Paper

Comparative Study of Wireless Sensor Networks Energy-Efficient Topologies and Power Save Protocols

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Abstract— Ad hoc networks are the ultimate technology in wireless communication that allow network nodes to communicate without the need for a fixed infrastructure. The paper addresses issues associated with control of data transmission in wireless sensor networks (WSN) – a popular type of ad hoc networks with stationary nodes. Since the WSN nodes are typically battery equipped, the primary design goal is to optimize the amount of energy used for transmission. The energy conservation techniques and algorithms for computing the optimal transmitting ranges in order to generate a network with desired properties while reducing sensors energy consumption are discussed and compared through simulations. We describe a new clustering based approach that utilizes the periodical coordination to reduce the overall energy usage by the network.

Keywords— ad hoc network, energy conservation protocols, topology control, wireless sensor network.

1. Introduction to Ad Hoc and Wireless Sensor Networks

An ad hoc network is a wireless decentralized structure network comprised of nodes, which autonomously set up a network. No external network infrastructure is necessary to transmit data – there is no central administration. Freely located network nodes participate in transmission. Network nodes can travel in space as time passes, while direct communication between each pair of nodes is usually not possible. Generally, ad hoc network can consist of different types of multi functional computation devices.

Wireless sensor network (WSN) is most often set up in an ad hoc mode by means of small-size identical devices grouped into network nodes distributed densely over a significant area. These devices, each equipped with central processing unit (CPU), battery, sensor and radio transceiver networked through wireless links provide unparalleled possibilities for collection and transmission of data and can be used for monitoring and controlling environment, cities, homes, etc. In most cases WSNs are stationary or quasi-stationary, while node mobility can be ignored. There is no prearrangement assumption about specific role each node should perform. Each node makes its decision independently, based on the situation in the deployment region, and its knowledge about the network. In the case of networks comprising several hundreds or thousands of nodes, it is necessary to choose an architecture and technology which will enable relatively cheap production of individual devices. For this reason, WSNs need some special treatment as they have unavoidable limitations, for example, limited amount of power at their disposal. Each battery powered device, participating in WSN needs to manage its power in order to perform its duties as long, and as effective as possible. Wireless sensors are thus characterized by low processing speed, limited memory and communication range.

Wireless sensor networks [1]–[3] can be used in different environments and situations and perform tasks of different kinds. Their application will condition the network topology and the choice of technology for its production. The network protocols used in the case of networks whose operating range covers a single building will differ from those operating within large space areas. The construction of a network capable of performing its task requires obtaining information on the devices (nodes) it comprises. The crucial data is the following: geographical location of network nodes, admissible power of radio transmitter and options for control of signal power, estimated number of network nodes, number of nodes that can be lost before the network is declared non-operational, assumed network functionality (maximization of nodes operational time, maximization of throughput, etc.).

In our paper we discuss the approaches to design the optimal w.r.t. minimal energy consumption WSN topologies. The short description of communication methods, energy conservation techniques (power save protocols) and algorithms for computing the optimal transmitting ranges in order to generate a network with desired properties while reducing sensors energy consumption (topology control protocols) is provided. Power save protocols attempt to save nodes energy by putting its radio transceiver in the sleep state. Topology control protocols are responsible for providing the routing protocols with the list of the nodes' neighbors, and making decisions about the ranges of transmission power utilized in each transmission. We analyze the properties of two location based distributed topology control protocols, and report the results of simulation experiments covering a wide range of network system configurations. Finally, we discuss the idea of our novel location based power save scheme utilizing hierarchical structure with periodic coordination of network nodes activity.

2. Communication Methods

Communication protocols used in modern wireless networks like IEEE 802.11 or Bluetooth (IEEE 802.15.1) enable ad hoc mode operation. However, for the protocols to operate in this mode in practice, several basic issues must be solved [2]–[4]. The most important ones are:

- **Limited resources**. Nodes comprised by the network are often small battery-fed devices, which means their power source is limited. The network's throughput is also limited.

- **Poor quality of connection**. The quality of wireless transmission depends on numerous external factors, like weather conditions or landform features. Part of those factors change with time.

- **Small communication range**.

