from a path.

B. Tree based routing algorithm (T-BRA)

In [17] four routing algorithms are compared. In the Row-to-Column routing algorithm, the nodes situated on the same line with the sink gather the data from the other sensors on their column and send them to the base station. In the Stream-Based routing algorithm, data packets are transmitted through all the other sensor nodes closer to the sink. The Cluster-Based routing algorithm divides the grid network in clusters that gather the data and the send it to the sink. The fourth algorithm is developed by the authors and exploits the Tree-Based routing. It has three phases: in the first one, the parent (P) node sends a broadcast SEARCH message. Then, in phase two, the neighbors who received the message respond with a REPLY message. In the last phase, P sends an ESTABLISH message to their children (CH). If a node receives two SEARCH messages, it responds only to one of them and chooses P. A timer is introduced in order to know if a node is a leaf. The final routes can look like in Fig. 2.b.



a) ARA b) T-BRA

Fig. 2 Algorithm's routing paths

C. ARA

T-BRA has the disadvantage of not taking into account the residual energy of the sensors. This way, after the network is made, the load may be unbalanced and some nodes may consume their energy much faster. Possible reasons for unbalanced energy consumption are: different sizes of the data packets; error control of the data, delay.

ARA takes into account the load balance and the residual energy of the sensors. The network is discovered with an algorithm similar to T-BRA. The sink sends an SEARCH message to find its CH. The nodes that receive that message respond with a REPLY message. Finally, P sends an ESTABLISH message to CH and the process goes on until it reaches the leaves. The difference in this case is that CH can have two P, in order to choose the efficient path to transmit data to the sink. This process is made only at the initialization of the network or if the network suffers any changes. Together with the exchange of messages, each node receives an ID similar with its place in the grid. The routes are shown in Fig. 2.a. CH will choose alternatively between a dotted arrow and a straight one.

Besides the ones placed on the i=1 and j=1 axes, each node has two options in transmitting data. Each new transmission of data is directed alternatively to a different P, P1 or P2. This avoids the energy consumption by transmitting permanently messages with the remained energy. At the beginning each P has equal energy (E1=E2) When P2, consumes 75% from E2, it announces CH. Next, CH will send data only to P1. When P1 achieves 25% from E1, CH continues to transmit to it until it reaches 25% of its remained energy (E1'). Then P1 is changed and continues with the same algorithm until one of them is left without energy. When a P consumes 75% from its energy, it announces both its children.

We built an adaptive routing algorithm that is aware of the path with the smallest energy at certain important moments in time, but at the same time, does not spend a lot of energy in updating the nodes with their energy.

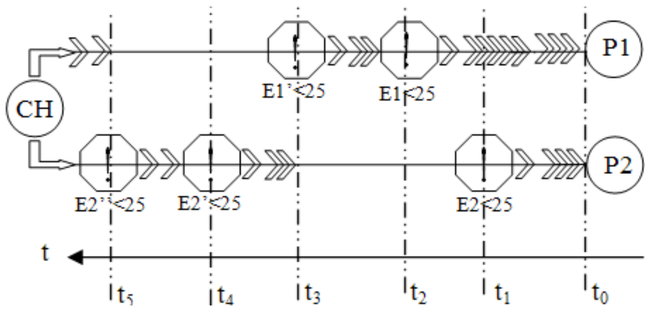


Fig. 3 Data transmission with ARA

Fig. 3 presents the algorithm. Node CH sends data alternatively to P1 and P2. At the time t_1 the P2 remains without 75% of E2. From this moment CH sends only to P1. At t_2, P1 remains without 75% of E1 but the CH continues to transmit until P1 remains at 25% from E1', at t_3. Then P1 is changed and it follows two cycles of discharge of P2 until 25% from E2'' (E2'' represents 25% from E2'). The algorithm stops when a P remains without energy and the lifetime of the network is over.

IV. DATA AGGREGATION TECHNIQUES

The main purpose of wireless sensor networks is to gather information from a certain area and transmit the data to a central unit, the sink, where it is used by the application. In many cases the data are similar at different nodes or at different moments in time. Therefore, it is desirable to combine them in order to eliminate the redundancy and minimize the number of bits transmitted that reflects on the totally energy spent.

