RADIO TRANSCEIVER CONSUMPTION MODELING FOR MULTI-HOP WIRELESS SENSOR NETWORKS

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Acest articol propune un nou model matematic pentru consumul de energie al emițător-receptoarelor radio folosite în rețelele wireless de senzori. Aceste rețele sunt supuse unor constrângeri severe de consum de energie iar extinderea timpului de viață al nodurilor senzoriale alimentate din baterii este o cerință importantă care mărește autonomia rețelei. Primul pas pentru atingerea acestui țel îl constituie modelarea subsistemelor din cadrul unui nod senzorial unde energia este consumată. În cadrul acestui studiu, propunem un nou model matematic pentru estimarea consumului de energie a unui nod senzorial și evaluăm parametrii acestuia atât pentru rețele tip single-hop cât și pentru cele multi-hop.

This paper discusses a energy consumption model for radio transceivers in Wireless Sensor Networks. Wireless Sensor Networks are systems that are subjected to severe energy consumption constraints and extending sensor node battery life is a paramount requirement for network autonomy. A better understanding of where energy is spent in a typical wireless sensor node is a first step towards achieving this goal. We propose a model for estimating the energy consumption of a sensor node's radio transceiver and evaluate its parameters for both single-hop and multi-hop wireless sensor network architectures.

Keywords: Wireless Sensor Networks; energy consumption modeling; multi-hop; path loss

1. Introduction

In 1991, Mark Weiser predicted a 21st century where everyday personal computers would be replaced by a considerable number of embedded networked devices which would be completely integrated into our environment up to the point where they would become unnoticed, or even invisible to the user [1].

Wireless Sensor Networks are a technology that can offer a significant contribution in completing Weiser's "ubiquitous computing" paradigm and should

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represent a new revolution in computing, as were the mainframe and the personal computer before them.

Growing importance of context-awareness as an enabler for more intelligent, invisible and autonomous applications and services has highlighted the need for a greater integration of the physical with the digital world. Energy in particular is becoming an increasingly important topic in our lives. As we become more aware of the limitations and the costs of the energy we consume in our daily life, in our personal environment, we look on technology to give us aid in optimizing our efficiency.

Wireless Sensor Networks are subjected to severe constraints, which are typically application-dependent. Constraints usually fall in, but are not restricted to, categories such as size, number of nodes, energy availability and processing capabilities [2]. However, the prevailing constraint in almost all sensor network applications is network autonomy, that is, the network should be able to organize, manage and repair itself with minimum or no need for human intervention.

In this paper, we propose an energy consumption model for radio transceivers, designed especially for Wireless Sensor Networks. We refine this model to estimate energy consumption for multi-hop sensor networks. While multi-hop routing is theoretically more efficient that single-hop routing [3], there are some real-world applications where single-hop routing was proven to be more efficient [4][5]. We use our model to perform a comparative evaluation of energy consumption caused by communication in single-hop and multi-hop architectures.

The paper is structured as follows: Chapter II presents the First Order Radio Model, Chapter III describes the refinement of the model for multi-hop Wireless Sensor Networks, Chapter IV includes the comparative evaluation of energy consumption in single-hop and multi-hop architectures and Chapter V presents the conclusions and future work.

2. First order radio model

Research in the area of low-energy radio integrated circuits is ongoing and is motivated mainly by the applications in mobile and embedded market. In most countries duty cycling is imposed at a certain value for the standard ISM bands [6] [7]. In Europe, for the 434MHz band, duty cycling needs to be smaller than 10% and smaller than 1% for the 868MHz band. The duty cycle is calculated as the percentage of time the radio is on during a predetermined time interval, which, for this standard is an hour. In order to increase the availability of a sensor network, duty cycling is one of the first parameters to be evaluated, as it has a drastic effect on the energy efficiency of the network.

In the following, we present a model for estimating radio energy consumption in a wireless sensor network. The main issue is how to estimate the energy needed to send a package of n bits of data from the transmitter to the receiver, as in Fig. 1.

