Testbed Implementation of Energy Aware Wireless Sensor Network

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Abstract: Wireless sensor networks (WSNs) are autonomous ad hoc networks designed and developed for potential applications in monitoring, surveillance, security, etc. The sensor devices that are battery powered should have lifetime of months or years. Therefore, energy efficiency is a crucial design challenge in WSN. In this paper the energy efficient communication techniques, i.e., activity control and power control protocols are presented and discussed. We focus on the implementation of energy aware algorithm for WSN – Geographical Adaptive Fidelity (GAF) – in our testbed network formed by the Maxfor devices. The results of experiments confirm significant energy savings that lead to network lifetime increase.

Keywords: wireless sensor networks; WSN; energy aware communication; activity protocols; power control protocols

I. Introduction to WSN

The last decade has seen tremendous interest in all aspects of wireless sensor networks (WSNs) – distributed systems composed of numerous smart, embedded and inexpensive sensor devices deployed densely in a sensing area [1], [2], [15]. The nodes of a network equipped with CPU, battery, sensing units and radio transceiver, networked through wireless links can be used in applications, in which traditional networks are inadequate. The important property of WSN is the ability to operate in harsh and hostile environments, in which human monitoring is risky, and often impossible. The lack of fixed network infrastructure components allows creating unique topologies and enables the dynamic adjustment of individual nodes to the current network structure in order to execute assigned tasks. Wireless sensor networks are deployed in various environments and are used in large number of practical applications concerned with monitoring, rescue missions and military actions. Ad hoc architecture of WSN has many benefits, however its flexibility come at a price. A number of complexities and design constraints are concerned with the characteristics of wireless communication,
i.e., limited transmission range and throughput, limited QoS, limited resources, and multihop nature of a network. Moreover, the quality of wireless transmission depends on numerous external factors, like weather conditions or landform features. Most of these factors can change in time.

For these reasons, WSNs need some special treatment. The most important constraint is concerned with limited power source. Nodes forming the network are often small battery-fed devices. Each device, participating in WSN needs to manage its power in order to perform duties as long and as effective as possible. Moreover, devices are often deployed in remote locations where replacing batteries is difficult or even impossible, and usually a high disparity between expected and real power drawn can be observed. Thus, power management is very important. A numerous energy aware communication methods and strategies have been developed, and are presented in literature [2], [12], [14]. In general, power management is a topic that has been a subject of intensive research in ad hoc networking in recent years.

In this paper we discuss the approaches to design energy aware WSN topologies. The main contribution of our work is to show the benefits of application of the energy aware communication protocol in real network system. We have implemented and verified the modified version of commonly known protocol GAF in our testbed network formed by the Maxfor devices. The results of tests in our laboratory were compared with simulation results presented by Xu et al. in [16]. In section II, we describe the energy consumption characteristics in WSN. In section III, we investigate some energy aware methods and algorithms, in section IV, the GAF protocol is described. The results of the performance evaluation of GAF through testbed implementation are presented and discussed in section V.

II. Energy Consumption in WSN

A lifetime of WSN is measured by the time interval before all devices have been drained out of their battery power or WSN is unserviceable – no longer provides an acceptable event detection ratio. To maximize the lifetime, all aspects such as architecture, circuits and communication protocols must be made energy efficient. Let us focus on the energy consumption characteristics of a sensor device (WSN node). Three main components that consume the energy are: microprocessor, sensing circuit and radio transceiver.

The energy consumed by microprocessor is determined by the sum of dynamic $P_d$ and static $P_s$ power, i.e., $P = P_d + P_s$. Many techniques have been developed to minimize the energy consumption, such as: dynamic voltage scaling, modulation scaling, and energy aware embedded, event driven operating systems.

The objective of a sensing unit is to translate physical measurements to electrical signals. Several sources of energy consumption can be listed: signal sampling, conversion of physical signals to electrical ones, analog to digital conversion, signal conditioning. The energy usage in this unit is relatively constant. In some applica-
tions the detectors can work in the event driven mode, and can be switched off for some time to save energy.

