Enabling the Sleep Mode in Non-beaconed 802.15.4 Multihop Networks - A Simulative Investigation

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ABSTRACT

Large wireless sensor network deployments used for environmental monitoring or cargo tracking, require energy efficient mesh topologies. This implies duty cycling of sensor nodes to be coordinated with the routing protocol. Staying in the context of ZigBee, we simulate the combination of the sleep enabled non-beaconed mode of 802.15.4 and AODV routing and compare the duty cycling effects of synchronized and unsynchronized sleep scheduling. We consider two different link layer feedback schemes for AODV, denoted as *regular* and *smooth* AODV.

1. INTRODUCTION

The large number of purposes, a Wireless Sensor Network (WSN) can be dedicated to, are as different as habitat monitoring, animal tracking, environmental surveillance, forest fire detection, cargo tracking, industrial automation, home automation or intrusion detection. All those situations have specific requirements and challenges, thus the deployed hardware, radio communication techniques and protocols are manifold.

The use of a standardized communication layer would simplify and enable the interoperability of different WSN deployments. Among the existing IEEE wireless communication standards, 802.15.4 [2] seems to be the most suitable. It specifies the PHY and MAC layer for low rate Wireless Personal Area Networks (LR-WPANs) and promises to enable cheap wireless networking for applications with limited battery power and small throughput requirements. ZigBee is a set of network, security and application layer protocols, that were specified upon 802.15.4 to create a universal platform for use cases like home, building and industrial automation [9].

In these situations, one hop star topologies, where a single (PAN) coordinator broadcasts beacons to synchronize surrounding devices, are most suitable. Thus, much work has been dedicated to the performance analysis of those so called *beacon-enabled* 802.15.4 networks. If however, large scale multihop 802.15.4 WSNs with battery powered nodes should be established, these have to be realized as *non-beacon-enabled* PANs. The most outstanding issue in such networks is their size: they are too large to be synchronized by a single PAN coordinator but nodes have also to switch to sleep state to increase the battery lifetime. It is proposed to use an AODV [4] like routing algorithm for non-beaconed PANs [9], hence, sophisticated distributed sleep scheduling strategies have to be deployed to make such a routing algorithm work. In this work we investigate non-beaconed 802.15.4 networks and especially the interdependency of multihop routing and sleeping sensor nodes. As most previous work has focused on beaconed 802.15.4, these problems have not yet been considered.

This work is structured as followed: In Section 2 we review related work. In Section 3, we describe the simulation setup in *ns-2* [7], we used for our performance evaluation, whereof we show results in Section 4. In Section 5 we conclude and give an outlook on future work.

2. RELATED WORK

One of the first performance evaluations of 802.15.4 is reported in [8]. The authors used *ns-2* to investigate the general performance of 802.15.4 and inquired various aspects like the efficiency of slotted and non-slotted CSMA/CA during the contention access period (CAP) of a 802.15.4 superframe more deeply. The authors did however not consider the problem of establishing a multihop routing topology and assumed, that their nodes were always on. To analyze the CAP and the influence of radio-shutdowns on the energy consumptions more deeply, the authors of [5] implemented a more realistic energy and node state model. More modifications to the code have been made by the authors of [6], who examined the influence of the number of backoff periods used for CSMA/CA in the CAP on the network efficiency.

The requirements for a WSN MAC protocol comprise more than just channel access. In order to guarantee a maximal lifetime and nevertheless maintain a certain transmission delay and throughput, the MAC layer is responsible for duty cycling the sensor node's radio unit [3]. As the challenges are manifold, more than 50 different proposals for MAC WSN protocols exist. The 802.15.4 standard, however, does only specify the channel access and does not consider sleep scheduling. As this is mandatory, if 802.15.4 shall be used for sensor networks, we examine the performance of two straightforward duty cycling concepts, namely synchronized and randomly scheduled sleep periods.

If 802.15.4 shall be used for a multihop WSN, a routing topology has to be established. The applicability of the classical AODV and several of its modifications has been investigated in a 802.15.4 testbed consisting of 15 nodes [1]. The results showed, that both the existing and the newly proposed protocols are not suitable for sensor networks, as the routing overhead consumes too much energy. We therefore extended the existing *ns-2* AODV implementation by some modifications discussed in the ZigBee specification [9], which concern the broadcast mechanism and the link layer feedback handling.

