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Abstract

Models and proposals to capture the energy consumption of sensor nodes are plentiful. Even if the majority of the various energy consumption models roughly agree about the energy consumed in the different states of the sensor node duty cycle, different approaches for abstracting the costs of radio operations exist. In our work, we investigate which factors are crucial for the modeling of transmission costs by establishing a general framework whose modular structure allows to compare existing abstractions. We analyze the impact of typical assumptions when they influence the creation of energy efficient routing topologies. We compare the resulting routing trees not only by topological characteristics, but also by estimating radio related energy consumptions, a metric which changes strongly with the MAC layer efficiency.

1 Introduction

For any huge scale sensor network deployment energy is the most critical topic: To maximize the lifetime of the network and the quality of the assembled data, the network has to be be designed in the most energy efficient manner as possible. At lot of work has been dedicated to the design of highly efficient MAC and routing algorithms, therefore the network topology and functionality can be adapted specific to the desired functionality. To optimize the energy consumptions even more, the duty cycle, the density and location of the sensor nodes or the number and positions of data collection points could be varied. Due to the large design space, it is therefore vital to rate the reasonableness of an intended deployment *before* actually bringing out the nodes, as any setting which already shows weaknesses on the drawing-board, won't perform better under harsh environment conditions. For this purpose, realistic simulations for determining energy consumptions and the lifetimes of battery operated nodes would yield the most accurate results, but they require a highly detailed model of the sensor nodes and their behavior. As those fine grained models are computationally expensive and time intense, analytical methods are thus preferable, if a quick estimation is required, or if large scale deployments have to be analyzed.

Obviously, any analytical approach for predicting the energy consumption in sensor networks has to find adequate abstractions for the sensor node behavior. As the possibilities for abstractions are countless, we want to identify the critical parameters which have to be modeled especially carefully. Our focus is on the network layer, we therefore chose two approaches for modeling radio operation costs exemplary out of the manifold proposals for evaluating the energy consumptions of sensor nodes, and examine them closely. For an investigation of the energy model impact, we try to answer the question in how far the decision between the two different link cost metrics is influencing analytically designed energy efficient routing decisions. To compare the resulting topologies not only due to graph theoretic metrics, we estimate the arising radio related energy consumptions which we find to be heavily influenced by the efficiency of the MAC layer.

The structure of this work is as follows: In Section 2 we review different approaches for estimating the energy consumptions of sensor nodes and their application to the problem of energy efficient routing. Section 3 describes the analytical framework, we use to compare the effect of energy model design choices on routing decisions. This section contains also our proposal for estimating the energy consumptions of a sensor node under the consideration of the MAC and routing layers. We present numerical results of the application of different energy metrics for energy efficient routing in Section 4, before we conclude our work in Section 5.

2 Related Work

The most widely used energy model for analyzing radio operations in sensor networks has been proposed by Heinzelman et al. [1]. The authors illustrate, that a routing algorithm which aims at finding energy efficient paths by minimizing the squared hop distances (an approximation of the path loss), may not produce lowest energy routes, as the power consumptions of the transceiver electronics are ignored by the simple metric. As an improvement, the authors propose to model the necessary amount of energy for a transmission over a distance d to be the sum of a constant and of the required transmission power which scales with a power of d. In addition to these terms, they include one more constant addend to account for reception costs.

As an energy efficient topology organization is a simple possibility for optimizing a wireless sensor network, many works have proposed reasonable opportunities for prolonging the network lifetime. So do Chang and Tassiulas [2] who demonstrated, that the attempt of establishing a Minimum Total Energy (MTE) routing tree, which aims at minimizing transmission and receptions costs for each routing path is not suited for battery operated networks. They proposed a new routing algorithm, which minimizes not only transmission and reception computed according to the metric proposed in [1], but takes also the residual energies of the nodes into account to consider the limited per node energy. Other examples for the use of this energy model for analytical routing topology establishment and sensor network analysis can be found in [3], [4], [5], and [6].

However, the application of the above mentioned results to a real world sensor network deployment has do be done very carefully: As shown by Landsiedel et al. [7], who analyzed the current consumptions, of the Mica2 mote [8], the transmission costs in terms of current draw are *not* directly related to the required transmission power, as assumed by [1]. Therefore the authors attack the problem of energy consumption modeling from a more hardware oriented point of view and created a sensor network emulator which is able to predict the energy consumed if specific applications are run. A similar approach is proposed by Polastre et al. [9] who estimate sensor node lifetimes by computing the node energy consumptions as the sum of the energy needed for transmitting, receiving, sleeping, channel scanning, and sampling data. Wang et al. [10] extend this hardware oriented approach to the network layer and consider varying transmission output powers: they find, that the drain efficiency of the power amplifier of the sensor node radio chip, i.e. the ratio of transmission output power and the consumed DC input power, is neither constant nor linear, but increasing with the output power. Based on this fact and under the use of a simple free space path loss model, they present novel insights in the establishment of energy efficient routing topologies.

More general insights on routing in multihop wireless networks are presented by Haenggi [11]. In his work, he gives twelve reasons why long hops should be preferred over short hops. His argumentation is based on a detailed physical layer model, considers end-to-end reliability, channel coding, routing overhead and many other factors and concludes with the statement, that all sensor nodes should always transmit as far as possible. However, in a situation where e.g. all nodes are able to gather energy from the environment, the establishment of a MTE routing tree is nevertheless of interest. Moreover, this problem has been well studied in the literature, we use it therefore, to illustrate the influence of energy model parameters in a non-linear topology in the following.

3 Analytical Framework

3.1 Radio Operation Energy Consumptions

To illustrate the importance of correct transmission energy consumption modeling for sensor network optimization, we establish a general energy consumption framework. To simplify, we do not consider the energy required by the other components of the sensor board, or consumptions for data handling, topology maintenance or medium access control. Our focus is on the networking aspect, we concentrate therefore on the model of the radio unit and neglect all those supplementary costs. Following [1] and [10], the energy for transmitting one bit over a distance d can thus be expressed as

$$E(d) = E_0 + \frac{T(c,d)}{\eta(c,d)} + E_{rx}. \tag{1}$$

In the above formula, E_0 represents the power consumption in the transmitters' signal processing and front-end circuits. This term is constant for transmissions over all distances. $T(c,d)$, the required transmission output power, is of course increasing with the distance d and depends furthermore on the channel characteristics given by c which represents the radio propagation model and the receiver sensitivity. $\eta(c,d)$ denotes the drain efficiency of the power amplifier, which is the ratio of transmission output power to DC input power [10]. For state-of-the-art transceivers it is varying with the output power T, depends thus also on c and d. E_{rx} finally, represents the power consumed for receiving a bit.

