Simulating Energy Efficiency of Routing and Link-Layer Protocols in Wireless Sensor Networks

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Abstract. One of the most important characteristics of Wireless Sensor Networks is energy efficiency. Exhausted batteries cannot be easily replaced and cause connectivity problems and reduced network life. Therefore it is crucial to develop methods to reduce energy usage in those networks. In this work some methods in the MAC layer and network layer were tested in simulations for energy efficiency. The best combinations of methods were used in real implementation for confirmation.

Keywords: Wireless Sensor Networks, lifetime, protocols, simulations, MAC, T-MAC, SEER, BEAR, HEED.

1 Introduction

Energy efficiency is a hot topic in wireless sensor network research since battery power is often the most crucial resource. Battery capacity is limited, recharging is difficult and often impractical while renewable energy sources are still too expensive, or too large [1]. Increasing the total amount of power available for node is hard to achieve, therefore, there is a constant strive for algorithms and methods that improve energy efficiency and extend network operation. A number of papers focus on radio communication as this is the most expensive operation (in terms of energy).

Energy efficiency can be achieved through technology improvements and improved network organisation. Technology improvements include development of more efficient radio transceivers (e.g. better power amplifiers, low noise amplifiers) or hybrid transceivers, where simple and low power radio is used just to wake-up and power-up standard transceiver capable to transmit data packets [2]. Organization methods include efficient MAC protocols, network structure and management [3], data aggregation or duty-cycling [4]. All methods aim to reduce the time nodes spend with radio transceiver enabled waiting for incoming communication (idle-listening) and reduce the number of transmissions. Time synchronisation between nodes simplifies implementation and allows to awake nodes periodically and simultaneously thus evading the need for long idle-listening.

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Although a number of solutions has been proposed, there is no comprehensive analysis of how different methods fit together and influence the energy efficiency of WSNs. This paper analyses 3 different MAC protocols and 5 routing protocols to verify which of them allows for the best improvement. [4–8].

This paper presents results of experiments conducted in WSN simulator OMNeT++ and real WSN network setups deployed in our laboratory. The aim of the experiments was to analyse energy efficiency and quantitatively compare different MAC protocols and routing algorithms. Quantitative comparison is based on two parameters: network lifetime and distribution of residual power among network nodes, when network operation ends.

Many definitions of network lifetime are used across different papers on WSNs. We assume that network lifetime is a time from network initialisation until the first node in the network depletes its battery. This definition is very restrictive but simultaneously it is topology- and routing-agnostic, easy to verify and can be seen as the worst case scenario for the network. Consequently, it allows to compare various MAC and routing algorithms and provide information on how they allow to improve minimal operation time of the WSN network.

Analysing residual power and its distribution among network nodes also provides interesting information about energy efficiency and algorithms used. It shows that maximising network lifetime is not about limiting power consumed by every node but limiting the power consumed by the node with the smallest amount of remaining power. Ideally, nodes having little power should be relieved and their tasks should be taken over by other nodes. Network lifetime can be therefore extended if power consumption is evenly distributed among all the nodes [9].

Simultaneous analysis of both MAC and routing methods is crucial as neither of them itself can improve both lifetime and energy distribution. MAC protocols deal only with peer-to-peer communication and are network agnostic, consequently cannot optimise network-wide parameters (even energy distribution). Routing algorithms can support even distribution of load (power costs) among the network nodes, but power costs incurred on transmission and reception are mostly defined by the MAC layer. Additionally, proper routing facilitates data aggregation and reduces the number of transmissions.

Our simulation results were compared with real case deployment in research greenhouse owned by Wrocław University of Environmental and Life Sciences.

2 MAC and Routing Algorithms

2.1 MAC Algorithms

A typical approach for MAC algorithms in radio networks with multiple access is to use channel sense multiple access protocols with additional collision avoidance – CSMA/CA. In this technique each radio transmitter listens to the radio channel before it starts its own transmission. When channel is busy the node backs-off for a random time and retries. CSMA/CA is a technique defined in IEEE 802.15.4 standard and is used by all compatible radio transceivers.