3. IMPLEMENTATION DETAILS

3.1 Sleep Scheduling

Minimizing energy consumption is a key challenge for any WSN deployment. Thus, in a non-beacon-enabled 802.15.4 WSN sleep scheduling has to be managed. As this is not specified for the non-beacon-enabled mode [2, 9], this problem has also not been considered by the existing *ns-2* implementations [5, 8]. The most intuitive idea of letting each node independently wake up for sending and going to sleep afterwards can't be applied, as in multihop networks most nodes have to relay packets for other nodes. We therefore decided upon another simple method and implemented the sensor node duty cycle as an on-off-process. Each node in the network is awake for the same fraction p_w of a constant time interval T and spends the rest in sleep state. $p_w = 100\%$ corresponds to an always-on node. To decide, *which* part of T the node is sleeping, we considered two different strategies: The *random* scheduling strategy starts the simulation by letting the nodes go active for $p_w T$ at randomly distributed times, then sleep for $(1 - p_w)T$ and so on. The *synchronized* scheduling strategy assumes, that the entire network is either on or off.

This fixed duty cycle is kept, expect for one situation: If a node is on the point of going to sleep, but still has a packet in the send queue, this packet is not discarded but sent, and therefore some time of the sleep period is cut off. Note that, in the random system, especially if $p_w < 0.5$, it can happen, that some nodes will not be able to communicate, as they are never awake, when their neighbors are. Moreover, the usage of randomly distributed starting points of sleep and wake phases introduces changing routes during the initialization process. This is not the case under the synchronized schedule, but the collision probability is increased in this case, as all nodes try to send during the same small activity period.

3.2 Routing

For routing in a multihop ZigBee mesh network, the ZigBee specification proposes an algorithm which is very similar to AODV [9]. For a first analysis, we thus take the existing *ns-2* AODV implementation [7] and include the proposed modification to jitter the route request broadcast. Moreover, link layer feedback (LLF) which is given after three not received acknowledgments, thus failed MAC layer retransmissions, is used to announce failed transmissions, upon which the link is considered as broken and the route error mechanism is started. This consists basically of starting possibly a local repair and sending out an error message to the neighboring nodes. However, the cause of the outstanding ACKs could not only be a dead, but also a sleeping destination or a packet collision which are quite frequent in dense or low duty WSNs. Thus, if messages are broadcasted after each LLF, these messages can easily flood the system, and decrease the system performance. We propose therefore *smooth* AODV with a modified LLF handling, as indicated within the ZigBee specification [9], and summarize this mechanism in Fig. 1. In contrast to the *regular* AODV, *smooth* AODV only assumes a link failure, if the number of LLFs n_c during a certain *guard interval* g does not exceed the *LLF threshold* L_T. We introduced these two parameters to tolerate occasional transmission failures and found, that they improve the system performance significantly.
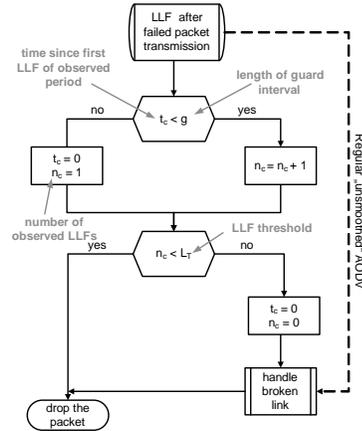
Figure 1: Modified LLF handling in smooth AODV

3.3 Simulation Setup

To investigate the performance of smooth AODV in a non-beaconed 802.15.4 multihop WSN, we used a grid layout of 49 nodes with an inter-node spacing of 5 meters. The PAN coordinator, also playing the role of the traffic sink, is in one of the grid's corners. We limited the radio range to 12 meters and assumed failure free transmissions, as our research is targeted on the interaction of MAC and routing layer. We used a simplified sensor node life cycle model and assumed, that each node is either transmitting, receiving which is equivalent to listening or sleeping and consumes a power of 35.28 mW, 31.32 mW or 0.144 μW respectively. These values have been taken from [5] and are representative for state-of-the art hardware. The duration of one simulation run was $t_{sim} = 10000$ sec, and we used $T = 1$ sec, $g = 12$ sec and $L_T = 3$. We assumed furthermore, that each node tries every $\Delta t = 50$ sec to send a data packet of size $s = 50$ byte to the sink.

4. SIMULATION RESULTS

The goal of this section is to investigate the performance of *regular* and *smooth* AODV for both *random* and *synchronized* sleep scheduling. The impact of the wakeup ratio p_w on the performance is investigated for the four different possible scenarios a) regular rand, b) regular sync, c) smooth rand, and d) smooth sync.