Small communication range in WSN networks results in communication limitations. Each node communicates only with the nodes present in its closest vicinity – the neighbors. For this reason, the natural communication method in wireless sensor networks is the multihop routing. When using multihop routing, it is assumed that the receiving node is located outside the transmitter's range. Contrary to single-hop networks, the transmitter must transmit data to the receiver by means of intermediate nodes. This is a certain limitation that hinders the implementation of routing algorithms but enables the construction of network of greater capacity. Multihop network enables simultaneous transmission via many independent routes. Independence of routes reduces the interference between individual nodes, which additionally enhances the wireless transmission speed in comparison to single-hop networks, where devices share a common space.
Individual WSN network node can collect data recorded by sensors but do not have enough power to process it. Moreover, analyzes require collection of information from many points. Therefore, efficient inter-node communication is necessary in order to transfer data to the base station.

3. Topology Control

Transmission of data package between two network nodes x_i and x_j requires power proportional to d_{ij}^2, where d_{ij} denotes the Euclidean distance between sender and receiver. Lets assume that instead of performing direct transmission, a relay node x_k is used. In such case two transmissions need to be performed: from a source node x_i to a relay node x_k (distance d_{ik}) and from the node x_k to the destination node x_j (distance d_{kj}). Lets consider a triangle $x_i x_k x_j$, also let α be an angle at vertex x_k. By elementary geometry we have:

$$d_{ij}^2 = {d_{ik}}^2 + {d_{kj}}^2 - 2 d_{ik} d_{kj} \cos\alpha, \tag{1}$$

when $\cos\alpha \leq 0$, total amount of energy spent to transmit a data package is smaller when a relay node is used.

Generally, short transmissions in the network are desired. They involve smaller power consumption and cause less interference in a network, simultaneously effected, transmissions, thus increasing the network throughput. In general, the goal of topology control (TC) [3] is to identify the situation when the using of the relay node is more energy-efficient than direct transmission and create the network topology accordingly. Topology control assumes that the nodes have impact on the power used to transmit a message. The basic task of TC algorithm consists in attributing the level of power used to send messages to every node in order to minimize the amount of power received from the power source, while at the same time maintaining the coherence of the network.

3.1. Topology Control Protocols

Topology control protocols are responsible for providing the routing protocols with the list of nodes' neighbors, and making decisions about the ranges of transmission power utilized in each transmission. The open systems interconnection (OSI) network model assumes that routing task is dealt with the network layer. On the other hand all functions and procedures required to send data through the network are stored in the OSI data link layer. Therefore the topology control layer is placed partially in the OSI network layer and the OSI data link layer, as presented in Fig. 1.

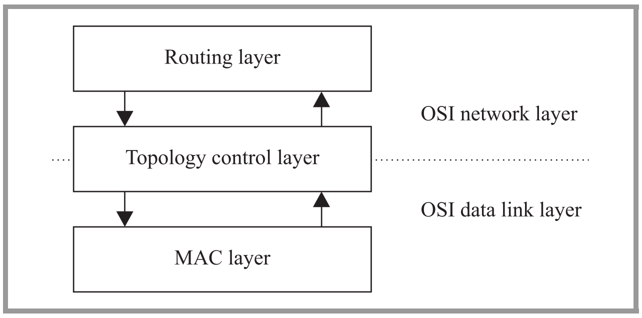

Fig. 1. Placement of topology control layer in the OSI stack.

Topology control protocols may utilize various information about a network, nodes localization and resources [3]–[5]. We can divide these protocols into several groups.

- **Homogeneous topology control protocols** assume that each node uses the same value of transmission power, which reduces the problem to simpler task of finding the minimal level of transmit power such that certain network property is achieved.

- **Location based topology control protocols** utilize the information about geographical location of nodes in the deployment area.

- **Neighbor based topology control protocols** assume that no information about location of nodes is available but each node can determine set of its neighbors and build an order on this set. Order may be based on round trip time, link quality or signal strength.

3.2. Location Based Protocols

We implemented and tested two location based protocols: R&M developed by Rodoplu and Meng, described in [6] and LMST (local minimum spanning tree) proposed by Li, Wang and Song in [7]. The short description of these techniques is provided.