In this case, the traditional approach in networks for data routing known as address-centric is replaced with data-centric. Address-centric refers to a routing protocol where the nodes transmit data to the sink along the shortest path, without any change of the packet on the way (Fig. 4.a). In a data-centric protocol the data packet is checked at every hop and combined with others data packets that have to be transmitted (Fig. 4.b). This way the numbers of bits transmitted could considerably decrease.

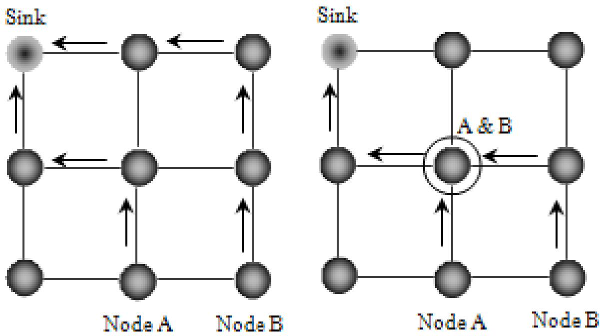


Fig. 4 a. Address-centric b. Data-Centric

The process is called data aggregation and represents the action of processing data at intermediate nodes from a multi-hop network, with the aim of reducing resource consumption. One of the most important resources that can be conserved with data aggregation is energy.

Data aggregation could be implemented through simple functions like *min*, *max*, *sum*, *avg* or complex functions with multiple inputs. These functions could compress and merge the information in a lossy or lossless approach. In addition, in-network aggregation is performed with size reduction or without size reduction, where multiple packets are merged into a single packet but without size reduction.

In this paper, we exploit data aggregation through temporal and spatial correlation. The function used in this case is the difference between data. This is performed lossless for the integrity of data, with size reduction.

A. Data Aggregation based on Temporal Correlation (DATC)

In monitoring applications, each node periodically performs observation and transmits the sensed data to the sink. The frequency of the sensing time intervals depends on the observed phenomenon. For example, in order to monitor the ambient temperature, it is not necessary to take values for less than a couple of minutes. Instead, if we want to observe the vibrations on a bridge, it is necessary to perform a continuous monitoring. In each case a temporal correlation of successive data appears, that can be characterized with a certain degree.

Consider that at the time t_i a certain node makes a measure m_i and the value of m_i is v_i. At the step i the sensor transmits the data v_i. At the time t_{i+1} the node make the measure m_{i+1} with the value v_{i+1}. As we explained before, the value v_{i+1} is, with a high probability, very close to the value v_i. For this reason, it is more efficient to transmit the value of the difference between the two data:

$$d_i = v_i - v_{i+1} \quad (1)$$

In a typical temperature monitoring, if the sensor has two consecutive data of 24°C and 25°C, it is more efficient to transmit 1°C, which can be coded with 2 bit, than 25ºC, which can be coded on 6 bits, including the sign bit.

B. Data Aggregation based on Spatial Correlation (DASC)

In a grid layout of WSN the nodes are placed at a certain distance one from the other. The pattern formed is an array. A sensor monitors a round area and, inevitably, certain regions are monitored by two sensors (Fig. 5).

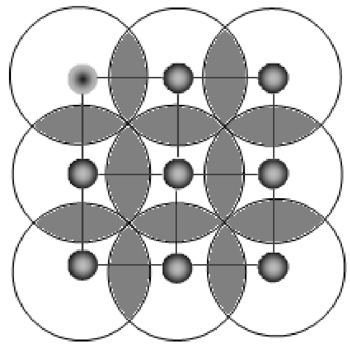


Fig. 5 Spatial correlation in a grid network

Some phenomena are hard to be delimited by a certain region and a similarity between data gathered from two adjacent regions is found. For example, the ambient temperature is highly probable to be the same at a distance of one hundred meters. Based on this, we can conclude that spatially proximal sensors data are correlated with a degree of correlation that increases with the decreasing of the distance between nodes.

Passing the data from node n_j to node n_{j+1}, the probability that the values of the measures are closer is very high. This way, we can use the same idea from DATC. The value of a measure m_{j+1}, p_{j+1}, can be aggregated with the value of the measure m_j, p_j, and for node j+1 only the value of the difference, e_j, can be transmitted, where:

$$e = p_j - p_{j+1} \quad (2)$$

This has a great advantage especially when the values are the same and the node will transmit only one value with two node IDs. At the sink, the data will be read based on the value of m_j and the differences assigned for each node ID. At each step, the nodes will retain only the measured value. The aggregation is made depending on the value measured by node *j*. It is possible that by using another node value, the bit stream will be smaller. This is the way a verification of the packets is made at every node. If it is more efficient to aggregate using another measured value, the node updates the data packets.