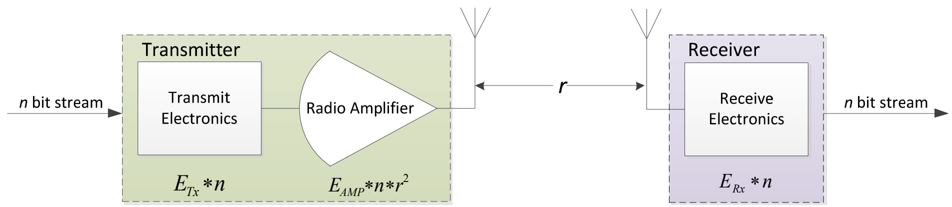

Fig. 1. Radio model for the transmission of n bits of information

In order to transmit a package of *n* bits at a distance of *r,* the radio transmitter will consume the following amount of energy:

$$E_{Tx}(n,r) = E_{tc}(n) + E_{amp}(n,r) \tag{1}$$

, where $E_{tc}(n)$ is the energy that the radio circutry needs to expend in order to process *n* bits, and $E_{amp}(n,r)$ is the energy needed by the radio amplifier circuit to send *n* bits at *r* meters.

We can further refine (1) by elaborating on the formula for $E_{amp}(n,r)$:

$$E_{Tx}(n,r) = E_{tc}(n) + E_{amp}(n,r) = n \cdot E_{trans} + n \cdot \varepsilon_{amp} \cdot r^{\gamma} \tag{2}$$

,where E_{trans} is the energy needed to process a single bit by the radio transmission circuits, ε_{amp} is the transceiver's energy dissipation and γ represents the path loss exponent.

Path loss is a major factor in estimating the link budget for a radio transceiver. For the present research, we used the standard log-distance path loss model:

$$PL = P_{Tx[dBm]} - P_{Rx}[dBm] = PL_0 + 10\gamma \log_{10}\frac{d}{d_0} + X_g \tag{3}$$

,where *PL* is the ideal path loss measured in dB, $P_{Tx[dBm]}$ is the transmitted power in dBm, $P_{Rx[dBm]}$ is the received power in dBm, PL_0 is the path loss at a reference distance d_0 (usually 1km), γ is the path loss exponent, *d* is the path length and $X_g$is the attenuation due to fading.

Path loss exponents are linked to the medium of propagation [8] and usually range from 2 to 4, where 2 is the path loss of free space propagation and 4 is the path loss exponent for lossy environments such as buildings or stadiums.

The Friis equation allows us to compute the received power of an antenna as a function of the distance from the transmitter.

$$P_{recv} = P_T \cdot G_T \cdot G_R \cdot \left(\frac{\lambda}{4\pi R} \right)^2 \tag{4}$$

, where P_T is the transmitter power output, G_T and G_R are antenna gains, λ is the wavelength of the microwave radiation and R is the distance between transmitter and receiver.

An explicit relation for ε_{amp} can be found in [9]:

$$\varepsilon_{amp} = \frac{\frac{S}{N_r} \cdot NF_{Rx} \cdot N_0 \cdot BW \cdot \left(\frac{4\pi}{\lambda} \right)^{\gamma}}{G_{ant} \cdot \eta_{amp} \cdot R_{bit}} \tag{5}$$

, where $\frac{S}{N_r}$ is the signal to noise ratio at the receiver, NF_{Rx} is the receiver noise figure, N_0 is the thermal noise for a 1Hz bandwidth, BW is the channel noise bandwidth, λ is the wavelength in meters, γ is the path loss, G_{ant} is the antenna gain, η_{amp} is the transmitter efficiency and R_{bit} is the channel data rate in bits per second.

Alternatively, we can express in the same way the energy required for the transceiver to successfully receive and process n bits of data:

$$E_{Rx}(n) = R_{rc}(n) = n \cdot E_{recv} \tag{6}$$

This model assumes that the communication through the radio channel is symmetric and that the energy to send a package from node A to B is the same as the one needed to send the same package from B to A, for a constant SNR. As can be seen in the above relations, any type of communication is not a low cost operation so the protocol stacks that run on the nodes should always try to minimize the number of transmit and receive operations in order to keep the energy budget of the network under a certain threshold.

3. Refining the model for multi-hop wireless sensor networks

So far, we have been focusing on modeling the communication between only two nodes, but the same model can be scaled up to estimate the energy consumption at network level. For this, there are two cases worth taking into consideration: a network in which nodes talk to the gateway using a direct communication protocol, and the more general multi-hop network scenario, in which messages are passed from neighbor to neighbor until they reach the data sink, as presented in Fig. 2.