In order to quantify the performance of the system, we use the packet delivery ratio PDR which is defined as the ratio of received application datagrams at the sink and the sent application datagrams of a node, $PDR = N_{rcvd}^{app}/N_{sent}^{app}$. The resulting overhead required to find a path from a node to the sink is expressed by the number of sent AODV packets, N_{sent}^{AODV}. In this context, the used energy E_b per successfully received bit and the end-to-end (e2e) delay D are used. The latter one is the time from starting to send the application datagram until the time of successful reception.

Fig. 2 shows the packet delivery ratio for the four considered scenarios. In Fig. 2(a), the PDR for each sensor node in the spatial network layout is plotted depending on its distance to the sink for a wakeup ratio of p_w=90%. Each simulation run was repeated five times and the corresponding confidence intervals at a significance level of 95% are illustrated as errorbars around the average PDR values. If the

(a) p_w=90% online ratio   (b) $p_w = 50\%, 90\%, 100\%$
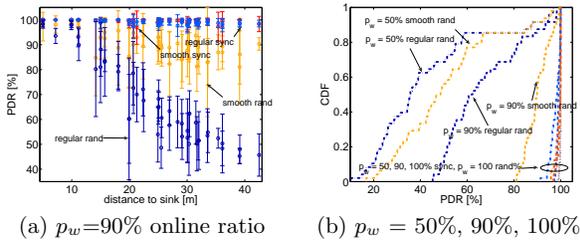
Figure 2: Packet delivery ratio PDR

(a) p_w=100% online ratio   (b) p_w=90% online ratio

Figure 3: Sent AODV packets

nodes are synchronized, i.e. regular sync or smooth sync, the PDR is nearly 100% for each node independent of the node's distance to the sink, but smooth AODV shows a marginally better performance than regular AODV. If the nodes are active in an unsynchronized fashion, the PDR drastically changes. While smooth AODV still leads to a PDR larger than 80%, the PDR using regular AODV drops below 50%, although the nodes are online 90% of the time.

Considering different online times, expressed by a different p_w, yields the same result. Fig. 2(b) shows the cumulative distribution function (CDF) of the average PDR values for each node, as given by the dots in the previous scatter plot. We now vary p_w from 100%, to 90% and 50%. If the nodes are always on, i.e. p_w=100%, or the nodes are synchronized, then the PDR is about 100% with only slight differences. For p_w=90% the difference between smooth and regular AODV is very large with 23% on average. For shorter online periods with p_w=50%, the difference of the PDR between regular and smooth AODV narrows and leads to very small PDRs in the unsynchronized case. To challenge this problem, the nodes in the sensor network should try to coordinate and in the best case to synchronize their wake times.

An explanation for this dramatic decrease of the PDR is given by the number N_{sent}^{AODV} of sent AODV packets per node, as depicted in Fig. 3. First, we consider the CDF of N_{sent}^{AODV} when the nodes are always active. In that case, the synchronized and the unsynchronized scheduling scheme lead to the same results. As soon as a node has found a route to the sink, there is no need to change it anymore. Nevertheless, there is already a small difference between regular and smooth AODV. This is caused by dropped datagrams, which is indicated by dropped AODV packets, cf. Table 1. Smooth AODV does not try to find a new route for each failed data transmission and uses additionally the guard interval to smoothen its reaction. Reasons for dropped AODV packets are packet collisions, a bad link quality according to a too low link quality indicator (LQI), or system drops because of elapsed time-to-live counters.

Fig. 3(b) shows the CDF of the number of sent AODV packets for each of the 48 nodes in the network. Note that the x-axis is scaled logarithmically in this case. The first observation is that N_{sent}^{AODV} strongly varies between the four different scenarios: For route establishment using both regular AODV and smooth AODV, under the random sleep scheduling scheme, one order of magnitude more AODV packets than under the synchronized scheme are required. Observe, that smooth AODV decreases the number of sent AODV packets significantly. The average number of sent AODV packets per node is about a) 1557 for regular rand, b) 102 for regular sync, c) 173 for smooth rand, and d) 30 for smooth sync during $t_{sim} = 10000$ sec.