The communication system is the major energy consumer during wireless network operation. The radio transceiver unit can operate in one of four modes, which differ in the consumption of energy: transmission – signal is transmitted to other nodes (greatest power consumption), receiving – message from other nodes is received (medium power consumption), stand-by (idle) – inactive transceiver, turned on and ready to change to transmission or receiving mode (low power consumption) and sleep – transceiver is switched off. In order to extend the lifetime of a network, it is frequent practice that radio transceivers of some nodes are deactivated. The nodes remain inactive for most time and are activated only to transmit or receive messages from the network.

The energy consumption strongly depends on the transmission range and modulation parameters. Generally, short transmissions in a network are desired. They involve smaller power usage and cause less interference in a network, simultaneously effected transmissions, thus increasing the network throughput.

III. Energy aware communication

A. Methods and Algorithms

In this paper we focus on energy aware protocols for IEEE 802.15.4 (ZigBee) based networks. The protocol used by the node of WSN consists of the application, transport, network, data link and physical layers [1]. The energy management in WSN is emphasized in data link and network layers. The MAC protocol guarantees efficient access to the transmission media while carefully managing the energy allotted to the nodes. Typically, this objective is achieved by switching the radio to a low-power mode based on the current transmission schedule.

Energy efficiency is considered mostly by protocols provided by network layer. Energy aware routing ensures the survivability of low energy networks. In commonly used wireless senor networks it is assumed that the receiver is not located within the transmitter’s range. The transmitter must transmit data to the receiver by means of intermediate nodes. Thus, the natural communication method in WSNs is a multi-hop routing. This is a certain limitation, but on the other hand it enables the construction of network of greater capacity – a multi-hop network enables simultaneous transmission via many independent routes, and managing available energy. Moreover, each node of a network can attribute the level of power used to send a message to the other node in order to minimize the amount of energy received from the battery, while at the same time maintaining the coherence of the network. Due to a significant node redundancy (nodes are densely deployed), and the assumption that each node of WSN has impact on the power used to transmit a message numerous low energy consumption communication methods and
energy conservation techniques have been developed, and are described in literature. In general, two main approaches for power saving in WSN can be distinguished:

- power control protocols,
- activity control protocols.

**B. Power Control Protocols**

The popular approach to energy efficient communication is controlling a transmit power of each node in a network. In general, short transmissions involve smaller power consumption and cause less interference and latency. Power control protocols (PCs) 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. Therefore, the PC protocols are placed partially in the OSI network layer and the OSI data link layer [14]. A numerous PC protocols have been developed and are described in literature. They utilize various information about a network and network nodes, i.e., location of nodes and its neighbors or direction from which the signal was received. Based on these information power control techniques may be divided into following groups: location-based (nodes are able to determine their exact positions), direction-based (relay on the ability of all nodes to estimate relative directions of their neighbors) and neighbor-based (determine all neighbors within the maximal transmission range). The detailed survey of PC protocols can be found in [14]. The results of performance evaluation of selected techniques through simulation are presented in [12].

**C. Activity Control Protocols**

The other approach to energy efficient communication is controlling a number of active nodes in a network. Due to a significant node redundancy and multiple paths between nodes we can turn off selected intermediate nodes while still guarantee full connectivity and maximum link utilization constraints. Dynamic power management is an efficient approach to reduce system power consumption and extend the lifetime of individual node without significantly degrading the network performance. The basic idea is to deactivate the radio transceiver of selected nodes when not needed and wake them up when necessary. Hence, radio devices remain inactive for most working time and are activated only to transmit or receive messages from other nodes. In general, dynamic power management is a complex problem. It can involve the limitation of accessible band, and can also interrupt the data transfer in the network. Therefore, implementing the correct policy for radio switching and estimating the optimal value of radio transceiver’s switch-off time are critical for a network performance.