Using the direct communication approach, each node has direct access to the gateway. As the distance between nodes and the gateway is not constant and can vary within radio connectivity range, some remote nodes will need greater amounts of transmit power to communicate with the data sink. In this case, r in (2) is large, which leads to more energy spent and quicker battery drainage. On the other hand, there is no need for the nodes to receive any information from their neighbors, as the communication is done over a star topology network. This could prove advantageous or even optimal if nodes are in close proximity to the gateway or the cost of reception on the battery-powered nodes is sizeable.

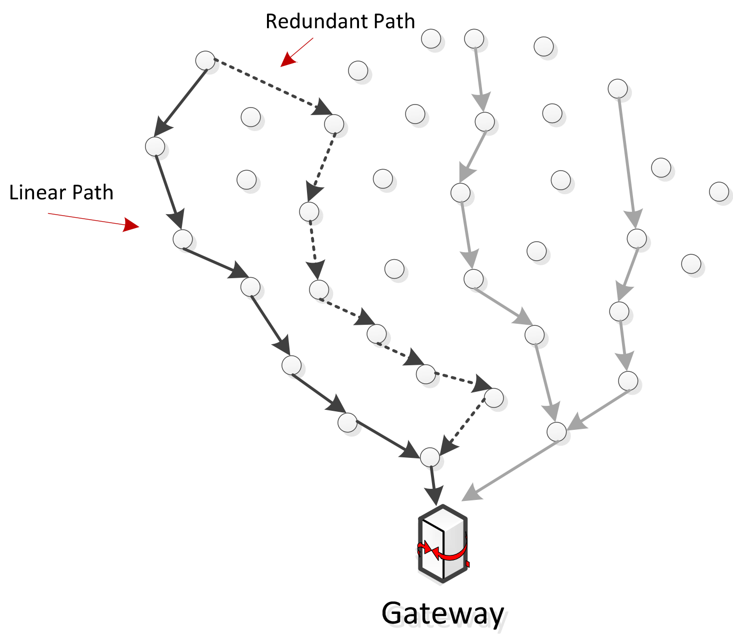

Fig. 2. Linear and redundant paths in a sensor network

The second approach is to use a power-aware multi-hop routing protocol, as discussed by [10], [11], [12], [13]. In this case, data is disseminated in the network though paths that will ultimately lead to the sink. These paths are chosen according to the routing algorithm used by the protocol stack and can vary, depending on the different metrics involved.

Consider the example in Fig. 3, which represents a typical linear sensor network where nodes are spread at equal distances from each other. Based on the equations we described earlier, we can estimate the energy cost of communication in such a network.

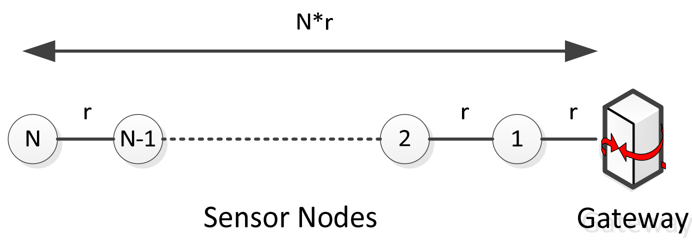

Fig. 3. Simple linear sensor network

First, for the single-hop case, the node is communicating directly to the gateway. For the N-th node, this would imply that it needs to increase its transmitter signal strength in order to cover the entire distance to the gateway, which would in turn lead to higher energy consumption.

This can be expressed as:

$$E_b(N,n,r) = E_{Tx}(n, N\cdot r) = n\cdot E_{trans} + n\cdot \varepsilon_{amp}\cdot (N\cdot r)^{\gamma} \tag{7}$$

For the multi-hop case, the N-th node needs to send data to his nearest neighbor, which would expend energy in receiving the package and retransmitting it to its nearest neighbor, and so on until it reaches the data sink.

The total energy expenditure of the network can be calculated as a sum of *N* transmits and *(N-1)* receives:

$$\begin{aligned} E_{MH}(N,n,r) &= N\cdot E_{Tx}(n,r) + (N-1)\cdot E_{Rx}(n) \\ &= N\cdot n\cdot (E_{trans} + \varepsilon_{amp}\cdot r^{\gamma}) + (N-1)\cdot n\cdot E_{recv} \\ &= n\cdot (N\cdot (E_{trans} + E_{recv} + \varepsilon_{amp}\cdot r^{\gamma}) - E_{recv}) \end{aligned} \tag{8}$$

, where n is the number of bits in a message.