One of the most popular MAC algorithms running on WSN nodes is Berkeley MAC protocol – B-MAC [4]. Detection of pending transmissions uses clear channel assessment that periodically samples the radio channel and measures the signal strength. Samples are stored in FIFO queue and used to calculate moving average that is then used to decide if the channel is busy or not. Simplicity and no need for time synchronisation are the biggest advantages of the B-MAC protocol, but collisions and jamming are still possible as only transmitter assesses the channel status (e.g. hidden terminal problem). The lack of time synchronisation also implies asynchronous communication. This means that all the nodes in the network need to stay in idle-listening mode burning power even if there are no transmissions. To minimise this drawback B-MAC puts nodes asleep and wakes them periodically. While asleep, radio transceiver is disabled thus saving the energy. However, due to lack of synchronisation, transmission starts with preamble that lasts longer than sleep time. This ensures that all nodes will wake up before the actual transmission starts – nodes keep the radio on when preamble is detected.

T-MAC protocol presented by Dam et al. [5] avoids collision by using time synchronisation between nodes and flow control signals (request to send – RTS, and clear to send – CTS). Time synchronisation limits channel capacity and requires additional management, but synchronised nodes do not waste time on idle-listening nor need to have long preambles before the actual transmission. In contrast to B-MAC, time of activity is not fixed. Instead, nodes are put asleep if there is no transmission for a predefined period of time.

2.2 Routing Algorithms

The most straightforward routing algorithm uses fixed routes that constitute a tree structure with base station in its root and nodes in branches and leaves. Consequently, each node has a single neighbouring node to which it transmits all the messages. Fixed routing is easy to establish but is more likely to cause uneven power consumption among network nodes.

A bit more complex algorithm (random routing) extends the fixed routing by establishing several routing trees. Each node in the network stores information about several neighbours that are closer to the base station. Upon message transmission node randomly selects a neighbour that it will send the message to. Random routing improves even power consumption among network nodes as network traffic is distributed among a number of routing paths and nodes.

Routing complexity is extended in Simple Energy Efficient Routing (SEER) algorithm [6]. In this protocol each node stores information about all neighbouring nodes together with their distances to the base station and remaining power. When routing path is selected a node selects its neighbour that is closer to the base station and has the largest remaining energy. If there is no such neighbour, then nodes that are at the same distance are analysed. SEER also implements a very simple method to minimise probability of routing loops but this does not ensure there are no loops in transmission. Information about residual power in nodes is updated periodically by broadcast messages or during periodic network reinitialisation.

Balanced Energy Aware Routing (BEAR) [7] extends previous routing by taking into account distance to the base station, residual power of each neighbour node and additionally, information about the neighbour's neighbours. This way the transmitting node can forecast two successive transmissions and select the node that is more likely to improve the resulting energy efficiency. Additionally, BEAR assumes that each node constantly sniffs the radio channel and overhears neighbouring communication. In this way nodes get information about residual power of neighbouring nodes that is piggybacked in data packets. This reduces the overhead of network management.

Aforementioned routing protocols are often classified as flat network organisation protocols in contrast to hierarchical protocols. In hierarchical protocols nodes are organised in groups with one node selected to act as a group leader. Leader is responsible for collecting the messages from its group members and routing between neighbouring group leaders. This approach aims to limit long range communication (nodes within a group communicate over a short range), reduce interferences in radio communication channel, facilitate data aggregation and simplify routing (as only group leaders take part in routing messages from nodes to the base station). Hybrid Energy Efficient Distributed [8] clustering (grouping) protocol is one of the most popular methods to establish hierarchical structure of the WSN network. Clustering in HEED is set up locally by neighbouring nodes that decide on group leader (cluster head) based on residual energy in each node. HEED is a randomised protocol meaning that it is more likely that nodes with larger residual power will become leaders.

3 Simulations

In our research we used OMNeT++ as the main simulation engine [10]. To add wireless communication we used MiXiM [11] framework. Simulations were repeated multiple times in order to achieve valuable results. Each time we saved and used exactly the same node layouts for comparison between different protocol sets. We assumed a network simulation containing 100 nodes placed in random positions with uniform distribution. Size of the network area was 300×300 m. Communication range of each node was set to reflect those of real devices operating in 2.4 GHz band, which is usually smaller than 100 m. Each simulated node was running the same application. Each node was sending a message every randomly picked time from a given range. Base station was set in one corner of the area. These assumptions were chosen to resemble a real-life deployment scenarios.