The R&M and LMST protocols. Let N be a set of n wireless nodes deployed in the certain region and forming WSN. Assuming that R_i denotes the maximal transmission range assigned to ith node we can generate the communication graph $G = (N,E)$ induced by R on a given WSN. The E denotes a set of directed edges, and the directed edge $[x_i,x_j]$ exists if x_i and x_j are neighbors, i.e., $d_{ij} \leq R_i$, where d_{ij} denotes the Euclidean distance between sender and receiver. The communication graph G obtained when all the nodes transmit at maximum power is called *maxpower graph*.
Let us consider the situation when all nodes transmit the collected data to one (or more) master node(s) x_m – a base station(s). We can formulate the minimum energy all-to-one communication problem of calculating the optimal reverse spanning tree T of maxpower graph G rooted at x_m:

$$\min_{T} \sum_{x_i \in N, i \neq m} C(x_i, Pred_T(x_i)), \qquad (2)$$

where $Pred_T(x_i)$ denotes the predecessor of ith node in the spanning tree T and $C(\cdot)$ the energy cost of transmission from x_i to its predecessor.
The R&M protocol calculates the most energy-efficient path from any node to the master node. It is composed of two phases.

- **Phase 1**. The goal is to compute the enclosure graph of all nodes in WSN. Each node sends a broadcast message, at maximum power, containing its ID and location information. As such message is received by x_i from any neighbor node, x_i identifies the set of nodes locations for which communicating through relay node is more energy efficient than direct communication (the relay region of x_i). Next, x_i checks if the newly found node is in the relay region of any previously found neighbors. A node is marked *dead* if it lays in the relay region of any neighbor of x_i, and *alive* otherwise. After receiving broadcast messages from all neighbors, the set of nodes marked with *alive* identifier creates the enclosure graph of x_i.

- **Phase 2**. In the second phase the optimal, i.e., minimum-energy reverse spanning tree rooted at the master node is computed. The Bellman-Ford algorithm [8] for shortest path calculation is used on the enclosure graph that was determined in the phase 1. Each node computes the minimal cost, i.e., minimal energy to reach the master node given the cost of its neighbors, and broadcasts the message with this value at its maximum power. The operation is repeated every time a message with a new cost is received. After all nodes determine the minimum energy neighbor link, the optimal topology is computed.

The second considered protocol LMST can be used to WSN with nodes equipped with transceivers with the same maximum power. LMST operates in three phases.

- **Phase 1**. Each node sends a broadcast message, at maximum transmit power, containing its ID and location information to its one hop neighbor in the maxpower graph.

- **Phase 2**. The topology is generated. Each node determines a set of its neighbors, calculates Euclidean distance to every neighbor, and finally creates a minimum spanning tree based on its neighbors and computed distances (edge weights in the MST). Final network topology is derived from local MST created by all nodes. Neighbor set of each node consists of nodes, which are its direct neighbors in its local MST. Unfortunately, created topology may contain unidirectional links. Two approaches are proposed to solve this problem: it is assumed that all of them are bidirectional links or all unidirectional links are removed.

- **Phase 3**. Transmission power required to reach every neighbor in a given topology is calculated based on the broadcast messages transmitted in the first phase. Based on the measurements of power of the broadcast messages and knowledge about power level used when transmitting the message, it is possible to compute power level needed to reach the target neighbor.

Simulation results. The performance of R&M and LMST in terms of energy conservation was investigated through simulation. We carried out a set of experiments for various wireless sensor network topologies. It was assumed that all data collected in sensors were transmitted to one base station. We compared the results obtained using both algorithms with those when energy consumption was not considered while routing calculation. The key metric for evaluating the listed methods was the energy consumption used for data transmission. All experiments were conducted using the popular software for network simulation – ns-2 [9]. We implemented R&M and LMST protocols based on modules provided in ns-2 library of classes. The sensor networks with 50 – 300 nodes simulating the commercially available MICA2 sensors [10] with randomly generated positions in a square regions 400×400 to 3000×3000 were considered in our experiments. The technical parameters of sensors were taken from [11], i.e., the radio power consumption for transmission was from 8.6 mA (RF transmission power -20 dBm) to 25.4 mA (RF transmission power 5 dBm), the initial energy resource of each node was assumed to be equal to 21 kJ.

The objective of the first series of simulations was to compare the topologies calculated using described algorithms. The results are presented in Figs. 2 – 4. The base station is marked with the bold dot in presented figures. Figures 3 and 4 show the topologies formed using the LMST and R&M protocols. The obtained results can be compared with the topology generated without utilizing any TC algorithm (Fig. 2).