The activity control protocols (AC) employ dynamic management of radio devices. The objective is 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 AC protocols are presented in literature, and are applied to WSN systems. Similarly to PC protocols, they utilize various information about a network and network nodes, i.e., location of nodes in a network, nodes density, connectivity, etc. Many of them implement clustering techniques. It was observed that grouping nodes into clusters can reduce the overall energy usage in a network. Based on utilized information activity control techniques may be divided into several groups: location-based (GAF [16], GeRaF [6]), connectivity-based (Span [7]), clustering-based ([LEACH [9], HEED [17], PANEL [5], PRWST [3]) and hierarchical (EEHC [4], CGPS [12]).

It should be pointed that activity control protocols should be capable of buffering traffic destined to the sleeping nodes and forwarding data in the 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 lifetime of the network.

IV. GAF Algorithm

The Geographic Adaptive Fidelity (GAF) algorithm developed by Y. Xu et al., and described in [16] selects nodes responsible for relaying traffic in the network based on their geographical position estimated using the GPS system or calculated using any other location system [2], [11]. GAF assumes covering the network deployment area with a virtual grid. The location information is employed to form clusters.

The GAF protocol relies on the concept of “node equivalence”. Two nodes are equivalent when they are equally useful as relays in communication between other nodes. Problem of selecting equivalent nodes is nontrivial. It can be easily observed that network nodes equivalent in communication between a given pair of nodes do not have to be equivalent in communication between other pairs of nodes.

To select equivalent nodes GAF divides a spatial domain, where nodes are distributed into cells that form a grid, see Fig. 1. The size $d$ of each cell is calculated due to transmission ranges of nodes, i.e., $d \leq r / \sqrt{5}$, where $r$ denotes the maximal transmission range assigned to network nodes. It is assumed that each node in a cell is in transmission range of all other nodes within adjacent cell. The construction of such a grid allows to preserve the network connectivity. All nodes in a network may switch between one of three states: active, discovery and sleep. In the active state a node is responsible for relaying traffic on behalf of its cell. In the discovery state nodes exchange discovery messages, trying to detect other nodes with higher energy in the same cell. However, the overhead due to discovery messages is not very high. The following load balancing energy usage is proposed. After spending a fixed amount of time $T_A$ in the active state, a node switches to the discovery state, and another node from the same cell switches to the active state. After spending a fixed amount of time $T_D$ in the discovery state, the node backs to the active state.
Whenever a node changes the state, it sends a message containing its identifier (ID) and its ranking value (RV). The ranking value is used to select the relay node to transmission a message. Several rules are proposed to determine a node’s RV. In general, a node that is in the active state has a higher rank than a node in the discovery state, and nodes with longer expected lifetimes (calculated with respect to energy consumption characteristics) have higher rank than the others.

Nodes in the active and discovery states may switch to the sleep state whenever they find a node in the same cell with higher RV. When a node enters the sleep state, it cancels all pending timers, and powers down the radio. After spending the fixed amount of time \( T_S \) in the sleep state the node turns on its radio and switches to the discovery state. The sole concept of GAF is to maintain only one node with its radio transceiver turned on per cell, see Fig. 1. The mentioned parameters, i.e., \( T_A, T_D, T_S \), are used to tune the algorithm. In our improved version of GAF (GAF-M) the value of the interval \( T_D \) is estimated independently for each cell, and depends on the number of nodes that form a given cell. The bigger the number of nodes the shorter \( T_D \) time. Moreover, we prohibit switching between different states the nodes with very low battery level.

The GAF algorithm was designed for IEEE 802.11 networks. It can run over any routing protocol for ad hoc networks. Y. Xu et al., discuss the performance of GAF combined with two reactive routing protocols AODV (Ad-hoc On-Demand Distance Vector) [13] and DSR (Dynamic Source Routing) [10]. We adopted GAF to work in 802.15.4 networks. In our implementation we used DYMO (Dynamic Manet On-demand) [8] routing protocol that is a successor of AODV. DYMO shares many benefits of AODV but is slightly easier to implement. Y. Xu et al. claim that GAF provides longer lifetime of WSN with minimal loss in data delivery rates compared to pure AODV and DSR protocols. The simulation results presented in [16] confirm the good performance of the algorithm. It is worth to note that simulation results show that GAF extends the network lifetime proportionally to the increase of nodes density in the deployment area.
V. GAF Performance In Testbed Network

The main objective of our research was to implement and validate the GAF algorithm using testbed implementation in our laboratory formed by physical sensor devices.