In most cases, however, all nodes in the network need to send packages to the base station. For the multi-hop case, we can generalize the relation in (7) to *N* nodes:

$$\begin{aligned} E_{MH}^{all}(n,r) &= \sum_{i=1}^{N} E_{MH}(i,n,r) \\ &= N\cdot E_{Tx}(n,r) + (N-1)\cdot E_{Rx}(n) \\ &= \frac{N(N+1)}{2}\cdot n\cdot (E_{trans} + \varepsilon_{amp}\cdot r^{\gamma}) + \frac{N(N-1)}{2}\cdot n\cdot E_{recv} \end{aligned} \tag{9}$$

The same generalization can be made with the single-hop case given by (6):

$$E_b^{all}(n,r) = \sum_{i=1}^{N} E_{Tx}(n, i \cdot r) = n \cdot N \cdot E_{trans} + n \cdot \varepsilon_{amp} \cdot r^{\gamma} \sum_{i=1}^{N} i^{\gamma} \tag{10}$$

Using the equations in (8) and (9), we can derive the conditions for which direct communication to the gateway has a lower energy cost for the whole network, compared to the multi-hop scenario. This is equivalent to the following condition:

$$E_b^{all}(n,r) \le E_{MH}^{all}(n,r) \tag{11}$$

Certain assumptions must be made in order to simplify the above relation. First, we can assume that the energy expended in processing one bit for transmission is roughly equal to the energy of processing a received bit, as most radio transceivers use the same electronics for both functions:

$$E_{trans} = E_{recv} = E_{circ} \tag{12}$$

Secondly, we can assume a constant path loss exponent for the entire network. In most cases where it cannot be easily measured, the path loss exponent is estimated to be the standard value for free space propagation, γ=2.

Using these two assumptions, we can write the relation in (11):

$$n \cdot N \cdot E_{circ} + n \cdot \varepsilon_{amp} \cdot r^2 \cdot \sum_{i=1}^{N} i^2 \le \frac{N \cdot (N+1)}{2} \cdot n \cdot (E_{circ} + \varepsilon_{amp} \cdot r^2) + \frac{N \cdot (N-1)}{2} \cdot n \cdot E_{circ} \tag{13}$$

$$N \cdot E_{circ} + \varepsilon_{amp} \cdot r^2 \cdot \frac{N \cdot (N+1) \cdot (2 \cdot N+1)}{6} \le \frac{N \cdot (N+1)}{2} \cdot (E_{circ} + \varepsilon_{amp} \cdot r^2) + \frac{N \cdot (N-1)}{2} \cdot E_{circ} \tag{14}$$

$$\varepsilon_{amp} \cdot r^2 \cdot \left(\frac{(N+1) \cdot (2 \cdot N+1)}{6} - \frac{N+1}{2} \right) \le (N-1) \cdot E_{circ} \tag{15}$$

$$\frac{E_{circ}}{\varepsilon_{amp}} \ge \frac{N+1}{3} \cdot r^2 \tag{16}$$

The relation in (15) is applicable for an ideal medium, without any interference.

A model that is nearer to reality can be obtained if we modify the path loss exponent to a value of 3, which is typical for environments such as office buildings or stores:

$$\frac{E_{circ}}{\varepsilon_{amp}} \ge \frac{(N+1) \cdot (N+2)}{4} \cdot r^3 \tag{17}$$

For a very lossy indoor environment, such as an industrial environment with a lot of electromagnetic interference, the path loss exponent increases to a value around 4. Rewriting (11) for this new parameter value yields the following equation:

$$\frac{E_{circ}}{\varepsilon_{amp}} \geq \frac{(N+1)\cdot(6\cdot N^2+15\cdot N+16)}{30}\cdot r^4 \tag{18}$$

, where N is the number of nodes in the linear path and r is the distance between nodes.

4. Evaluation

We consider a linear network which has a maximum of 10 nodes, with 1 to 10 meters between consecutive nodes. Energy is evaluated for an ideal medium, in which γ=2 and a lossy medium, which has γ=3.