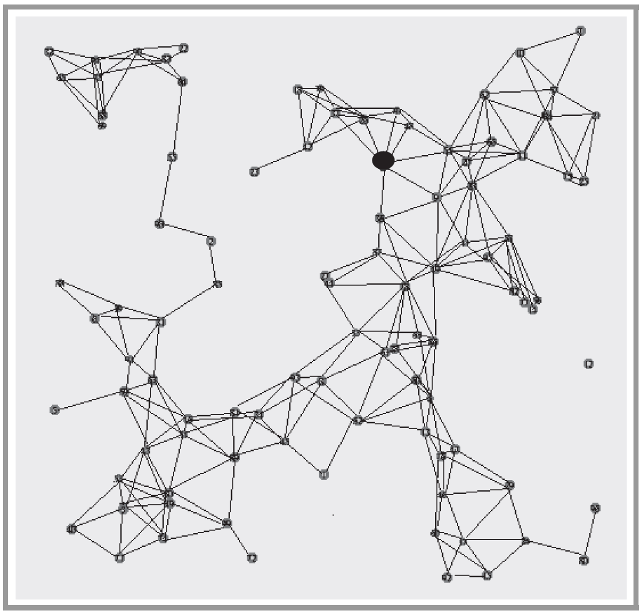

Fig. 2. Topology calculated without TC protocols.

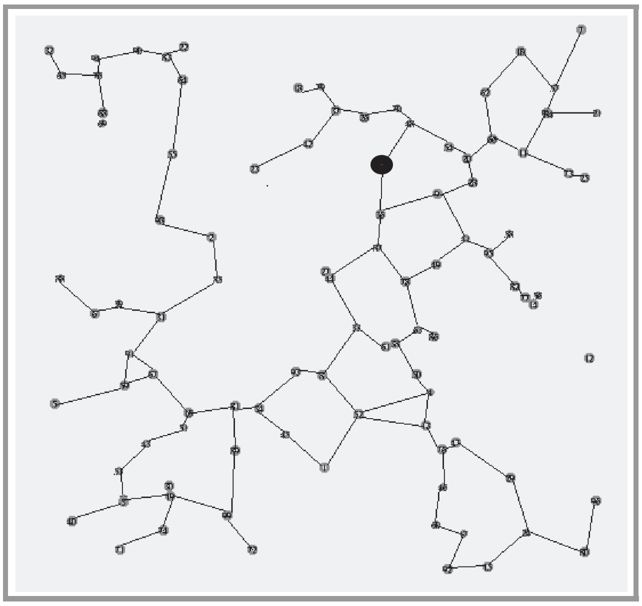

Fig. 3. Topology calculated using LMST method.

The second case study was related to simulation of data transmission in WSNs. Different sizes of networks were examined. In this experiment it was assumed that each node in WSN generates a single message that has to be delivered

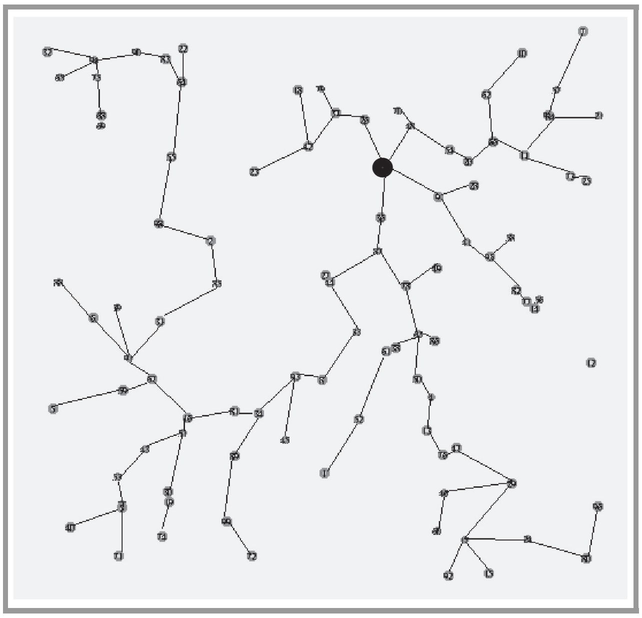

Fig. 4. Topology calculated using R&M method.

to the base station. In addition all nodes could play the role of relay nodes. The shortest path from each node to the destination was calculated taking into account topologies generated using R&M and two versions of LMST: LMST0 (topology can contain unidirectional links), LMST1 (topology contains only bidirectional links). The total energy consumed by all nodes for data transmission was divided by the number of nodes.