For parameterizing Eq. (1), we consider two different energy consumption models, which we describe in the following: A *Theoretical Model (TM)* which is based on the work of Heinzelman et al. [1] and a *Hardware oriented Model (HM)*, which is inspired by the insights presented by Wang et al. [10] and tries to capture the characteristics of a typical sensor node transceiver, Chipcon's CC1000 [12] transmitting in the 868 MHz band as it is used in Mica2. To make our work comparable to other authors, we assume, that the transceiver is operating with a constant voltage of 3 V.

3.1.1 TM

From [1], we adopt $E_0 = E_{rx} = 50$ nJ/bit. Furthermore, the authors propose

$$T(c,d) = \begin{cases} c_1 d^2 & \text{if } d < d_0 \\ c_2 d^4 & \text{if } d \geq d_0 \end{cases} \tag{2}$$

and use the vector c with $c_1 = 10$ pJ/bit/m^2 and $c_2 = 0.0013$ pJ/bit/m^4 to model receiver sensitivity, free space and multipath signal propagation respectively. As no numerical value for d_0 is given, we use $d_0 = \sqrt{\frac{c_1}{c_2}} = 87.71$ m. Moreover, the authors assume a direct relation of transmission power and energy consumptions, thus $\eta(c,d) \equiv 1$ under TM.

3.1.2 HM

According to [10], the non-distance related power consumptions in the transmission circuit are slightly smaller than the power amplifiers consumption for the smallest transmission output power. Therefore, we use the power consumptions needed for the smallest transmission output power as an approximation for E_0 and obtain $E_0 = 671.875$ nJ/bit and $E_{rx} = 750$ nJ/bit. To obtain the necessary output power T required for a transmission over distance d, we use the empirical ground plain channel model proposed in [13] and model the transmission energy consumptions as

$$T(c,d) = \begin{cases} c_1 d^{2.35}/\eta(c,d) & \text{if } d < d_0 \\ c_2 d^{3.6}/\eta(c,d) & \text{if } d \geq d_0 \end{cases} \tag{3}$$

where $d_0 = 6.2$ m and the channel characteristics vector c for this two slope model is given by $c_1 = 0.0152$ pJ/bit/m$^{2.35}$ and $c_2 = 0.0016$ pJ/bit/m$^{3.6}$. In Fig. 1, we depict η for the considered transceiver chip in dependence of the transmission distance. To obtain the interdependency between d and η, we used the above described channel characteristics. We use light blue circles to show the values obtained from a calculation of η using the typical current consumptions indicated in the CC1000 data sheet and a dark blue line to represent a simple linear fit which we also use in the remainder of this work.

3.2 Estimation of Energy Consumptions

To compare the resulting topologies, we propose a simple model which allows to approximate the radio related energy consumption of a sensor node. A rough abstraction

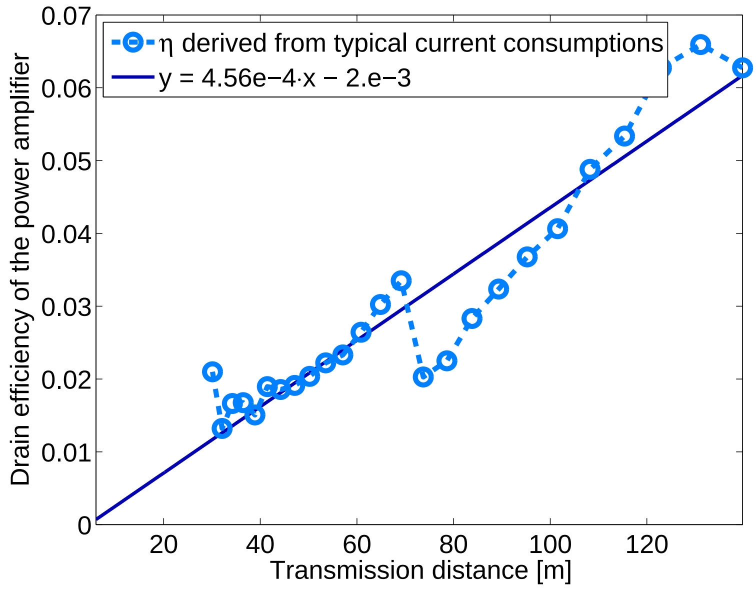

Figure 1: Drain Efficiency of the CC1000 Transmitter Power Amplifier

of the sensor node state cycle, similar to the approaches presented by [9] is used for this purpose: We assume that the radio unit of sensor node i is either transmitting or receiving data, listening for incoming packets or sleeping, and that all nodes operates at a regular schedule, i.e. have the same duties during all time units u. Idle listening and receiving data consume the same amount of energy, therefore we do not distinguish between those two states. The mentioned state cycle translates thus to the following partition of u:

$$u = t_i^{tx} + t_i^{rx} + t_i^{s}. \tag{4}$$

We assume, that each node in the set of all nodes N is equipped with the same radio unit whith the same typical power consumptions $P^{tx}(T)$, P^{rx} and P^s required for transmissions with an output power T, receptions and sleeping respectively, the electrical energy, node i needs for radio activities during one time unit u can thus be calculated as

$$E_i^{radio} = t_i^{tx} P^{tx}(T_i) + t_i^{rx} P^{rx} + t_i^{s} P^{s}. \tag{5}$$

