A Closer Look at the Association Procedure in Low Power 802.15.4 Multihop Sensor Networks

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ABSTRACT

IEEE 802.15.4 proposes the advantage of a standardized low power low data rate communication stack and is therefore also an option for deploying low power wireless sensor networks (WSNs). Most studies of 802.15.4 based WSNs concentrate on the *operational* phase and neglected the *initial* startup phase. This bears however also potentials for energy savings, as the 802.15.4 association procedure has to be executed to make the network operational and is not optimized for low power networks. In this study, we point out directions how to perform the association in a self organizing and energy saving way.

1. INTRODUCTION

Among the existing standardized wireless communication solutions, the IEEE 802.15.4 standard [5] seems to be the most suitable for WSN purposes, as it is targeted at low power, low bandwidth networks, characteristics which match most sensor network applications. For home automation and industrial control purposes, the ZigBee Alliance [2] and the HART Communication Foundation [1] respectively specified higher layer protocols based on the 802.15.4 PHY and MAC. These protocols enhanced 802.15.4 and made it very popular for commerical applications with limited battery power and small throughput requirements.

In the academic community, the interest for 802.15.4 has also grown and numerous studies focused on the performance evaluation of the WPAN standard made its benefits and deficiencies well known. If, however, 802.15.4 WNS running on batteries shall become reality, one major problem resides. If the network is running in the *beacon mode*, a central coordinator broadcasts beacons, i.e. special command messages for synchronization purposes to all nodes in the network. This enables all devices to operate with superframes consisting of an active and a passive phase, where devices can be put to sleep mode. In the absence of a central coordinator, this fixed structure is not existing in the *nonbeacon mode*, which enables larger and more flexible topologies and is hence a good choice for 802.15.4 WSNs. If the network shall enable a distributed routing solution, no energy saving options for the nonbeacon mode are given in [5]. In earlier works we therefore investigated the effects of a simple sleep scheduling solution, where the sensor nodes duty cycle at a regular schedule and loosely synchronize with their neighbors. Allowing the sensor nodes to sleep a fraction $1 - p_w$ of a fixed epoch length T, this algorithm operates between the 802.15.4 MAC and a ZigBee routing layer and promises acceptable packet delivery ratios even at low duty cycle for the price of an increased end-to-end delay [7].

The question how such a duty cycle network can successfully start up both autonomously and efficiently, has not yet been considered. Each sensor node wanting to join a 802.15.4 network (also called personal area network (PAN)), has to *associate*, i.e. exchange a sequence of organizational messages with the PAN coordinator or with an other node which already has associated with the PAN. This procedure is mandatory for 802.15.4 networks and has not been designed under consideration of duty cycled or lossy networks. A closer look on the energy optimization potentials of the association procedure will therefore be presented in the following: In Section 2 we review related work. In Section 3, we formalize the association procedure using an analytical framework. In Section 4 we present some early simulation results, before we conclude in Section 5 and outline our future research.

2. RELATED WORK

One of the first performance evaluations of 802.15.4 in ns-2 [9] is reported in [11]. This code is still the base of the actual 802.15.4 WPAN ns-2.33 simulation framework we adapted for our purposes. Among other mechanisms, the association procedure was also studied in [11]. The association process as outlined in the standard is not optimized for the case of large, duty cycled or lossy networks with only one coordinator: It does e.g. not handle the situation, that a node wanting to join a PAN does not receive a beacon upon its active channel scan. To solve this issue, [11] proposes each device which is unable to associate at first attempt to retry to associate after an *associationRetryInterval* $a = 1$ sec later. As the authors focus on beaconed networks, and the sensor nodes do never go to sleep state, those results are of limited use for the case of non-beaconed low power networks.

In [6], the authors establish analytical models for computing the time and energy consumptions for 802.15.4 specific mechanisms. Furthermore, typical power consumptions and goodput for devices and coordinators are derived and verified by simulation. The reassociation procedure, i.e. the case where a node loses the contact to the coordinator it associated with, is handled, the initial association procedure is not covered. Furthermore duty cycling nodes are not considered, the analysis is thus difficult to apply to our problem.

The authors of [4] exploit the hierarchical dependency resulting from the 802.15.4 association procedure for a establishing a hierarchical routing scheme. HERA, as this algorithm is called, outperforms AODV, which is proposed by the ZigBee Alliance for self organizing 802.15.4 networks, in simulations in terms of packet loss, delay and energy consumptions. This is mainly due to routing overhead, as HERA gets the initial routes for free by exploiting the association messages. The authors do not mention whether HERA can be extended to duty cycling networks and do also not analyze the association procedure. Their interest is just on the operational phase of the network lifetime, demonstrating the benefits of the association procedure. Together with an optimized energy efficient association procedure, HERA could be a promising approach for low power networks.