Figure 5 depicts the results of calculations, i.e., the average energy used by one node in WSN for data transmission.

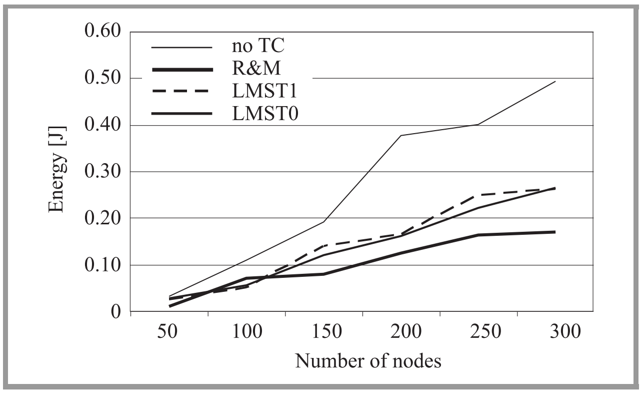

Fig. 5. Average energy consumption by one node for single transmission to the base station; different TC methods and network size.

Figures 6 and 7 show the average amount of energy used by one node for data transmission in case of different TC protocols, number of relay nodes transmitting to the base station and distance to the base station. WSN with 150 nodes was considered. It can be observed that in case of R&M and LMST protocols the energy usage for transmission in the whole network decreases while increasing the number

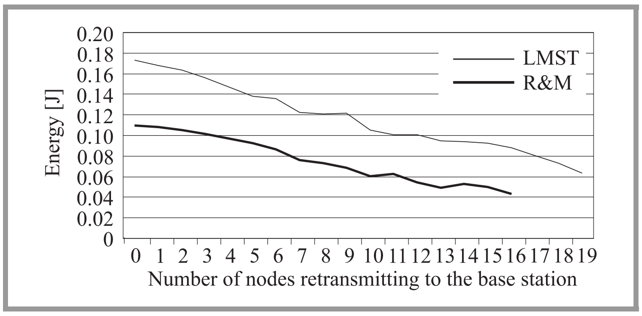

Fig. 6. Average energy usage for transmission w.r.t. the number of relay nodes; different TC methods.

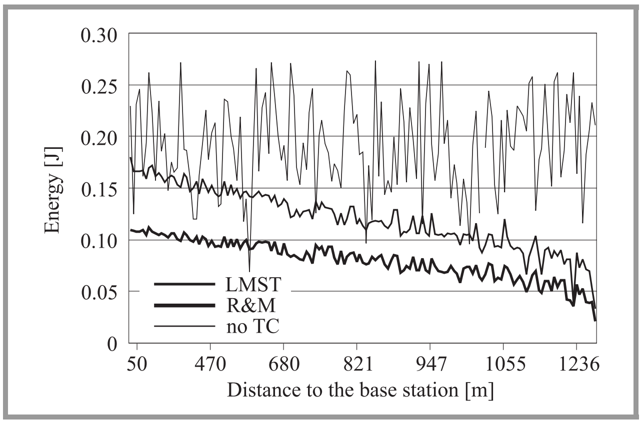

Fig. 7. Average energy usage for transmission w.r.t. the distance to the base station; different TC methods.

of relay nodes transmitting to the base station. It is obvious that the energy used for data transmission by nodes located far from the base station is smaller than those used by nodes closed to the master node, which have to retransmit a lot of messages (Fig. 7).

Table 1 contains the average number of messages generated by one node in WSN that can be transmitted to the base station up to its batteries are dead. The results obtained for different networks and topologies are compared.

Table 1
Average number of messages transmitted by one node to the base station

TC methods	Network size			
	150	200	250	300
Without TC	109 950	55 633	52 380	42 543
R&M	261 241	167 177	127 328	123 549
LMST0	173 893	130 485	94 130	78 850
LMST1	150 233	126 389	84 181	80 001

Discussion. The R&M and LMST protocols can be successfully used to calculate optimal topology in many WSN application scenarios. Both methods have to spent some energy to build the topology, which is concerned with beacon messages broadcasting in the first phase of their operation. However, the energy consumption for topology generation is small, i.e., LMST – 0.0011 J and R&M – 0.052 J for WSN of 50 nodes and energy resource of each node equal 21 kJ. Both protocols generate energy-efficient topologies (see Fig. 5). The energy consumption for data transmission in case of small size of the network (less than 150 nodes) is similar, while using topologies formed by R&M and LMST. In case of large size networks the R&M protocol seems to be much more efficient.