For example we consider three nodes A, B, C that measure values of temperature: v_1=25°C, v_2=23°C and v_3=23°C. Node A reads the value *v*1 and sends the data to B. Sensor B reads the value *v*2 and sends a packet composed from the value measured by A, the difference between that value and its measured value and the nodes ID. Sensor C reads the value *v*3 and, after update, sends the value *v*3, the difference between this and v_1 and the difference between this and v_2. After crossing the three nodes will be like in Fig. 6.

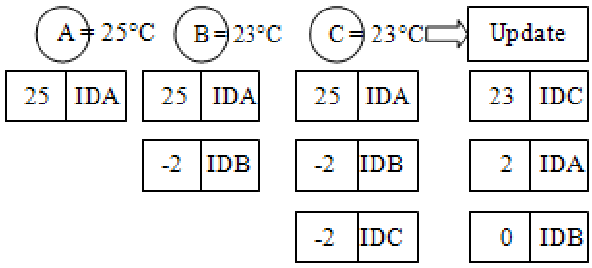


Fig. 6 Example of DASC with three nodes

If no aggregation is made, the total bit stream of the values will be 18 bits. With the implemented scheme, the size will be reduced at 12 bits and after updating the size, it will be 10 bits.

Temporal correlation is used for data aggregation at the same node, meanwhile spatial correlation is used for data aggregation at different nodes. It is possible to combine DATC and DASP at the same time. In this case DASC aggregated the values obtained after applying the DATC technique at each node.

V. Experimental Results

In order to evaluate ARA, simulations were carried out on OmNET++ platform. Our objectives were to compare ARA with T-BRA and reveal the improvement in network lifetime using ARA. Also we proposed to see the advantages brought by implementing DATC and DASC, separately and together, over ARA. Other simulation were performed in order to discover the most efficient place of the sink in a grid network and the best topology suited for grid WSN.

Considering that a node can transmit using ZigBee over 100m, we simulate a sensor network that could monitor a surface of about $1km^2$. This network contains 81 sensors, placed 9X9, and the sink is placed at the point (0,0). We considered that a node consumes 4 units at transmission, 3 units at reception, 2 units in transmitting the energy information and 1 unit in receiving the energy information. Each node was initialized with 10000 units of energy and the sink has unlimited energy. The energy spent in discovering the network was not taken into account. A perfect technique of data aggregation is considered, where, if a node receives one or two messages, it is capable of aggregating and transmitting only one message. The lifetime of the network is equal to the lifetime of the first node that dies and is measured in number of acquisitions steps made.

In [17] from comparison with others algorithms, the authors conclude that when the sink is in the corner the T-BRA algorithm obtained the best results in network lifetime. In our simulation, ARA is compared with T-BRA and the results can be observed in Fig. 7.

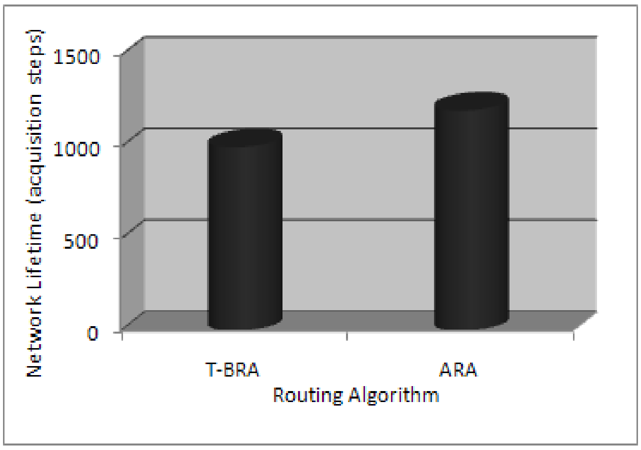


Fig. 7 Comprison diagram of network lifetime between T-BRA and ARA

From this figure we can conclude that ARA improves the lifetime of a grid sensor network with approximately 20%.