The time each sensor node spends transmitting, receiving or sleeping depends on several factors. One is of course the radio's data rate which determines, how fast packets are transmitted. Another factor influencing the part of the time a node spends sending and receiving data is the load of the sensor node which is given by the routing topology. To include this factor in the analysis, we need the number of measurement packets created and sent to the sink per time unit u. For now, we assume, that all nodes create exactly λ packets during u. The number of packets S_i, sent by node i during one time unit u, is thus given by the number of nodes, which use i as a relay towards the sink. S_i

could be a random variable, if packet losses, collisions or data aggregation are modeled and increases if acknowledgments and retransmissions are considered. We assume for this analysis, that this is not the case, S_i is thus just the sum of the number of measurement data packets generated by i and its children in the routing tree:

$$S_i = \lambda(c_i + 1). \tag{6}$$

c_i represents the number of children node i, has, if i is not relaying data, $c_i = 0$. If all data packets have always the same size and can be sent and received within t_{dat}, the part of u, node i is busy with sending is thus given by

$$t_i^{tx} = S_i t_{dat} = \lambda(c_i + 1)t_{dat}. \tag{7}$$

To simplify our model, we neglect protocol overhead and assume that all transmissions succeed. However, we investigate one aspect of wireless networks more deeply. It is a well known problem, that sensor nodes in the radio range of a sending node are forced to overhear this transmission unless their radio is in sleep state. This phenomenon can e.g. increase the sensor node duty cycle, if a wake on radio policy with periodic channel polling is deployed. The costs for discarding such unwanted packets depend strongly on the deployed protocol, but we assume that all MAC protocols used in sensor networks follow rather simple strategies which allow the radio unit of a not addressed sensor node to return to sleep state after heaving read the address field of the packet i.e. an amount of time t_{disc}. To model the effectiveness of the MAC protocol, we introduce the variable $\epsilon \in [0, 1]$ which gives the fraction of unwanted transmissions a sensor node could theoretically receive, the node actually *has* to receive and to discard. $\epsilon = 0$ describes the ideal situation, where no sensor node overhears unwanted transmissions of its neighbors. With this extension, and with $R_i = \lambda c_i$, the number of data packets, i receives per time unit, we obtain the part of a time unit, i is busy with receiving as

$$\begin{aligned} t_i^{rx}(\epsilon) &= R_i t_{dat} + \epsilon \sum\nolimits_{j \in N} S_j \vartheta_{ji} t_{disc} \\ &= \lambda[c_i t_{dat} + \epsilon \sum\nolimits_{j \in N} (c_j + 1)\vartheta_{ji} t_{disc}]. \end{aligned} \tag{8}$$

The boolean variable ϑ_{ji} expresses, whether the messages, j sends to its next hop k could be overheard by i: $\vartheta_{ji} = 1$, if i overhears transmissions of j and it is 0 otherwise.

The second term in Eq. (8) represents the time, i needs for receiving and discarding unwanted packets. Obviously, the main influence factor on this term is the node's position in respect to the sink: If i could theoretically overhear all transmissions from and to s, its unnecessary reception time will increase, as all data packets generated in the entire sensor network have to be forwarded to s. Moreover, this time will increase with the network density and with the transmission output power, which increase both the number of nodes which are within communication range.

Finally, the time, the radio unit of node i can spend in sleep state, is obtained as

$$t_i^s(\varepsilon) = u - (t_i^{rx}(\varepsilon) + t_i^{tx}). \tag{9}$$

It is evident, that if one evaluates Eq. (7) - (9) for a given network topology and one specific routing tree, the figures obtained from Eq. (5) can merely be used as an absolute lower bound estimator for the total energy consumptions of the sensor nodes. This model does not include energy consumptions required for data sensing, processing or by other circuits, for a more realistic estimation, battery discharge characteristics had to included and parameters had to be chosen in accordance to experiments with real motes. However, our simple model allows to roughly describe the energy consumptions of the radio unit, we will therefore use it to compare the effects of parameter choices on routing topologies in the next section.

4 Numerical Results

4.1 Comparison of Transmission Costs

To examine the influence of modeling decisions concerning the constant transmission costs, the reception costs, the channel model and the characteristics of the power amplifier, i.e. parameterizations of E_0, E_{rx}, c and η respectively, we compare variations of the models described in Section 3.1. For both the Theoretical and the Hardware Oriented Model, we evaluate Eq. (1), if one of the four parameters is set according to the other metric. As an example: for the variation denoted as “TM, c HM”, we compute the transmission costs for d under TM, but use the channel characteristics given by HM. Thus, $E_0 = E_{rx} = 50$ nJ/bit, $\eta(c, d) \equiv 1$ and $c_1 = 0.0152$ pJ/bit/m$^{2.35}$ and $c_2 = 0.0016$ pJ/bit/m$^{3.6}$. We depict the energy required for receiving and transmitting one bit in dependence of the transmission distance according to those possible eight variations in Fig. 2 and Fig. 3. As the channel model results in a maximal transmission distance of 139.8 m for the considered chip, we do only show costs for distances up to this border. As a further variation, we show also the costs of a transmission, when reception is ignored, i.e. $E_{rx} = 0$.

In both figures, we depict the resulting costs from the pure TM and HM with red stars and dark blue circles respectively. Recall that for HM, we use a fit of the empirical η (see Fig. 1). Due to the nonlinear nature of the drain efficiency, the dark blue curve, using this fit, is thus much smoother than the light blue stair plot which gives the transmission costs obtained using the empirical values for η. Observe that in both figures, the curves depicted by the triangles in magenta, the squares in olive green and the black diamonds, are mere linear shifts of the costs resulting from the pure model. Take Fig. 2 as an example: if one uses the channel model and the drain efficiency according to HM, but decreases the transmission independent constant and reception costs, that is, assumes either $E_{rx} = 50$ nJ/bit, $E_0 = 50$ nJ/bit or $E_{rx} = 0$ nJ/bit, the slope of the resulting cost curve is the same, as the resulting costs are just the result of a simple subtraction.