In summary, both techniques generate different topologies and have some advantages and drawbacks. In case of R&M we obtain more energy-efficient topologies but two potential drawbacks of the algorithm can be observed. The computation performed in the second phase of R&M requires the exchange of global information, which induces message overhead, and the explicit radio propagation model is used to compute the optimal topology. Hence, the calculated topology strongly depends on the accuracy of the channel model. Data transmission while applying the LMST protocol is more energy-intensive, but created topology is more robust and preserves connectivity in the worst case. In addition, it can be computed in a fully distributed fashion.

4. Energy Conservation

4.1. Power Consumption

The handling of the wireless transceiver contributes significantly to the node's overall energy consumption. Depending on the state of the transceiver, different levels of power consumption are being observed. Table 2 summarizes the sample power consumption of some 802.11 wireless interfaces.

In order to extend the working time of individual devices, it is frequent practice that some node elements are deactivated, including the radio transceiver. They remain inactive for most time and are activated only to transmit or receive messages from other nodes. Radio transceiver in WSN network node can operate in one out of four modes, which differ in the consumption of power necessary for proper operation: transmission – signal is transmitted to other nodes (greatest power consumption), receiving – message from other node is received (medium power consumption), stand-by (idle) – transceiver inactive, turned on and ready to change to data transmission or receiving (low power consumption), sleep – radio transceiver off.

Table 2
Aspiration and reservation levels

Interface	Power consumption [W]			
	transmit	receive	idle	sleep
Aironet PC4800	1.4–1.9	1.3–1.4	1.34	0.075
Lucent Bronze	1.3	0.97	0.84	0.066
Lucent Silver	1.3	0.90	0.74	0.048
Cabletron Romabout	1.4	1.0	0.83	0.13
Lucent WaveLAN	3.10	1.52	1.5	–

4.2. Power Save Protocols

The power-saving protocols used in sensor networks impose reduced consumption by putting the radio transceiver into the sleep mode. The use of such protocols involves the limitation of accessible band, and can also interrupt the data transfer in the network. Adequate choice of radio transceiver's switch-off time introduces further difficulty in the implementation of network protocols. The literature (e.g., [3]) present algorithms designed to limit the power consumption while simultaneously minimizing the negative impact on the network throughput and on the efficiency of data transmission routing. Different types of protocols are used depending on the application of the network. Two categories can be distinguished.

- **Synchronous power save protocols**, where it is assumed that nodes periodically wake up to exchange data packets. The sleep cycles of all nodes are globally synchronized. The main issue is to adjust length of sleep and wake phases that will minimize energy consumption and impact on a given network's throughput.
- **Topology based power save protocols**, where a subset of nodes which topologically covers whole network is selected. Nodes belonging to this set are not allowed to operate in the sleep mode. Other nodes are required to be periodically awake in order to receive incoming traffic.

Power save protocols should be capable of buffering traffic destined to the sleeping nodes and forwarding data in partial network defined by the covering set. The covering set membership needs to be rotated between all nodes in the network in order to maximize the life time of the network.

It was observed that grouping sensor nodes into clusters can reduce the overall energy usage in a network. Clustering based algorithms seems to be the most efficient routing protocols for wireless sensor network. Abbasi and Younis in the paper [12] present a taxonomy and general classification of clustering schemes. The survey of energy-efficient clustering based protocols can be found in [13]–[16].

We developed a new clustering based power save protocol that utilizes the periodical coordination mechanism to reduce the energy consumption of a network. The proposed algorithm is an extension of the popular geographic adaptive fidelity (GAF) protocol.

The GAF protocol. The GAF protocol described in [17] is a power save protocol that utilizes the information about the geographical location of the nodes. It relies heavily on the concept of *node equivalence*. The nodes A and B are *equivalent* with regard of data transmission between nodes C and D if and only if it is possible to use either node A or node B as a relay for the transmission between nodes C and D. The *node equivalence* is a feature that is not easily discovered. It is easy to notice, that nodes A and B, *equivalent* with regard of data transmission between nodes C and D do not have to be *equivalent* with regard of transmission between nodes D and E.