First, we evaluate the ratio between the radio amplifier analog circuitry and digital energy consumption, as represented in Formulas (16) and (17). The values for the ideal and lossy medium are represented in Fig. 4, in which the horizontal axis represents the distance between two consecutive nodes (r), the depth axis corresponds to the number of hops (N). The two surfaces represent the results for the ideal and lossy medium. The results for the lossy medium are up to 90 times higher than the ones for the ideal medium.

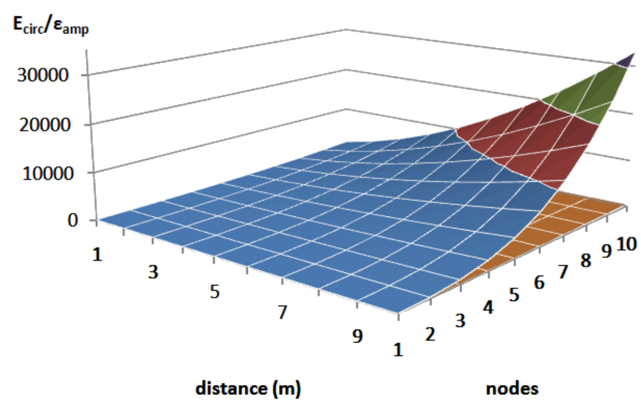

Fig. 4. Ratio between analog and digital energy consumption

We determine the energy consumed by Wireless Sensor Networks with multi-hop and single-hop architecture in the ideal medium. The results are represented in Fig. 5, in which the vertical axis represents energy consumption. The two surfaces represent the results for the single-hop and multi-hop cases. The single-hop communication consumes up to 7 times more energy than multi-hop in the ideal medium.

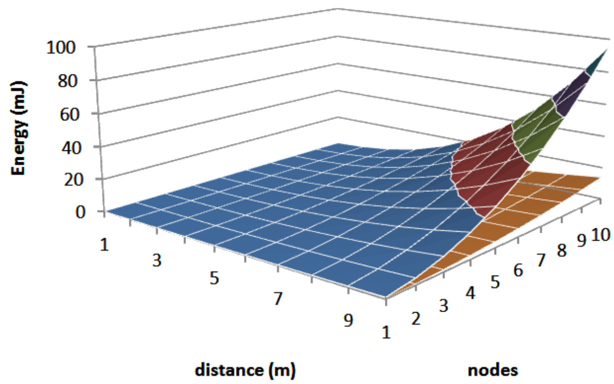

Fig. 5. Multi-hop versus single-hop in the ideal medium

The energy consumed in the multi-hop and single-hop scenarios, in a lossy medium, is represented in Fig. 6. The single-hop scenario consumes up to 55 times more energy than the multi-hop scenario in the lossy medium.

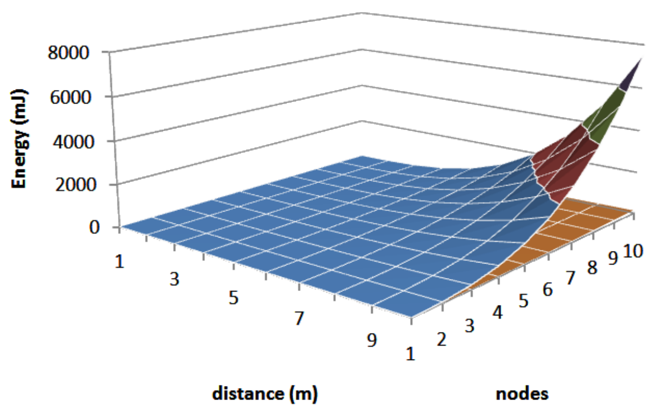

Fig. 6. Multi-hop versus single-hop in the lossy medium

5. Conclusions

Wireless Sensor Networks are composed of resource-constrained devices, which are powered from battery. Therefore, energy consumption is an important issue that should be taken into consideration when designing Wireless Sensor Networks.

In this paper, we proposed a first order radio model for estimating the energy consumed by the radio transceivers in a Wireless Sensor Network. This model was further tuned for sensor networks with multi-hop architecture.

We used the model to evaluate energy consumption in the case of sensor networks with single-hop and multi-hop architecture. We compared the consumption for the two architectures considering both ideal and lossy mediums.

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