The impact of the channel characteristics and the drain efficiency, whose variation we represent by dark green plus signs and ocean green hexagrams, is more severe: In both figures, the most heavily increasing curve depicts the combination of the channel characteristics proposed by TM and the output power dependent drain efficiency model proposed by HM. These large cost variations are due to higher transmission powers

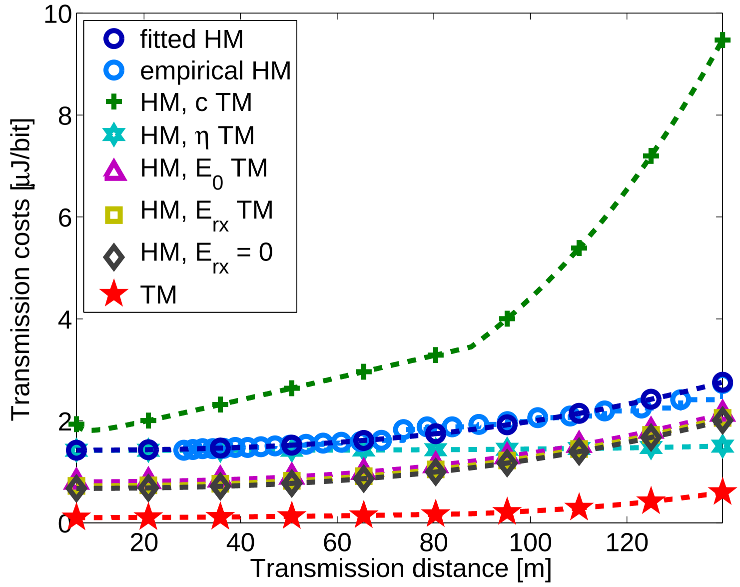

Figure 2: Communication costs according to variations of HM

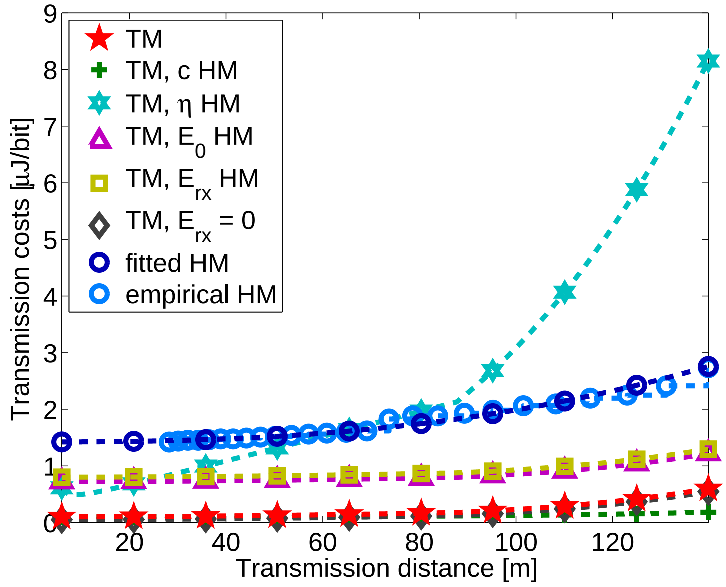

Figure 3: Communication costs according to variations of TM

resulting from the channel model with a path loss exponent of 4 proposed in TM, resulting in significantly higher energy consumptions, if the influence of the drain efficiency is taken into account. The comparison of those two metrics to the other curves shows, that results obtained by these combinations have to be interpreted with care.

The comparison of the curves with the red stars and the green plus signs in Fig. 3 illustrate, that the influence of the channel model, in this case, the decrease of the path loss exponent is not as severe, if the drain efficiency is assumed to be equal to one. The fact that the choice of η is influencing the computed transmission costs quite heavily can also be seen in Fig. 2: The comparison of the curves depicted by blue circles and ocean green hexagrams shows that assuming $\eta \equiv 1$ instead of including a distance related drain efficiency, leads to significantly smaller costs, especially for larger transmission distances.

All in all, we see that, the model of the channel characteristics has a major influence on the analysis of transmission related energy consumptions. Moreover, the parametrization of η, i.e. the mapping of transmission output power to consumed DC input power has to be done carefully, as this parameter has an major influence, too. These insights are quite natural and have already been mentioned in the literature, e.g. [10], [11], but to our knowledge, nobody has examined the impact of those different transmission costs on the characteristics of energy minimizing topologies. This will be the subject in the remainder of this section.

4.2 Comparison of Minimum Total Energy routing trees

To obtain insights in the influence of energy consumption modeling on sensor network design, we take a well known, widely studied problem as an example for the various optimization problems existing in sensor network research: We assume that all nodes are mains powered or are able to gather energy from the environment. To make optimal use of the resources, a MTE has to be set up which minimizes the per path energy consumptions, i.e. which minimizes the energy required for sending the measurement data, each sensor node collects, to the sink node. For a numerical evaluation, we assume that a set of identical sensor nodes is randomly deployed in a quadratic area of size l^2 according to a spatial Poisson process with density ϱ. Furthermore, each node periodically sends measurement data to one sink s which is located in the upper left corner of the area.

We use Monte Carlo simulation technique to examine different network snapshots and are thus able to obtain the MTE for the two considered energy consumption models and the previously discussed variations using the Dijkstra algorithm. For a real world realization of such a theoretically established MTE, the deployed sensor nodes have to be able to adapt their transmission output powers to the smallest value required for reaching their next hop. As this may not always be feasible in reality and for comparison purposes, we additionally consider two minimum hop (MH) topologies, where all nodes operate with transmission output powers fixed to the minimum and maximum possible value respectively. For the CC1000, these are -20 and 5 dBm respectively, which translates to maximal reachable distances of 28.25 and 139.8 m according to the used channel model.

We investigated different scenarios with varying l and rho and also analyzed topologies for a central sink. The obtained results showed all the same trend, in the following, we therefore present only results for topologies obtained in the setting with $l = 400$ m and $\varrho = 0.02$ and the sink placed in the upper left corner. We choose this scenario, as the distance between nodes and the sink increases up to 560 m and the resulting routing topologies vary more strongly than in the case of smaller areas, where all paths are either one or two hops long.