For the simplicity of the algorithm presentation the sink was placed at the point (0, 0). In Fig. 8 an evaluation of the network lifetime depending on the sink position in the grid is presented. The grid is composed also from 81 nodes, deployed 9X9. The aggregation is not taken into consideration. Each node receives a packet for all the nodes connected up to it. The energy consumption is the same as described in the first simulation. Each node has 10000 units of energy and the sink

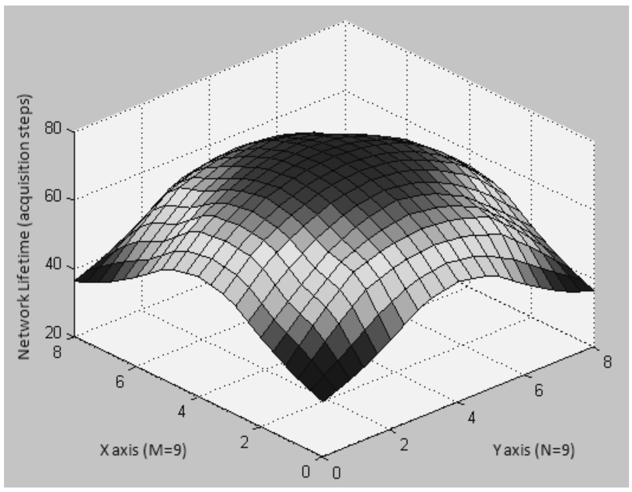


Fig. 8 Network lifetime depending on the sink position in the grid

has unlimited energy. A node consumes 4 units of energy at transmission, 3 units at reception, 2 units in transmitting the energy information and 1 unit in receiving the energy information.

It can be seen that the network lifetime increases when the sink is placed near to center. When the sink is positioned in a corner the network lifetime is minimized.

In order to improve the energy saving of the sensors, we implemented the DATC and DASC on ARA. A comparison between ARA, ARA with DATC and ARA with DASC can be observed in Fig. 9. For each case we considered the grid size 5X5 and the sink situated in a corner.

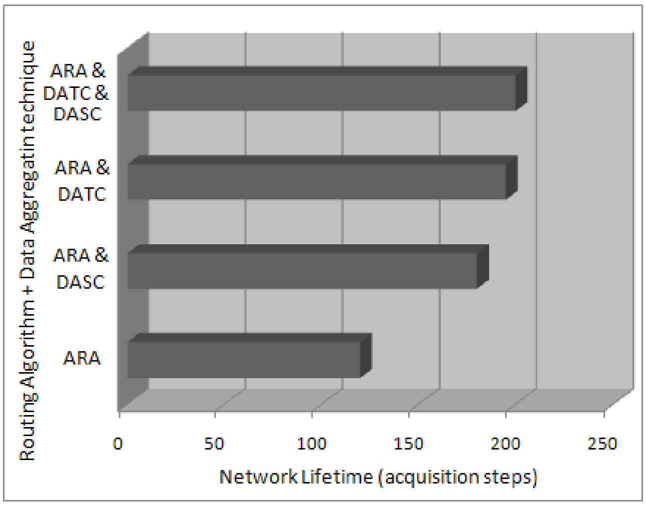


Fig. 9 Comparison diagram between ARA and ARA with DASC and DATC

We consider the packet length of maxim 2 byte, one byte for node ID and maxim one byte for data. Only the measured data can be aggregated, while the length of the node ID remains the same. As data, we considered values of the ambient temperature from a public data base [19].

Each node has 10000 units of energy and the sink has unlimited energy. The energy consumption of the nodes remains the same: 4 units of energy at transmission for a two byte packet, 3 units of energy at reception for a two byte packet, 2 units in transmitting the energy information and 1 unit in receiving the energy information. Since the length of data packets differs, the energy consumption in transmitting and reception is proportional with their length. The energy spent in discovering the network was not taken into account. Also, the simulation is performed by taking into account only the data and the node ID bits, and not the packet encapsulation bits.

In DATC case, at the beginning of the acquisition the sensors transmit the data as it is, in a 2 byte packet. After the first step the nodes aggregate their data temporally and transmit only the difference between two consecutive measured values.

In DASC case, at each step, the nodes that initiate the transmission (the leaves) transmit the data as it is. The nodes that receive data can aggregate their data with the incoming ones and transmit a much smaller packet. In this case the leaves will consume much more energy because each time they will transmit the whole information.