A. Testbed WSN – Hardware and Software

The experiments in our WSN laboratory were performed using testbed implementation involving MTM-CM5000 motes (http://www.maxfor.co.kr/eng/en_sub5_1.html) manufactured by Maxfor (see Fig. 2).

![MTM-CM5000 mote](image)

Figure 2. The MTM-CM5000 mote

The MTM-CM5000 mote is IEEE 802.15.4 compliant wireless sensor node based on the original open-source “TelosB” platform design, developed and published by the University of California, Berkeley. The mote’s architecture is presented in Fig. 3 and the general specification is given in Table I.

![MTM-CM5000 mote architecture](image)

Figure 3. Architecture of the MTM-CM5000 mote

The testbed networks were formed by three to eleven MTM-CM5000 motes and one base station, all operating under TinyOS system. TinyOS (http://www.tinyos.net/)
is an open source, highly portable operating system that can be used to on-line operation of WSN formed of real low-power wireless devices. Our application was written in nesC (Network Embedded Systems C) language provided by TinyOS system. TYMO (http://tymo.sourceforge.net/) – the implementation of DYMO protocol on the TinyOS system was used to work with GAF. The preliminary version of our implementation was done in TOSSIM simulator, and next transformed into physical network. TOSSIM (http://docs.tinyos.net/tinywiki/index.php/TOSSIM) is a discrete-events simulator for TinyOS wireless sensor networks. By exploiting the sensor network domain and TinyOS’s design, TOSSIM can capture network behavior at a high fidelity while scaling to thousands of nodes. The same code can be used for simulation and real WSN operating in TinyOS.

<table>
<thead>
<tr>
<th>Processor</th>
<th>TI MSP430F1611</th>
</tr>
</thead>
<tbody>
<tr>
<td>RF chip</td>
<td>TI CC2420</td>
</tr>
<tr>
<td>RF power</td>
<td>–25 dBm–0 dBm</td>
</tr>
<tr>
<td>Power supply</td>
<td>2.1 V–3.6 V – (AA or AAA battery)</td>
</tr>
<tr>
<td>Antenna</td>
<td>Dipole antenna / PCB antenna</td>
</tr>
<tr>
<td>RF current draw</td>
<td>Receive mode: 18.8 mA</td>
</tr>
<tr>
<td></td>
<td>Transmit mode: 17.4 mA</td>
</tr>
<tr>
<td></td>
<td>Sleep mode: 1.0 μA</td>
</tr>
<tr>
<td>Range</td>
<td>~150 m (outdoor), 20–30 m (indoor)</td>
</tr>
<tr>
<td>Sensors</td>
<td>Light, humidity, temperature</td>
</tr>
</tbody>
</table>

### B. Results of Experiments

Multiple experiments were performed in our laboratory. The goal of the first series of experiments was to evaluate the performance of the GAF algorithm in a physical wireless network. The wireless sensor networks implementing GAF and DYMO protocols were compared with networks with no power capabilities at all (implementing pure DYMO). The key metric for evaluating examined networks was the lifetime of the network. To compare the performance of a given network we used the following characteristic:

\[
LTI = \frac{\text{Lifetime}_{GAF+DYMO}}{\text{Lifetime}_{DYMO}}
\]  

where \(\text{Lifetime}_{GAF+DYMO}\) denotes the lifetime of a network implementing GAF and DYMO protocols, and \(\text{Lifetime}_{DYMO}\) is the lifetime of a network using only DYMO.

The goal of the second series of experiments was to test the influence of the nodes density into a lifetime of a given network.

In this paper the results of experiments performed for nine network configurations, i.e., examples E1–E9 describing different model size and topology are
presented and discussed. The detailed description of examined networks is given in Table II. The variable $N_{\text{cells}}$ denotes the number of cells that form a grid covering a deployment area, and $S_{\text{cell}}$ the number of motes in each cell. Figures 4 and 5 show the exampled network configurations.