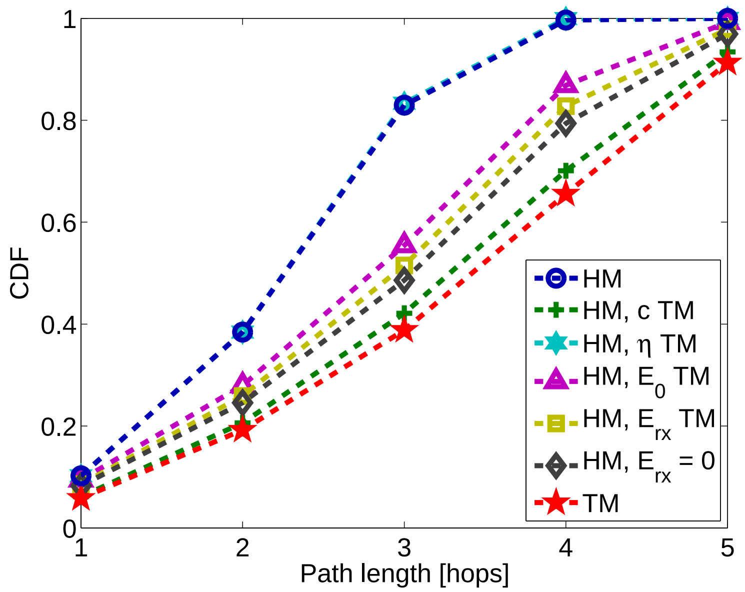

Figure 4: Path lengths in the MTE resulting from varied HM

One good metric for comparing routing topologies is the length of the routing paths, as the number of hops each piece of measurement data has to travel to the sink allows to compare the routing delays which determine the freshness of the data. Moreover, we consider a very simple setting, where no data is aggregated, thus an increase in hops means an increase of consumed bandwidth and hence both the times required for sending and receiving data and the risks of collisions and data losses are growing. Furthermore, the relaying load on the nodes within one hop distance of the sink is growing if paths with longer hops are on the majority. For the path length distributions in the considered MTE topologies, we compare the cumulative probability density function (CDF) in Fig. 4 and Fig. 5. In both figures, we depict the CDFs of the path length for the topologies resulting from the pure HM and TM with dark blue circles and red stars respectively. While the CDF of the path length obtained by using the fitted and the discrete values for η for HM are identical to the CDF of the path lengths in the MH topology for fixed transmission power of 5 dBm, the CDF for MH with $T = -20$ dBm, which we show using light green dots in Fig. 5, is clearly below those curves, as in this topology up to 25 hops are necessary to reach the sink node.

The CDFs visualized in Fig. 4 demonstrate, that the variation of η is the only parameter of HM which is not influencing the distribution of the path length. Decreasing the distance independent costs (again, represented by the triangles in magenta, the squares in olive green and the black diamonds) or the use of the channel characteristics from TM, shown by the dark green plus signs, make shorter hops more energy efficient and leads to topologies with more hops. However, the number of hops in the MTE resulting from the pure TM is never reached.

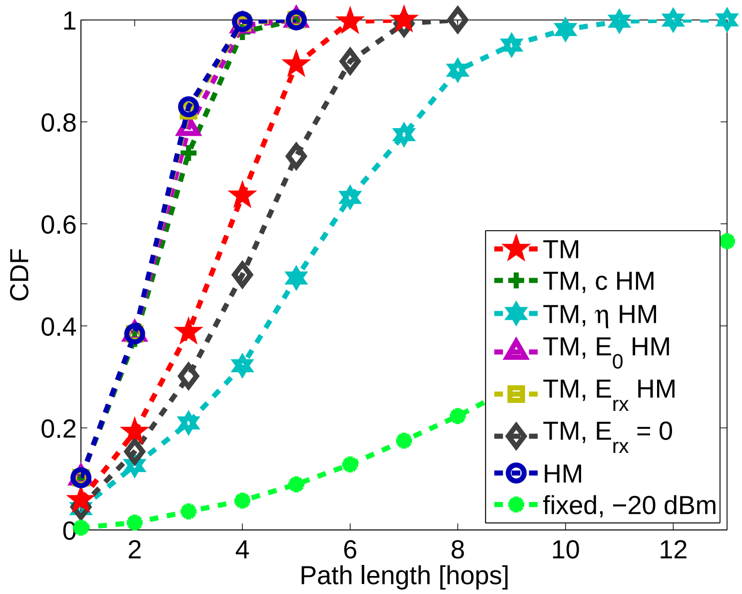

Figure 5: Path lengths in the MTE resulting from varied TM

Fig. 5 reveals more interesting facts: the CDF of the combination of theoretical channel model and distance dependent drain efficiency (ocean green hexagrams) shows, that in this topology longer paths than in all other considered MTE trees exist. This is due to the nature of the cost metric, which makes shorter links significantly less energy intensive and assumes low constant per hop costs (see Fig. 3). The other CDFs shown in this figure illustrate, that increasing the distance independent energy consumptions and decreasing the path loss coefficient makes longer hops more favorable, thus leads to a path length distribution identical to the one resulting from HM. Neglecting the reception costs leads to routing topologies with slightly shorter transmissions (depicted by the black diamonds).

The analysis of the path length distribution allows to rate the load on the nodes which are responsible for relaying data. We illustrate this statement, by visualizing the CDFs of the size of the child set, each node has in the routing tree, c_i. Recall that $c_i = 0$, if the node does not have to relay data for other nodes. Fig. 6 shows the CDFs of c_i in routing trees resulting from minimum energy routing with adaptive output power in respect to the Theoretical Model and the Hardware Oriented Model in red and blue, as before. This time, we distinguish between topologies obtained from the use of a fitted η (dark blue) and the empirical *eta* (light blues). We also show the CDF for minimum hop trees