In order to improve the lifetime of the network, a combination of these two data aggregation techniques is proposed.

From the results shown we can conclude that the implementation of described data aggregation techniques brings an improvement of the network lifetime from 50% to more than 60%. DATC obtained better results than DASC and that is because in DASC at each transmission the sensor sends a measured value, and all others value depend on this one. In DATC the measured standard value is transmitted only at the first acquisition and after that the new values are aggregated in time with this one. Combining the two techniques the results are improved.

The shape of the grid also depends on the field that has to be monitored. The usual topology used for grid networks is a square shape. Each sensor node has four neighbors with which it can communicate, two displayed horizontally and two vertically.

Another type of grid topology is the hexagonal one where each sensor has six neighbors. In Fig. 10 can be seen an example formed by 10 nodes of such a pattern.

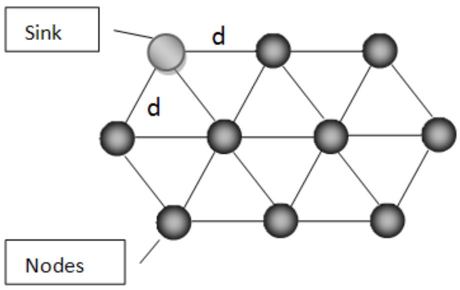


Fig. 10 Example of hexagonal topology of a wireless sensor network

Considering as a condition in transmitting data a minimum number of steps until the sink, each node has two options to forward the information, except the nodes located on the same horizontal line with the sink, the nodes from the same diagonal with the sink and the first nodes from the even lines.

In a square sensor network, if we denote with d the distance between sensor nodes, the surface covered by the network is approximately $(m+1)*(n+1)*d^2$, where m represents the number of nodes from the line and n represents the number of nodes from the column.

In a hexagonal sensor network, if we also consider d as the distance between sensor nodes, the surface covered by the network is approximately $(m+1)*(n+1)*d*\sqrt{3}/2$, where m represents the number of nodes from each line and n represents the number of lines.

As we can see the surface covered by a square sensor network is larger than the surface covered by a hexagonal sensor network. This reflects on the costs of the sensor network, but especially on the network lifetime. A higher density of nodes means a higher data redundancy. This affects directly the energy consumption because unnecessary data are been processed and transmitted. In WSN almost all the methods for maximizing the network lifetime take into consideration the elimination of the data redundancy.

For example if we consider a network with 81 nodes (Fig. 11), arranged 9X9, and a distance between nodes of 100m, the surface covered by the square sensor network is of approximately $1km^2$. In the hexagonal sensor network the covered surface is of approximately $0.86\ km^2$ (Fig. 12). To cover almost the same surface, in this case, the hexagonal network needs another line of 9 sensors. That means increasing the cost of the network with almost 10%.