Unfortunately the available energy model implemented in the simulator was insufficient. Therefore we improved the existing model of battery usage to reflect the energy consumption of real devices during idle periods, reception and communication with different available transmission power levels. Values used in energy model were taken from our earlier research [12].

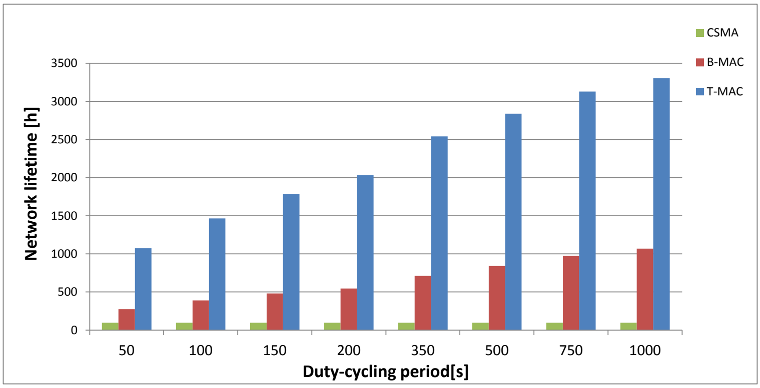

Fig. 1. Lifetime achieved for different MAC algorithms

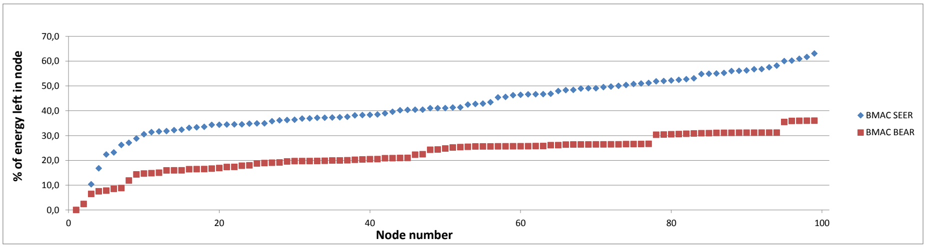

Fig. 2. Residual energy in batteries of nodes

4 Results

4.1 Simulation Results

Our results show that duty-cycling has the biggest impact on lifetime. This is consistent with our previous work showing that the most of node's energy is used by radio module (both for transmission and receiving). Because in most implementations radio service is provided by the MAC layer, the choice of MAC layer is crucial for network lifetime. Fig. 1 shows that when length of sleep time is changing, lifetime changes almost linearly. On the other hand frequency of packet transmission has negligible impact on lifetime when no duty-cycling is used.

If we assume that clocks in all nodes are well synchronized and nodes are able to wake up and fall asleep at the same time, it is possible to arbitrarily increase length of duty cycle. However, due to clock drift, duty cycles in individual nodes may desynchronize. When it happens, some messages may get lost. This increases the Packet Error Rate. Reducing this rate is possible only by retransmission. Unfortunately retransmissions increase energy usage. This is a trade-off between synchronization and length of duty cycle.

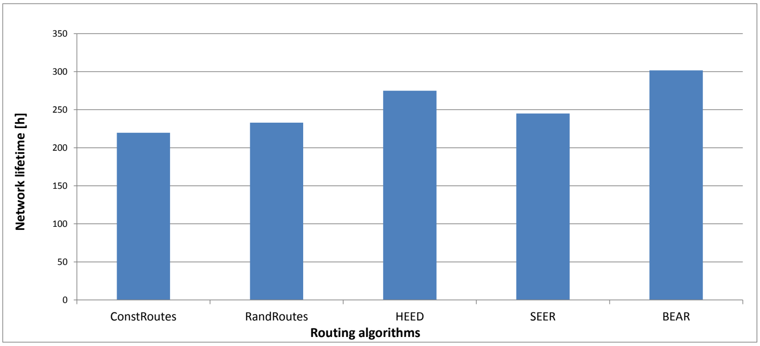

Fig. 3. Lifetime achieved for different routing algorithms

Routing algorithms also have influence on network lifetime. If we assume that network dies when first node looses all energy in battery it means that if we want to increase network lifetime we need to balance load in the network. Optimal situation occurs when the pace of battery usage is the same in all nodes. It may be impossible to achieve, but it can be the goal of the routing algorithms. Fig. 2 shows that routing algorithms should be also optimized to better balance energy usage. In our case network with SEER algorithm left more free residual energy when it finished its operation than with BEAR. On the other hand network lifetime differences shown in Fig. 3 are smaller than differences with different MAC protocols. Lifetime for T-MAC can be as much as 3 times longer than for B-MAC (Fig. 1).