3. ANALYTICAL FRAMEWORK

3.1 Problem Description

In the last section, we presented some examples out of the numerous energy efficiency studies of 802.15.4 algorithms. They are good example for all studies we know of, as they mainly concentrate on the operational phase of the network. For this purpose, the network is in general assumed to be associated and routes stable. A reasonable approach, if e.g. the average delay of a packet routed in a WSN is of interest. As the association procedure of 802.15.4 networks is a vital MAC layer functionality [5], we will concentrate on the initial phase of a 802.15.4 WSN in the following.

A good description of the association procedure can e.g. be found in [11], we only recall the most important facts: Sensor node n activated in a nonbeacon-enabled multihop PAN will start an *active channel scan*, i.e. it broadcasts a *beacon request command* and waits for a response for an application specific time. This procedure will be repeated on all or some of the available channels. The PAN coordinator or a device which has already associated, will send a beacon, containing information about the PAN it belongs to, in response to this request. After having scanned all channels, n chooses a PAN for associating among the PANs it got to know of and exchanges a sequence of command messages with the sender of the corresponding response.

As mentioned earlier, [11] proposes each device which is unable to associate at first attempt to retry to associate after an *associationRetryInterval* $a = 1$ sec later. For the case of a self organizing duty cycled network which may be not synchronized at the beginning, this solution is not always successful. Especially in sparse and low duty cycled networks, a node may have *physical* neighbors, i.e. nodes within its range, but may be *temporally* isolated, as it does not share waketime with the nodes in its radio range. Using a fixed a will thus very likely not result in a successful association.

In this initial work we will point out directions for enabling a low power association procedure, investigating the following strategies:

1. choose a at random, but dependent on the duty cycle, e.g. $a = U(0, xp_w)T$, where $0 < x \leq 1$,
2. choose a at random, but independent from the duty cycle, e.g. $a = U(0, x)T$, where $0 < x \leq 1$,
3. choose $a = x$, where x is an arbitrary constant.

Above, $U(a, b)$ stands for a random variable, uniformly distributed in the interval $[a, b]$. Those simple choices already result in a vast parameter space, we postpone the investigation of advanced options, like deriving from the fixed duty cycling schedule therfore to future works.

3.2 Evaluation

To compare the benefits and trade-offs of the different solutions, we will use the following metrics for all nodes n of a WSN topology. Numerical values for the metrics are obtained as averages from ρ simulation runs.

- $s_A(n) \in \{0, 1\}$ indicates if n was able to associate during a target time Δ. Averaging $s_A(n)$ over ρ runs clearly leads to $0 \leq s_A(n) \leq 1$.
- $t_A(n)$, gives the time when n is associated.
- $E_A(n)$ denotes the energy n consumes until it is associated.

Obviously, these metrics vary heavily between nodes of the same topology. But the influence of the duty cycle, the starting order of the nodes, the used transmission output power, the network density and more factors make it hard to obtain a general closed form analytical expression. Before we evaluate the different association strategies in topologies with varying characteristics in a simulation, we have a closer look at the different metrics.

3.2.1 *Association Success* $s_A(n)$

The most straightforward metric of our model is the association success or percentage: Given a typical initial tolerance interval Δ, with which probability are the nodes able to associate? In the optimal case, $s_A(n) = 1$ for all nodes, but in some scenarios it could happen, that not all nodes are able to associate to the network resulting in $s_A(n) < 1$.

3.2.2 *Association Time* $t_A(n)$

The association time is obtained from simulations, but it may be broken down analytically, too:

$$t_A(n) = t_0(n) + n_A(n)t_{scan}(c) + (n_A(n) - 1)a + t_a. \quad (1)$$

The first component of $t_A(n)$, $t_0(n)$ denotes the randomly distributed time, node n waits between the deployment of the network and its first attempt to associate. The number of association attempts $n_A(n)$ is greater or equal than 1. Node n will thus scan $n_A(n)$ times the channel, needing a time $t_{scan}(c)$ which is application specific [5] depends additionally on the number of channels to scan, c, which we adopt to be equal to 3 [11]. Upon an unsuccessful association attempt, n will wait for a before retrying, until it requires finally a timespan t_a for exchanging the association command messages [5].