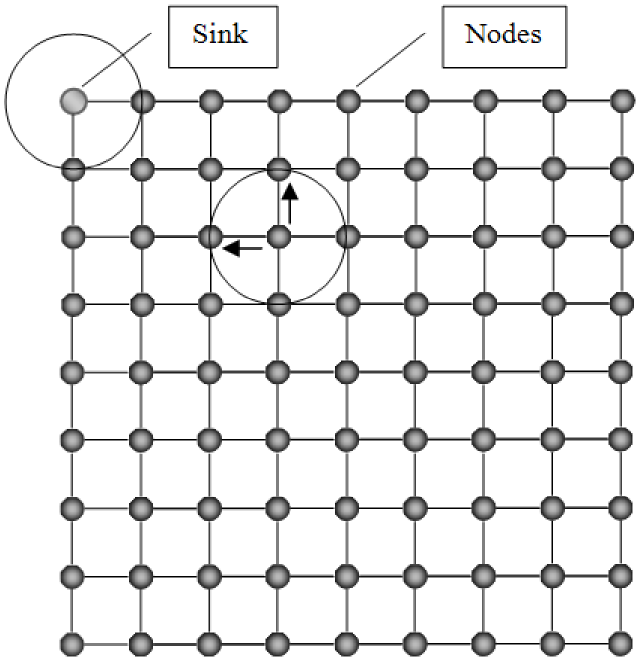


Fig. 11 WSN hexagonal topology formed by 81 sensors

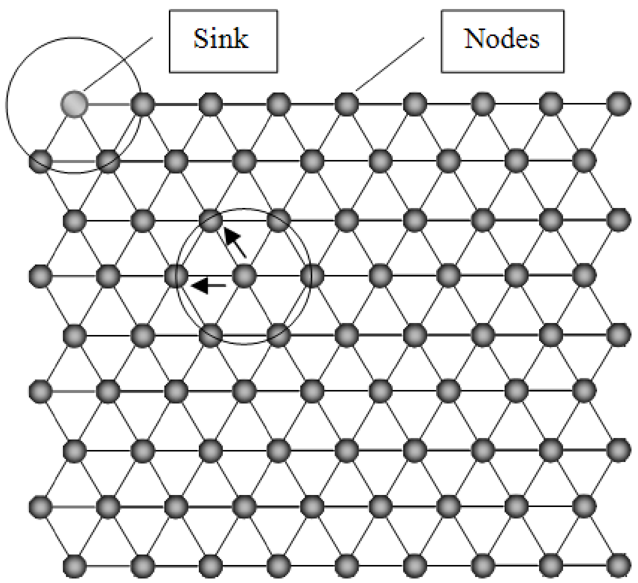


Fig. 12 WSN hexagonal topology formed by 81 sensors

In Fig. 13 a comparison between the lifetime of the square sensor network and the hexagonal sensor network, both using ARA, is presented. The sink is placed at the upper-left corner. The energy conditions are the same as in previous simulations: a node consumes 4 units at transmission, 3 units at reception, 2 units in transmitting the energy information and 1 unit in receiving the energy information. Each node was initialized with 10000 units of energy and the sink has unlimited energy. The energy spent in discovering the network was not taken into account. Also, a perfect technique of data aggregation is considered.

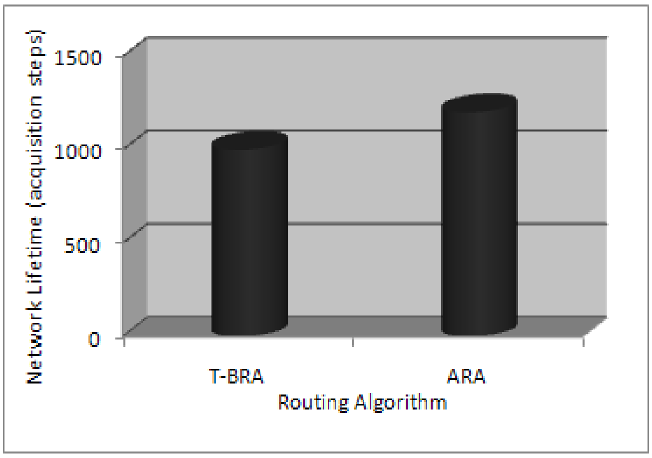


Fig. 13 Comparance diagram of network lifetime between T-BRA and ARA

We can observe that the lifetime of the square sensor network is higher with approximately 5%. Although the sink has three neighbors that gather the data from the entire network, the energy bottleneck is in the second line of sensors, nodes that are placed at two hops.

VI. Conclusion

This paper presents an adaptive routing algorithm suited for grid layouts of WSN. ARA offers an improvement of the network lifetime by taking into account the residual energy of the sensor nodes and creating an adaptive route path. In the simulation performed, ARA provides a network lifetime growth of about 20% from other algorithms. We have presented the importance of the place of the sink in a grid WSN. We observed that position of the sink is highly important in increasing the lifetime of the network. The closer it is to the center, the higher the lifetime. Also we compared two types of grid WSN topology: hexagonal and square. The simulation performed revealed that the square sensor network is more efficient than the hexagonal sensor network, although its coverage surface is greater.

In order to reduce the total amount of transmitted bits that reflects into saving energy, some data aggregation techniques were proposed. DATC and DASC can be implemented together or separately, and eliminate the redundancy of data through temporal and spatial correlation. DATC recorded better results than DASC and when both data aggregation techniques where applied to ARA, a growth of network lifetime of over 60% was observed.

ARA can be implemented also in WSN with randomly deployed nodes. The nodes can be grouped in clusters and the clusters can be arranged in grid topologies. This way the cluster-head can be considered as a node from the grid. In future work, we will study the improvements brought by lossless compression algorithms together with ARA on grid wireless sensor networks specialized for monitoring and data acquisition.

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