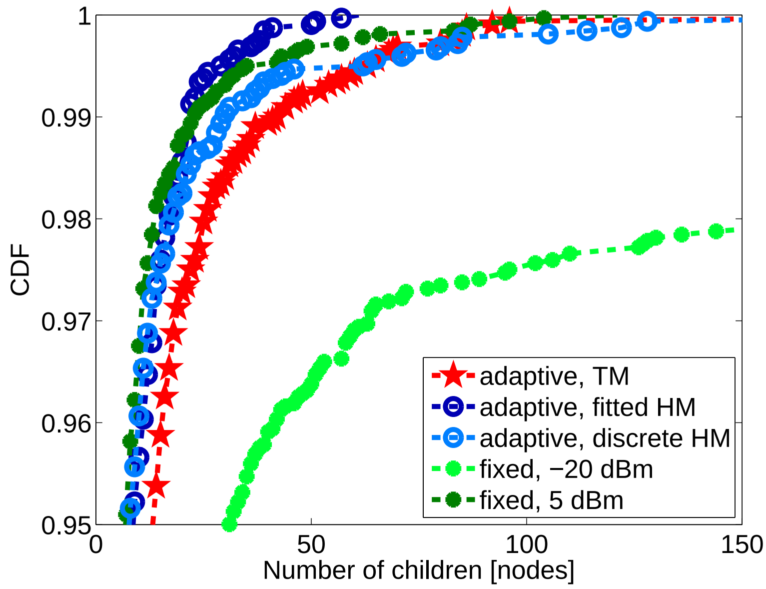

Figure 6: Relaying load in different topologies

for fixed output power in light and dark green for -20 and 5 dBm respectively. Observe that, while distributions of the path length in the topologies resulting from the use of the fitted and the empirical η could not be distinguished from the situation of fixed maximal output power, this is not the case for the number of children each node has. This is due to the nature of the cost metrics which we used with the Dijkstra algorithm: While discrete metrics (hop count and typical current consumptions for a limited number of output powers) were used for minimum hop trees and the empirical η under HM, for the creation of an energy minimizing topology using the Hardware oriented Model with the fitted η, the continuous metric shown in Fig. 2 was used. The CDFs demonstrate, that for load balancing purposes, a continuous cost metric like HM seems to be better suited. The other fact illustrated by this figure is that, longer hops result in an increased number of relaying nodes, thus both in the MTE established according to TM and in the minimum hop topology for the small output power, the number of heavily charged nodes is higher and the number of nodes not required as relay is smaller.

In the case, where minimum energy trees are established, we assume perfect power control, i.e. we consider an idealistic scenario where the nodes are able to adjust their transmission power to the minimal value required to reach their next hop. Thus, the comparison of the distribution of the link lengths in the resulting topologies is another criterion to differentiate the routing topologies. In Fig. 7, we therefore show the probability density function (PDF) of the link length, i.e. the distance between one sensor node and its next hop on the path towards the sink. To illustrate the capabilities of the radio chip, we indicate the transmission distances corresponding to the different possible transmission output powers of CC1000 by vertical dotted lines. We show again the

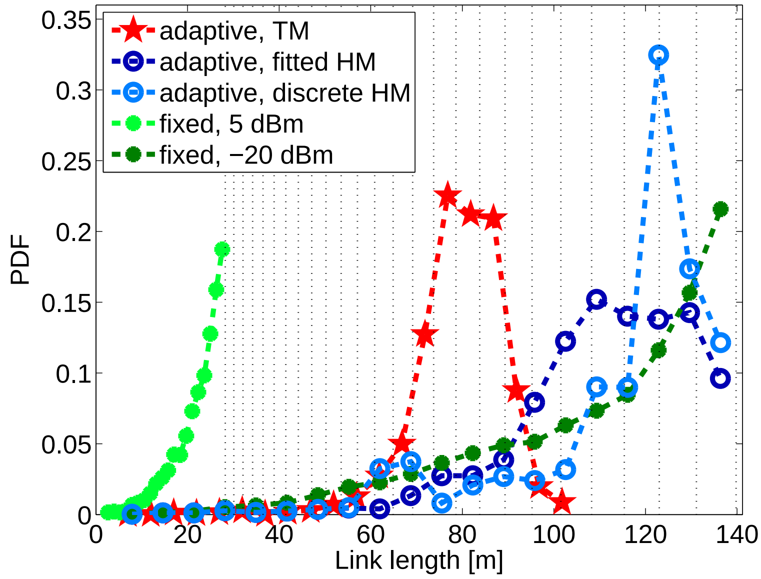

Figure 7: Link lengths in different topologies

PDFs of the link length in the topologies with transmission output power fixed to -20 and 5 dBm in light and dark green. It can be nicely seen, that for the first case, all links are shorter than 28 m which corresponds to the maximal achievable distance with this power. In the case, where all nodes use the maximal power, over 20 % of all links have the maximal feasible length of 139.8 m. Shorter links exist only between nodes which are closer to the sink than this border. The comparison between the PDFs representing the topologies generated according to HM and TM (shown in blue and red) yields the same result illustrated earlier: due to the higher path loss exponent and the low reception costs under TM, shorter hops are preferred, if routing is done according to this model. The discrepancy between the representation of topology created according to HM using the fitted and the empirical η shown in dark and light blue respectively, is explained by studying the characteristics of the empirical η and its fit, depicted in Fig. 1: in general, the linear fit is roughly capturing the values obtained from typical current consumptions, but the curve representing the empirical values is not monotonically increasing, which results in the peaks in the PDF representing the distribution of the link length for the empirical HM.

Next, we compare the transmission output powers which would be required by sensor nodes using the CC1000 in the 868 MHz band to build the theoretically established routing tree. That is, we determine for each node the minimal transmission output power which would be necessary for Mica2 nodes to reach its next hop. The resulting PDFs are shown in Fig. 8 and Fig. 9. As in the other figures in this section, we observe again that in the MTE established under the Theoretical Model, depicted by red stars in both figures, longer paths, thus shorter hops and smaller transmission powers are