3.2.3 *Association Power Consumptions* E_A

Our interest is on layer 3 and below, we therefore neglect power consumptions for data acquisition, handling etc. and focus on estimating the energy consumptions of the transceiver. For this purpose, we abstract the sensor node radio unit to a state machine and use the periods, a sensor node spends in each state to estimate the transceiver power consumptions. For 802.15.4 performance evaluations, this approach which has been introduced by [3]. We extend upon this model by including the results of [10]. The authors propose to use a simplified radio control state machine extracting values for current consumptions and times required in states or for state transitions from transceiver data sheets and using a typical voltage of $U = 1.8V$. By measurements, they showed that that this so called Communication Subsystem Energy Consumption Model (CSESM) is exact enough for an analysis. In Fig. 1 we show the corresponding simplified state machine for Texas Instruments' CC2420 [8], which is a widely used 802.15.4-compliant transceiver module. The durations and power consumptions of states and transitions are taken from [8] or estimated as the average of the two initial and final state for the transition [10].

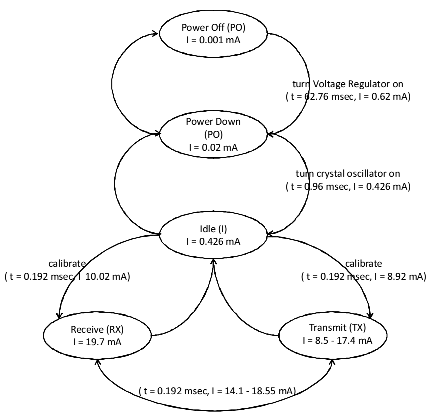

Figure 1: Simplified state machine of CC2420

For analyzing $E_A(n)$, we focus on node n and neglect the costs the node which with n associates has for sending the association beacons to n. As CSESM is not yet implemented in our simulation framework, an estimation for $E_A(n)$ is obtained using Eq. (1):

$$E_A(i) = E_{start} + n_A(i)E_{scan}(c) + (n_A(i) - 1)E_R + E_a, \quad (2)$$

where E_{start} denotes the energy required for the transition from "Power Off" to "Receive" state. In our simulation, nodes always transmit at maximum power, we therefore overestimate E_{scan} and E_a by multiplying t_{scan} and t_a respectively by U and $I_{RX} > I_{TX}$ [8]. The energy consumed during the period where the node waits for a retry to associate is obtained by adding the energy consumptions for transitions from and to "Power Save" state to the energy consumptions in "Power Save" for the remaining time of a.

4. SIMULATION RESULTS

For analyze the performance the 802.15.4 association procedure under varying conditions, we simulate it in ns-2.33. To reduce side-effects, we concentrate on a very simple topology: 9 sensor nodes and one sink node, taking the role of the PAN coordinator, are situated on a line, separated by either 4 or 5 m. We use node IDs from 0 to 9, for the sink node and the sensor nodes in increasing distance from the sink. The node with ID 9, has thus the greatest distance to the PAN coordinator. Using the default loss-less ns-2 two ray ground channel model with the radio characteristics of CC2420, and considering varying transmission output powers, each node can communicate with 1 to 4 neighbors per direction. Furthermore, we chose $\Delta = 5$ min for $T = 1$ sec. To obtain repeatable results, we use the seeds from 1 to 20 for 20 simulation runs which were found enough to result in satisfying confidence intervals for all considered mean of the considered metrics. For sakes of clearness, confidence intervals are thus not shown.

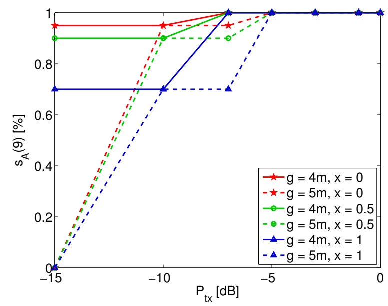

Figure 2: $t_A(9)$ for strategy 3

A self organizing PAN initialization is simulated as follows: The nodes 1-9 are activated in a random order, with a time of $U(0,1) \cdot 60$ sec between the start times. After having started, each node tries to associate to a PAN using the procedure described in Section 3.1. During most of our simulation runs, Δ was found to be enough for all nodes to associate. Only for $p_w < 5\%$, a transmission output power resulting in the smallest connectivity degree, and nodes close to the sink starting last, it occured, that the outmost nodes were not able to associate. The association success of node 9, $s_A(9)$ for the extreme scenario $p_w = 1\%$ is thus a good metric for the quality of an association strategy. In Fig. 2, we illustrate the percentage of simulation runs, node 9 was able to associate under varying transmission powers, inter node spacings and parameters for setting a according to strategy 3, i.e. $a = x$. Different colors and markers show different values for x. Sparser topologies, i.e. with the inter grid spacing $g = 5$ m are shown by dashed lines, solid lines are used for $g = 4$ m. The monotonic increase of the curves and the fact that the association success for $g = 4$ m and the same value of x is always greater or equal then for the same x and $g = 5$ m, illustrates, that the association success is increasing with the connectivity of the network. While this is an obvious result, another observation is more surprising: The highest association success is guaranteed for $a = 0$, i.e. if node 9 immediately retries to associate after an association failure. Our studies showed, that in denser topologies, this behavior leads to unnecessary channel contentions, choosing a larger, but randomized a is more advantageous in these scenarios.