The second observation is that a high activity ratio of
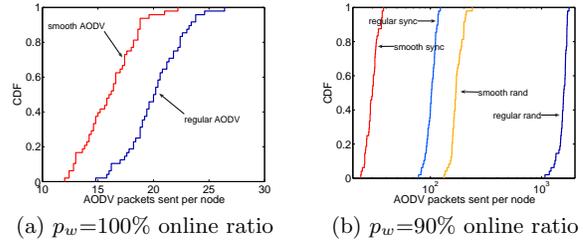
p_w=90% already requires a lot of AODV overhead if the nodes are unsynchronized and start their wake/sleep cycle at a random time instant. This means that for a random observer a node is offline with a probability of $1 - p_w$. For a route with H hops between source and sink, the probability that all nodes on the route are online is thus p_w^H. In the considered layout, we obtain for each path about 4 hops on average per node and about 7 hops at most. In the worst case, the packet is routed successfully with a probability of only p_w^H=0.48 for H=7 and p_w=0.90. Due to the emerging frequent route requests, the number of dropped AODV packets due to collisions or bad link quality increases which intensifies this effect even more, cf. Table 1. As a consequence, the packet delivery ratio will decrease even stronger in high load situations.

Next, we investigate this assumption by varying the offered load per node in the unsynchronized case and compare regular and smooth AODV in Fig. 4. Therefore, the interdeparture time Δt of two application datagrams at each sensor node is varied between 1 sec and 25 sec. Fig. 4(a) shows the normalized number $\hat{N}_{sent}^{AODV}$ of sent AODV packets depending on Δt for p_w=25%, 75%, 100%. The normalized number $\hat{N}_{sent}^{AODV}$ takes the online time of a node into account during which the AODV packets can be sent. It is $\hat{N}_{sent}^{AODV} = N_{sent}^{AODV}/(p_w \cdot t_{sim})$. Note that the y-axis is logarithmically scaled in Fig. 4(a). For p_w=25% and p_w=75%, $\hat{N}_{sent}^{AODV}$ is about 2.5 and 2.8 times larger for regular AODV than for smooth AODV, respectively. In both cases, the factor is independent of the time betwenn two packets, Δt. For p_w=100%, the smaller Δt, i.e. the higher the offered load, the larger is the difference between regular and smooth AODV. As expected, the normalized number of sent AODV packets is increasing, if p_w is decreasing. Fig. 4(b) shows the corresponding PDRs for the same scenarios. As mentioned above, the PDR is highly affected by the system load. For p_w=100%, smooth AODV softens significantly the impact of a high datagram frequency and reaches a PDR of 95%, while regular AODV results in a PDR of roughly 75%. For shorter online times, smooth AODV always outperforms regular AODV.

In Fig. 5, the sensitivity of smooth AODV is evaluated

Table 1: AODV packet collisions and LQI

		collisions		LQI	
		regular	smooth	regular	smooth
100%	un-/sync	991	733	752	577
90%	sync	5249	1958	4488	1006
	unsync	50215	9890	68693	6691
50%	sync	9369	2368	9276	1294
	unsync	22921	10690	32738	11936

(a) Sent AODV packets   (b) PDR
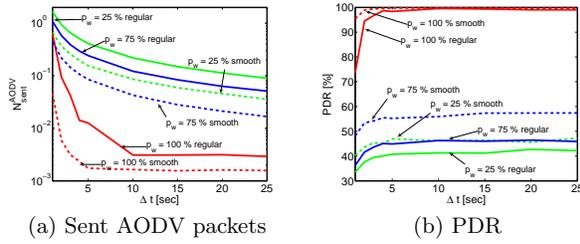
Figure 4: Impact of traffic load

with respect to the wake time of a node. From application layer's point of view, the end-to-end delay D and the used energy E_b per successfully received bit are the important performance metrics. The latter one implicitly describes the PDR, as in our system the energy for sending and receiving is almost the same and therefore E_b mainly depends on the wake time $p_w T$ during the interval T. The energy required per successfully received bit can thus be estimated as

$$E_b = \frac{t_{sim} \cdot p_w}{PDR \cdot s \cdot t_{sim}/\Delta t} P. \qquad (1)$$

The energy used during the online time is $t_{sim} p_w P$ with the average power consumption P for transmitting and receiving which is constant for all nodes with the same p_w. The number of successfully received bits at the sink is $PDR \cdot s \cdot t_{sim}/\Delta t$ with the packet size s.