Placement of nodes within the network considerably changes the behaviour of routing algorithms, which influences the network lifetime. Behaviour of routing algorithms highly depends on routing tree set in their beginning phase. Fig. 4 shows that locations of nodes have significant impact on lifetime when duty cycling is used. The main cause of this fact is the number of packets which must be sent through the routing tree. However, when duty cycling is turned off (like in CSMA/CA) all nodes run down battery in approximately the same time. In this case the number of routed messages does not matter.

4.2 Hardware Results

To verify simulation results we deployed a test network in our laboratory and have tested a subset of algorithms that we have already simulated. For data collection and testing setup we used WSN-TCP gateway architecture described in [13]. Test results matched the simulation results. Fig. 5 shows results from deployment with mixture of nodes with and without duty cycling. When battery level fell below permissible level in nodes 19, 20, and 21, node 22 still had high energy level. Results from the greenhouse show high correlation with our simulation results. Network lifetime achieved by our network was about 4 days when duty cycling was not used. However, when duty cycling was implemented in application, the lifetime reached over 18 days.

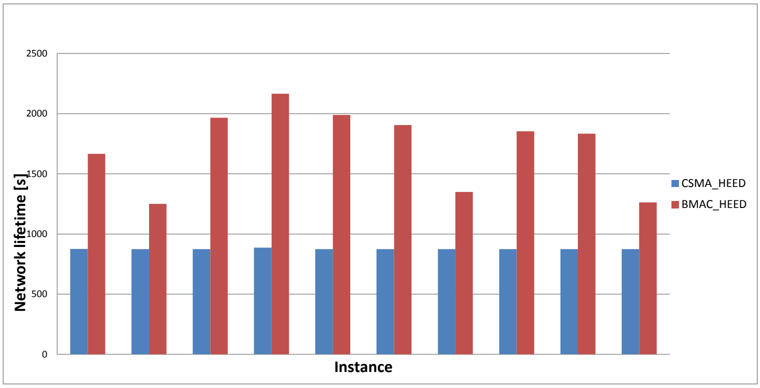

Fig. 4. Network lifetime in different deployment instances

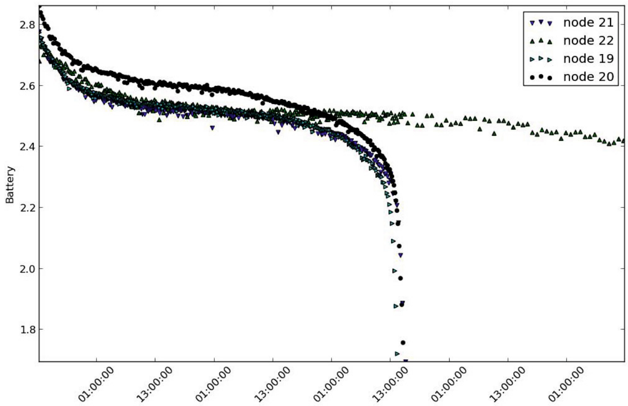

Fig. 5. Draining of battery power with TinyOS Low Power Listening switched on (node 22) and off (nodes 19, 20, 21)

5 Conclusions

In our simulations we have analysed 3 MAC protocols and 5 routing methods that are representative to various types of solutions presented in literature so far. These methods were also tested in deployed network. Both the simulations and real-case tests show that to extend the network lifetime, the most important choice is the proper MAC algorithm. Recent hardware is optimized for small energy usage in low power modes. However, the amount of energy used during transmission is still considerable. To avoid energy waste, nodes should work in duty cycle, with long sleep time and short time for transmission and sensing. The results show that the routing algorithms have smaller impact on lifetime than MAC algorithms. Though there still exists a design space for better algorithms which should improve the balance of energy usage. Tested networks ended their lifetime with high variation of residual energy in batteries. Theoretically, this is the energy which might be used to extend network lifetime.

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