Fig. 3 illustrates how the time required for successful association varies with the relative position of the node and the duty cycle in a topology where all nodes can only communicate with their direct neighbors and under strategy 1, with $x = 0.1$, i.e. $a = U(0, 0.1p_w)T = 1$ sec. We use a surface plot and study the influence of very small duty cycles more closely. Observe, that $t_A(n)$ is increasing strongly with the distance from the sink and the sleep time $(1 - p_w)T$. This increase was observed for all chosen parameterizations of a and all topologies, but differs in magnitude for varying radio range and parametrizations of a. Keep in mind, that the surface plot shows mean values obtained from 20 simulation runs: the results obtained from the individual runs varied more strongly, as t_A depends strongly on the startup time of the different nodes.

Eq. (2) makes clear, that the energy a node consumes

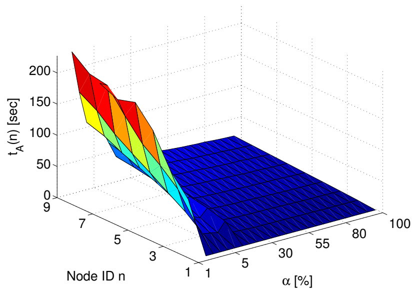

Figure 3: t_A for varying activity and strategy 1

associating to the network is proportional to the number of association attempts $n_A(n)$ it has to make. Our studies showed, that in most cases, node 9 has to make the most association attempts, the energy consumptions of node 9 are thus suitable as benchmark metric. We illustrate the association energy consumptions of node 9, $E_A(9)$ for a transmission output power of -15 dBm which corresponds to a node being able to communicate with its next hop neighbor in Fig. 4. Estimations for the energy consumptions were obtained from Eq. (2) under strategy 2, i.e. $a = U(0,x)T$ are presented. The most straightforward observation is that energy consumptions obtained for $g = 4$ m are smaller than for $g = 5$ m. This is in accordance with Fig. 2, as an increased network density reduces $n_A(n)$. Next, the curves representing results for the same g intersect indicating, that the optimal length of a depends on the activity ratio p_w. Moreover, the curves increase strongly for $p_w < 5\%$, leading to association energy consumptions in the range of 10 J and make it hard to identify the most advantageous strategy. This illustrates, that more studies for very low duty cycles and more sophisticated algorithms for the association procedure are necessary.

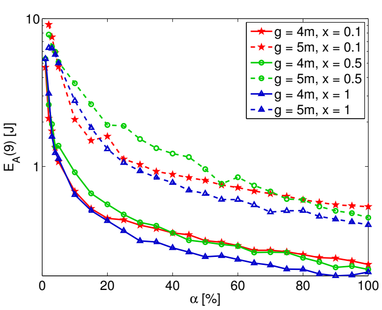

Figure 4: $E_A(9)$ for strategy 2

5. CONCLUSION

In this paper, we examined possibilities for enabling the association process in a self organizing low power 802.15.4 nonbeaconed sensor network. To our knowledge, this problem has not been studied before. We pointed out directions for an efficient solution, by examining three different simple strategies for proceeding after the initial association attempt fails. To compare the benefits and trade-offs of the individual solutions on the performance of the WSN startup phase, we used three metrics suitable for characterizing the qualitative and quantitative performance of a specific association solution.

Our results illustrate the inherent energy saving potentials of the often neglected start up phase of a 802.15.4 sensor network. In dependence of the strategy and the network connectivity, the association retry interval has to be chosen with care in order to avoid wasting energy: We found, that, under some conditions, too short retry intervals lead to unnecessary channel scans and beacon collision, thereby deteriorating the association performance. Under other conditions in contrast, shorter retry intervals are speeding up the association procedure significantly. Our results thus demonstrated, that extensive studies on a wide range of parameters are necessary, as many interacting factors influence the performance of the association process and that an optimal strategy has to consider a huge range of aspects. An extensive factor screening for comparing the benefits and trade-offs of different association mechanism will therefore be the topic of future works.

6. REFERENCES

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