Fig. 5(a) shows the minimum, maximum, and average E_b of all nodes in the layout. In the synchronized scenario, the PDR of each individual node is almost 100% and nearly all sent packets are received at the sink. Thus, there is no difference between minimum, maximum, and mean E_b. In the unsynchronized scenario, the maximum PDR is almost 100% for nodes which are directly sending the application datagrams to the sink. However, there are datagramms which are routed over several hops before they reach the sink. Hence, the average and the maximum PDR over all nodes in the network depends on the actual wakeup ratio p_w. Accordingly, the used energy E_b differs for the individual nodes in the layout and the average and maximum value is much larger than in the sychnronized scenario.

The related e2e delays of the considered simulation scenarios are depicted in Fig. 5(b). The maximum and the average e2e delay of successfully delivered application datagrams is computed over all nodes in the system. As the wakeup ratio p_w impacts the amount of packet collisions and the resulting retransmissions of packets, the e2e delay decreases with an increasing activity ration p_w. For the same reason, the synchronized sleeping schedule shows a better performance than the unsynchronized one. A consequence of multi-hop routing is the difference between the average and the maximum delay. However, this difference vanishes with increasing p_w.

(a) Energy E_b per bit   (b) End-to-end delay D
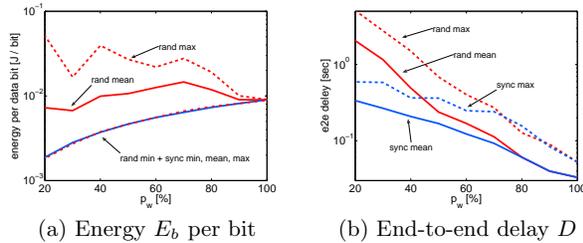
Figure 5: Impact of wakeup time on smooth AODV

5. CONCLUSIONS

In this paper, we simulated the combination of the sleep enabled non-beaconed mode of 802.15.4 and AODV routing. Two duty cycle schedules were compared: random scheduling and global synchronization. AODV used immediate and smooth - with several drops as trigger - link layer feedback for route maintenance. The performance of the synchronized system under low load was not seriously limited by the duty cycles, however, smoothing AODV reduced the routing overhead significantly. The unsynchronized system performance broke down to 50% already for sleeping only 25% of the time. Again, smoothing AODV improved the situation slightly. While the energy for a successfully transmitted information could be descreased with for a less active node in the synchronized case, the energy consumption in the unsynchronized case could not be reduced. We saw, that the variation of the energy consumption were even increased if the nodes are sleeping longer, i.e. some nodes may not be efficient enough to fulfill their role in the WSN if the duty cycle is cut down.

The results indicate the need for synchronization mechanisms for wireless sensor networks. Our future work will be dedicated to the evaluation of sleep scheduling mechanisms for 802.15.4 WSNs with regard to the overhead induced by in band signaling and the effects of concentrating the traffic load on a fraction of the bandwidth.

6. REFERENCES

[1] C. Gomez, P. Salvatella, O. Alonso, and J. Paradells. Adapting AODV for IEEE 802.15.4 Mesh Sensor Networks: Theoretical Discussion and Performance Evaluation in a Real Environment. In *WOWMOM '06*, Buffalo, NY, USA, June 2006.

[2] IEEE Computer Society. IEEE Standard 802.15.4: Wireless Medium Access Control and Physical Layer Specifications for Low-Rate Wireless Personal Area Networks, October 2003.

[3] K. Langendoen. Medium Access Control in Wireless Sensor Networks. In H.Wu and Y. Pan, editors, *Medium Access Control in Wireless Networks, Volume II: Practice and Standards*. Nova Science Publishers, 2007.

[4] C. Perkins, E. Belding-Royer, and S. Das. Ad hoc On-Demand Distance Vector (AODV) Routing. RFC3561, 2003.

[5] I. Ramachandran, A. K. Das, and S. Roy. Analysis of the Contention Access Period of IEEE 802.15.4 MAC. *ACM Trans. Sen. Netw.*, 3(1), 2007.

[6] V. Rao and D. Marandin. Adaptive Backoff Exponent Algorithm for Zigbee (IEEE 802.15.4). In *NEW2AN 2006*, St.Petersburg, Russia, May 2006.

[7] USC Information Sciences Institute. Network Simulator NS2. http://www.isi.edu/nsnam/ns.

[8] J. Zheng and M. Lee. Will IEEE 802.15.4 Make Ubiquitous Networking a Reality? *IEEE Comm. Mag.*, 42(6), June 2004.

[9] ZigBee Alliance. ZigBee Specification, December 2006.