### Table II. Specification of Eight Testbed Networks

<table>
<thead>
<tr>
<th>Testbed Networks (examples)</th>
<th>E1</th>
<th>E2</th>
<th>E3</th>
<th>E4</th>
<th>E5</th>
<th>E6</th>
<th>E7</th>
<th>E8</th>
<th>E9</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N_{\text{cells}}$</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>$S_{\text{cell}}$</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>3</td>
</tr>
</tbody>
</table>

Figure 4. Network E4 formed by 7 motes (source, sink and one cell of 5 nodes)

Figure 5. Network E9 formed by 11 motes (source, sink and three cells of 3 nodes each)

During the tests, we calculated the lifetime of a network measured by the time interval before WSN was unserviceable (all motes in one cell were drained out of their battery power). The performance of examined algorithms GAF+DYMO and pure DYMO for networks E4 and E9 are presented in Fig. 6 and 7. The summary of results – extensions of network lifetimes using GAF and DYMO over pure DYMO for eight experiments is presented in Table III.
Figure 6. Extension of WSN lifetime using GAF; network E4

Figure 7. Extension of WSN lifetime using GAF; network E9

<table>
<thead>
<tr>
<th>Method</th>
<th>Testbed Networks (examples)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E1</td>
</tr>
<tr>
<td>DYMO</td>
<td>1</td>
</tr>
<tr>
<td>GAF+DYMO</td>
<td>1.78</td>
</tr>
</tbody>
</table>

The goal of the third series of experiments was to compare the performance of the original version of GAF with the modified version GAF-M implementing our scheme for $T_D$ time interval calculation. The performance of examined algorithms GAF-M and pure DYMO for network E4 is presented in Fig. 8.
The summary of results for this case study are presented in Table IV and Fig. 9. The modified GAF-M allows to extend the network lifetime up to 30%.

Table IV. Summary of Results (Values of LTI For 5 Testbed Networks)

<table>
<thead>
<tr>
<th>Method</th>
<th>Testbed Networks (examples)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E1</td>
</tr>
<tr>
<td>DYMO</td>
<td>1</td>
</tr>
<tr>
<td>GAF+DYMO</td>
<td>1.78</td>
</tr>
<tr>
<td>GAF-M + DYMO</td>
<td>1.93</td>
</tr>
</tbody>
</table>

Figure 9. Sensitivity to network density
The results of experiments confirm the strength of the GAF algorithm. GAF provides longer lifetime compared to pure DYMO routing protocol. The results of tests performed in our testbed networks formed by the physical devices were not worse than simulation results described in [16]. We can even say that the combination of GAF and DYMO provides better results than the application that combines GAF and AODV. Similarly to the conclusions presented in [16], we could observe that GAF extends the network lifetime proportionally to the increase of nodes density in the deployment area. Tables III and IV, and Fig. 9 show that time of accurate network operation strongly depends on the number of nodes that form each cell of a grid covering the deployment region. Moreover, our modifications of GAF improve the performance of the algorithm that leads to network lifetime increase.

VI. Summary

Many challenges arise from ad hoc networking and development of real life wireless sensor systems. In this paper we focused on energy aware networks. We described a functionality of the popular activity control protocol GAF for power saving in WSNs, and our testbed implementation that combines GAF and routing protocol DYMO. We evaluated the performance of our application in the laboratory, and improved the algorithm performance w.r.t. original version. The results of experiments confirm good performance of GAF in real life networks. In our future work we plan to make experiments with higher dimension networks and compare GAF with other activity control protocols described in literature.

As a final observation we can say that the design of wireless sensor networks should account for trade-offs between several attributes such energy consumption (due to mobility, sensing, and communication), reliability, fault-tolerance, data collection latency, and quality of information, and their impact on mission objectives. Therefore, strategies and techniques for energy efficient, reliable and secure communication in wireless sensor network has become a hot debate nowadays.

Acknowledgment

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