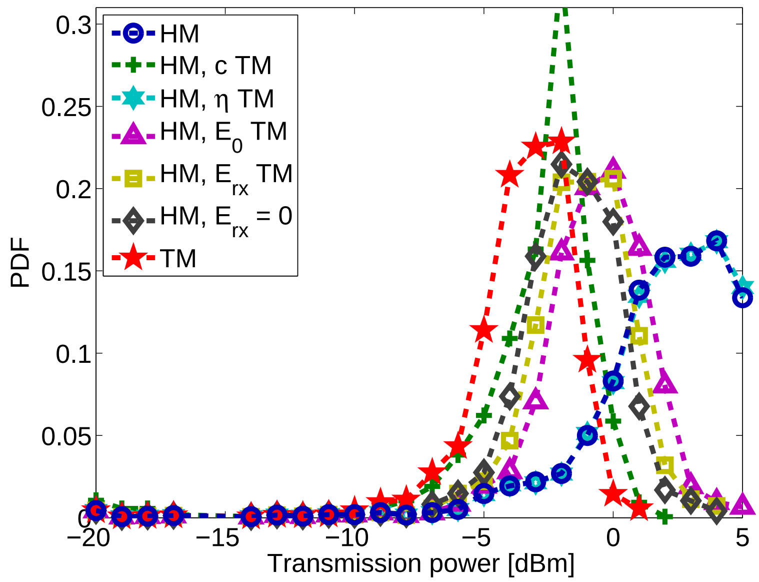

Figure 8: Transmission powers in the MTE resulting from varied HM

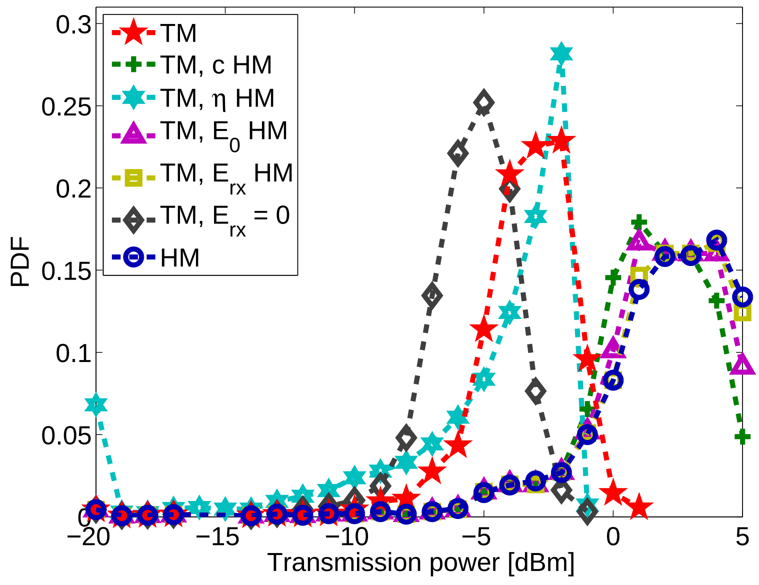

Figure 9: Transmission powers in the MTE resulting from varied TM

dominant compared to the topology emerging from the use of HM, for which we use dark blue circles. The PDFs in Fig. 8 demonstrate once more, that decreasing the distance independent costs in HM leads to slightly smaller transmission powers, whereas the variation of the path loss model leads to significantly smaller output powers. The analysis of the PDFs depicted in Fig. 9 reveals that the use of a distance dependent η under the Theoretical Model would result in topologies with high variant transmission output power distributions: while over 25 % of all nodes are using rather high powers, the percentag of nodes which operate at the smallest possible power is significantly higher than in the other MTE topologies. The other PDFs demonstrate, that while neglecting transmission costs leads to more smaller output transmission powers, all other variations result in metrics favoring longer hops, thus higher transmission powers. Once more, we see, that energy models for routing decisions have an enormous impact on the shape of energy efficient routing trees.

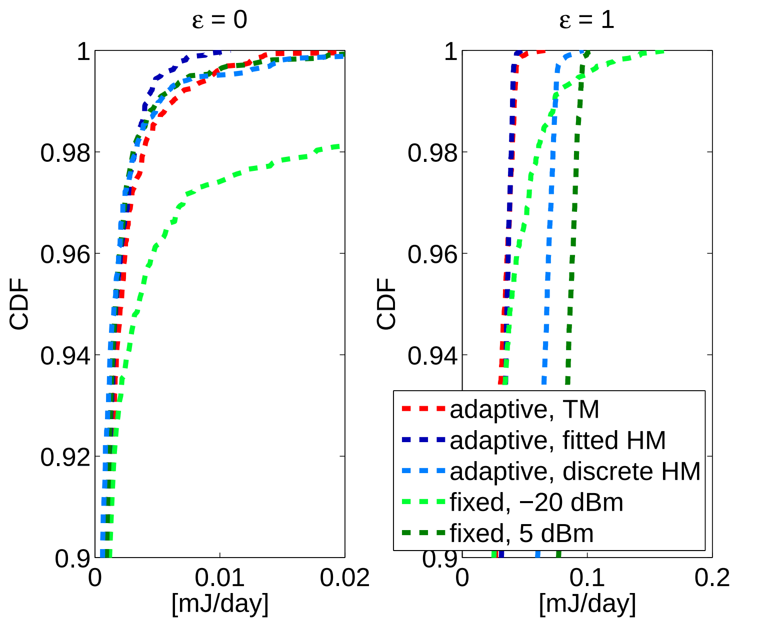

Figure 10: Daily energy consumptions in different topologies

The last three figures in this paper are dedicated to the analysis of the energy efficiency of the created topologies. To obtain numerical results, we assume sensor nodes that have Mica2's characteristics, i.e. need 0.6 μW in sleep state, 28.8 mW for receiving and between 25.8 and 76.2 mW for transmissions in the 868 MHz band, if $U = 3$ V is assumed. Per $u = 1$ minute, each node has to create and send $\lambda = 1$ measurement packet towards the sink node. All transmitted data packets carry 10 byte of measurement data, 4 byte are needed for addressing purposes. To illustrate the influence of the MAC efficiency, we depict results for an idealistic MAC protocol, where no sensor node overhears foreign transmissions and for the case, where everything is overheard, i.e. $\epsilon = 0$ and $\epsilon = 1$ respectively. Any reasonable MAC protocol will result in a value somewhere in between, we use the extreme values for a demonstration of the impact of this factor. In the case, where the node receives a packet which it is not addressed to it, it can return to sleep state, after having read the address field.

In Fig. 10, we compare the CDFs of the daily radio related energy consumptions obtained from the model presented in Section 3.2 for topologies obtained for adaptive and fixed transmission power. We consider again MTEs created in respect to the pure HM and TM and minimum hop trees for fixed output power. The left figure, which describes the ideal situation, illustrates, that higher transmission output powers result in smaller per node energy consumptions, if overhearing effects are neglected. This is simply due to the smaller amount of consumed bandwidth and has been observed earlier [11]. In the case, where all transmissions have to be overheard, depicted on the right, the estimated energy consumptions are nearly ten times higher. Next, according to this metric, the two MTEs are nearly equal and the use of the empirical η for HM leads to topologies with higher energy consumptions. Furthermore, the average energy consumption in the minimum hop topologies for higher output power is not significantly smaller any more than compared to smaller transmission output power. This is explained by the structure of Eq. (8): the number of eventually overheard messages increases with the transmission power, if all messages are overheard, this leads to a significant reduction of sleep time and hence an increase of energy consumptions.