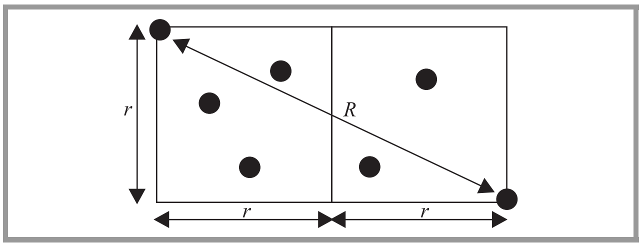

Fig. 8. Network grid construction for GAF protocol.

In order to solve this problem, the GAF protocol partitions the network using a geographic grid. The grid size *r* is defined such that each node in one grid square is in transmission range of all nodes within adjacent grid squares. The sample construction of such a grid is depicted in Fig. 8. With elementary geometry we have grid size of $R/\sqrt{5}$, where *R* denotes the maximal transmission range assigned to each node. The construction of such a grid allows the GAF protocol to preserve the original network connectivity.

The sole concept of the GAF protocol is to maintain only one node with its radio transceiver turned on per grid square. Such a node is called an *active* node and is responsible for relaying all the network traffic on behalf of its grid square. When there are more nodes in a grid square, the function of an *active* node is rotated between all the nodes in a grid square. The full graph of state transitions in the GAF algorithm is depicted in Fig. 9.

Each node starts operation in the *discovery* mode, meaning the node has its radio transceiver turned on and is pending to switch to *active* state. The node spends a fixed amount of time T_D in discovery state, when the time has passed, the node switches to the *active* state. After spending a fixed amount of time T_A in *active* state, the node switches back to the discovery state. Whenever a node changes state to *discovery* or *active*, it sends a broadcast message containing node ID, grid ID and the value of a *ranking function*. If a node in *discovery* or *active* state receives a message from a node in the same grid and a higher value of the ranking function, it is allowed to change its state to *sleep* and turn its radio transceiver off for T_S. The ranking function and timers T_D, T_A, T_S can be used to tune the algorithm. Usually the ranking function selects nodes with "longest ex-

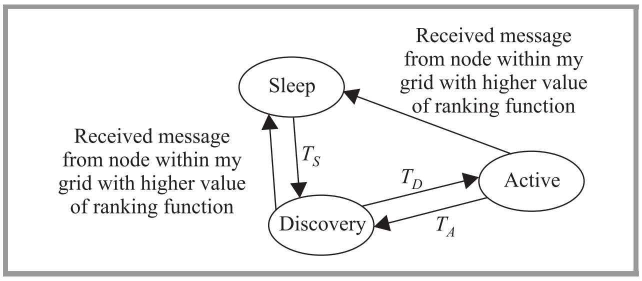

Fig. 9. State transitions in GAF protocol.

pected life time" as the active nodes. The GAF protocol can be easily adapted to mobility scenarios, in such a case the ranking function utilizes information about the time, when a node will leave the grid square.

The coordination-based power save protocol (CPSP). The typical wireless sensor network consists of large quantity of sensor nodes and a base station – a dedicated node which serves as a destination for messages generated by the sensor nodes. The base station is responsible for relaying information gathered by the network to the network operator. It can be assumed that the base station has significantly more resources than the sensor nodes and is directly connected to the power grid. The wireless sensor network is utilized to deliver messages generated by the sensor nodes to the base station. From the operator's point of view there is no difference between not having any nodes in the network and the nodes not being able to deliver their messages to the base station.

We propose to utilize the dedicated network node (or nodes) as a network coordinator (or coordinators) in order to ensure that the base station is able to receive messages from the network nodes for as long period of time as possible. The base station is a natural candidate to play a role of the coordinator. Our protocol assumes that the network is partitioned by a geographical grid in the same manner as in the GAF protocol. In addition we assume that not every network grid needs to maintain an active node. The cells that do not need to establish an active node are determined by the coordinator. The grids that must maintain an active node operate similarly to the grids in the GAF protocol. In remaining grids all nodes are put to sleep state until the next topology update.

The coordinator views the network grids as a graph. The nodes periodically send to the coordinator information about amount of power available to them, which enables the coordinator to assign weights to the edges in the graph. Periodically, the coordinator calculates minimum spanning tree on the graph with itself as the root of the tree. The leaves of the tree are network grids that do not need to maintain an active node. The structure of spanning tree was chosen in order to preserve the original network connectivity. The calculated network topology is sent to all network nodes using a dedicated broadcast algorithm.