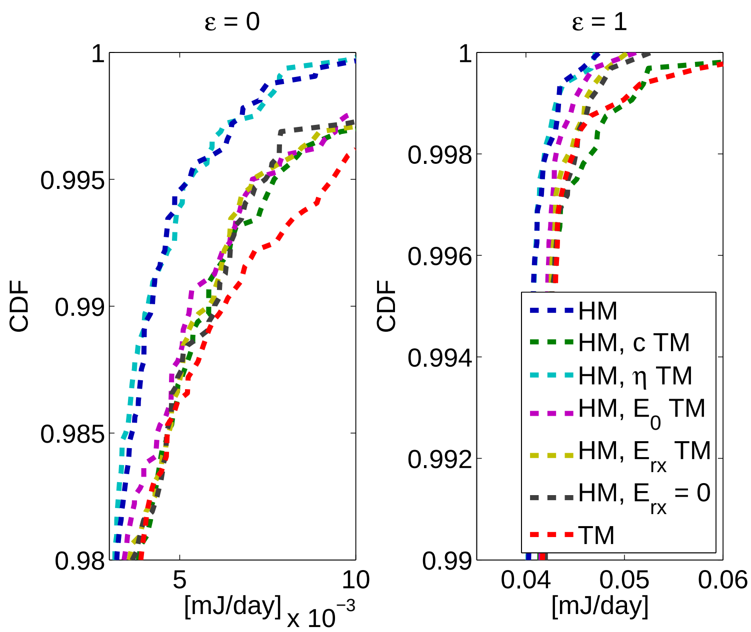

Figure 11: Daily energy consumptions under varying HM

In Fig. 11, where the daily per node energy consumptions for MTEs created according to variations of the Hardware oriented Model are shown, the same observations can be made. We saw however earlier in this section, that the topologies resulting from variations of HM do not vary strongly, the energy consumptions are thus rather similar, as the output powers differ not that strongly (see Fig. 8). One can nevertheless observe, that smaller output powers are only less energy efficient, if an ideal MAC protocol is assumed. Again, the differences in the daily energy consumptions between the topologies are stronger for the case of $\epsilon = 0$, as in this ideal situation the energy consumptions depend only on the load of the node. If the overhearing effect is taken into account, the energy consumptions is dominated by the reception of unwanted messages, hence all obtained CDFs are rather similar.

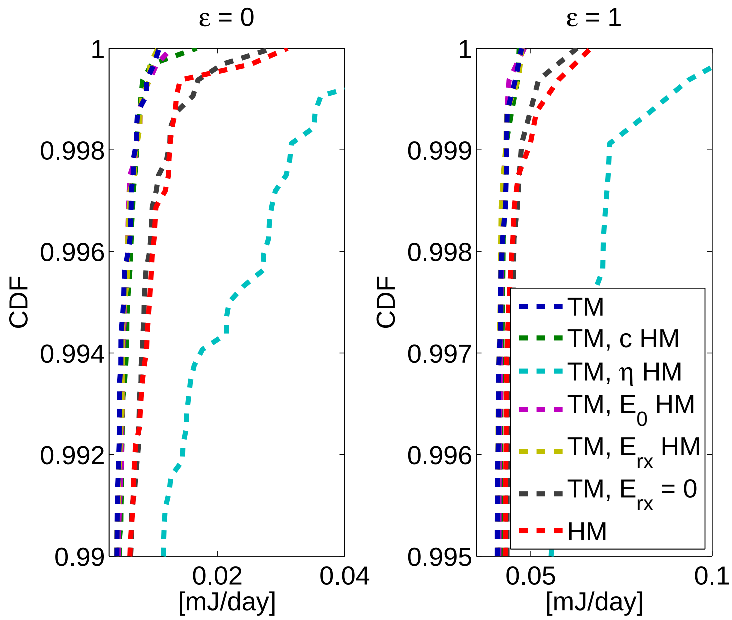

Figure 12: Daily energy consumptions under varying TM

A comparison of the CDFs of the daily per node energy consumptions in the minimum energy trees created according to variations of the Theoretical Model is shown in Fig. 12. It reveals first, that as in the other figures, the energy consumptions are ten times higher for the worst case MAC efficiency $\epsilon = 1$. Next we see, that again, the differences between the topologies become more striking for the case of $\epsilon = 0$ and vanish if $\epsilon = 1$. The significantly higher per node energy consumptions in the topology which is created with a path loss exponent of 4 and the distance dependent drain efficiency, depicted in ocean green, illustrates that an unsuitable energy model can lead to wrong routing decisions: Under this metric, each piece of data has to travel along more hops to reach the sink than in any other minimum total energy topology, as the metric predicts this choice as energy efficient. The CDF of the energy consumption distribution for this topology demonstrates, that if this theoretically designed routing tree will be established in a topology consisting of Mica2 motes, the resulting energy consumptions will be outstanding, as too many unnecessary hops will be used.

5 Conclusion and Outlook

The proposals for analyzing energy consumptions in sensor networks are countless, but for any analytical work, one model out of the large number of energy consumption abstractions has to be chosen. To compare the impact of the different modeling assumptions, we chose a well known analytical problem and investigated, in how far the shape of analytically designed energy efficient routing trees for a large sensor network deployment varies with the used energy consumption metric. To examine the influence of different modeling assumptions, we identified four components of the transmission costs and found that the abstractions of channel characteristics and the drain efficiency of the power amplifier influence the analysis of transmission energy consumptions more heavily than the precise value of constant costs, as long as they are not neglected. We furthermore estimated the energy consumptions in the created topologies and found that, if the influence of the MAC protocol, i.e. the number of unwanted transmissions a sensor node is forced to overhear is considered, the per node energy consumptions vary strongly. This often neglected factor is also responsible for a possibly wrong estimation of energy consumptions: if an ideal MAC protocol is assumed, topologies with a few long hops are rated to be by far more energy efficient than the ones with more short hops. This statement does not hold any more if the effect of overhearing is considered, as for larger transmission ranges, more energy may be consumed for discarding unwanted messages. Thus, for any statement concerning per node energy consumptions, the consideration of the MAC layer and the structure of the routing topology is vital. All in all, our findings illustrate, that energy models used for the design and analysis of real world deployments have to be chosen with care and in respect to the used hardware, as a bad design choice may lead to incorrect routing decisions.

Our future work will be dedicated to the deeper investigation of physical and medium access layer effects and their influence on energy modeling. We plan to extend our energy consumption estimation model by a more detailed analysis of lower layer overhead to investigate the impact of various factors on typical problems of sensor network analysis.

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