The CPSP broadcast algorithm. The CPSP broadcast algorithm relies heavily on the structure of the network and the information it is supposed to deliver to all network nodes. In order to perform the broadcast transmission, extended GAF discovery messages are utilized. Each discovery message contains the sequence number of latest transmitted network map. Since each network grid is able to receive discovery messages originating from neighboring grids, it is able to determine whether it is necessary to broadcast the latest received packet. If the grid determines that the neighboring grid has newer information, it sends a discovery message for neighboring grids to hear it. The size of broadcasted messages is kept as small as possible, information which cells should maintain an active node is sent as a bitmap – one bit represents one network grid.

Simulation results. The coordinated power save protocol was implemented in the environment of the ns-2 network simulator [9]. The proposed protocol was compared with the plain GAF protocol and a network with no power save capabilities at all. Figure 10 shows the performance of examined algorithms on a network with 60 stationary nodes distributed uniformly over a 800 x 800 meter region. Figure 11 presents the performance of the proposed broadcast algorithm against the plain GAF protocol.

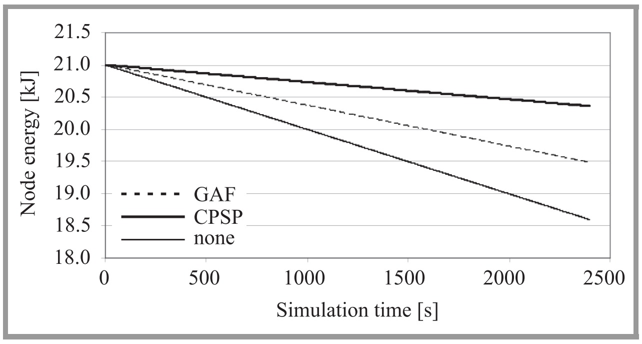

Fig. 10. Average energy consumption, various power save methods.

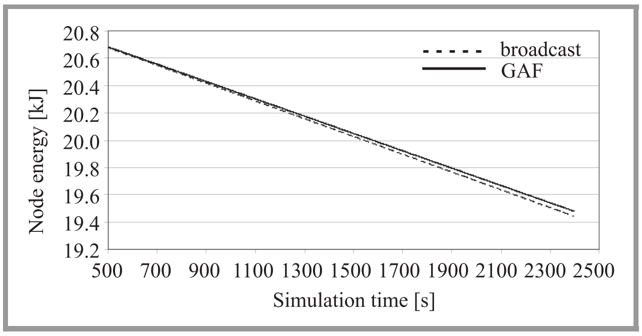

Fig. 11. Average energy consumption; CPSP broadcast and GAF comparison.

The initial energy resource of each node was assumed to be 21 kJ. Additionally it was assumed that the nodes utilize standard 802.11 radio transceiver. The traffic scheme utilized during simulation assumed random nodes sending messages to the base station at random moments of time. The messages sent to the base station were batches of 512 byte packets. The map of the network and the traffic scheme were generated using standard utilities shipped with the ns-2 network simulator.

The metric for evaluating the GAF and CPSP methods was the average amount of energy left in the node during the time of simulation. Although the main objective of CPSP algorithm is to optimize the lifetime of the network and the utilized metric does not directly show the performance of protocols in that area, it was chosen in order to be able to compare the proposed CPSP protocol with other power save solutions.

Discussion. The proposed coordinated power save protocol in its current state allows greater average energy savings than plain GAF protocol. The amount of energy saved is greater than in the GAF protocol due to larger number of sleeping nodes. The use of CPSP protocol introduces a slight overhead caused by the necessity of transmitting messages containing current statuses of nodes to the coordinator and broadcasting coordinator decisions to all nodes in the network. The proposed mechanism can be easily adapted to introduce a coordinator in a wireless sensor networks for other purposes than power saving.

5. Summary and Conclusions

The paper provides the short overview of the energy conservation techniques and algorithms for calculating energy-efficient topologies for WSNs. The efficiency of four location based approaches, i.e., two schemes for topology control and two power save algorithms are discussed based on the results of simulation experiments. The energy efficient method of introducing a coordinator to a WSN is presented. We show that our algorithm outperforms the results obtained for popular clustering based power save protocol GAF.

In general, the simulation results presented in the paper show that topology control and power save protocols effect the scheduling transmissions in a wireless sensor network, and confirm that all discussed approaches to reduce the energy consumption improve the performance of this type of network.

Acknowledgement

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