Reliability and Energy Efficiency in Multi-hop IEEE 802.15.4/ZigBee Wireless Sensor Networks

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***Abstract*—Wireless Sensor Networks (WSNs) are a very appealing solution for many practical applications. Recently, WSNs have also been deployed in industrial scenarios, even for critical applications. Two major requirements are needed for an effective deployment of WSNs in such scenarios. The first is energy efficiency, as a network lifetime in the order of months or years is usually required. The other is reliability, since an even moderate message loss cannot be tolerated in critical applications. In this paper we evaluate the performance of the IEEE 802.15.4 standard in multi-hop WSNs where sleep/wakeup scheduling protocols are used for energy conservation. We show through extensive simulation results that the MAC parameter settings significantly impact on the performance. We demonstrate how an appropriate tuning of the MAC parameters can improve the reliability of communications, resulting in a very high delivery ratio. In addition, our solution also obtains a low energy expenditure.**

***Keywords*-sensor networks; IEEE 802.15.4; multi-hop; sleep scheduling; ZigBee; reliability; energy efficiency.**

I. Introduction

Since a few years ago, wireless sensor networks (WSNs) have been deployed for real-life applications. Recent studies [1] forecast that the number of deployments will increase substantially in the future, especially for industrial applications (e.g., in the fields of logistics, automation and control). The employment of WSNs has been fostered by two standards recently released by the IEEE and the ZigBee Alliance. More in detail, the IEEE 802.15.4 standard [2] targets the physical and MAC (Medium Access Control) layers of the protocol stack, while the ZigBee specifications [3] address the networking and application layers.

In the classic WSN architecture, nodes are densely deployed in the sensing field, so that they can send their messages to a data collection point (usually referred to as *sink*) by using a multi-hop communication paradigm. In this specific scenario, two major problems arise. From the one hand, sensor nodes have a very limited energy budget, since they are battery-powered. Hence, the data collection process should be energy-efficient, in order to prolong the network lifetime. One of the most common approaches to energy conservation consists in defining a duty-cycle [4], so that nodes can alternate between active and inactive periods. Clearly, in multi-hop networks the schedules of nodes should be coordinated, so that nodes can communicate despite the (low) duty-cycle. To this end, sleep/wakeup strategies are usually defined, in many cases on top of the MAC protocol. From the other hand, the reliability of communication is of uttermost importance, especially in critical applications where even a low message loss cannot be tolerated. In multi-hop scenarios, the communication reliability is significantly affected by both the MAC protocol and the sleep/wakeup strategy. As a consequence, all these factors have to be considered for a comprehensive evaluation of the data collection process.

Many papers in the literature provided a performance evaluation of IEEE 802.15.4 in WSNs scenarios. For instance, an extensive evaluation is provided in [5], with special attention to energy conservation. A similar solution is presented in [6], which also considers some reliability issues. The specific problem of the MAC parameter tuning to improve reliability of IEEE 802.15.4 networks has been considered in [7]. However, all these papers focus on a star topology, hence they do not account the effects of multi-hop data propagation and sleep/wakeup scheduling. Actually, only a few papers like [8] provided a characterization of IEEE 802.15.4 in multi-hop scenarios. However, they have a little focus on reliability, and they have also devoted a limited attention to the impact of different sleep/wakeup scheduling policies.

In this paper we focus on the IEEE 802.15.4 MAC protocol, and evaluate its performance in multi-hop WSNs by considering different sleep/wakeup strategies, including a ZigBee compliant scheduling. We found that, similarly to the results in [7], the reliability of multi-hop WSNs based on IEEE 802.15.4 can be extremely low. Therefore, we investigate how MAC parameters and sleep/wakeup scheduling affect the reliability of communications. We show through extensive simulations that with a proper setting of the MAC parameters it is possible to significantly improve the delivery ratio. The rest of the paper is organized as follows. Section II overviews data collection in multi-hop WSN based on the IEEE 802.15.4 standard. Section III presents the simulation setup used for the subsequent evaluation, which is presented in Section IV. Finally, Section V concludes the paper.

II. Data collection in multi-hop WSNs

In the following, we will briefly introduce the IEEE 802.15.4 MAC, and then present sleep scheduling protocols

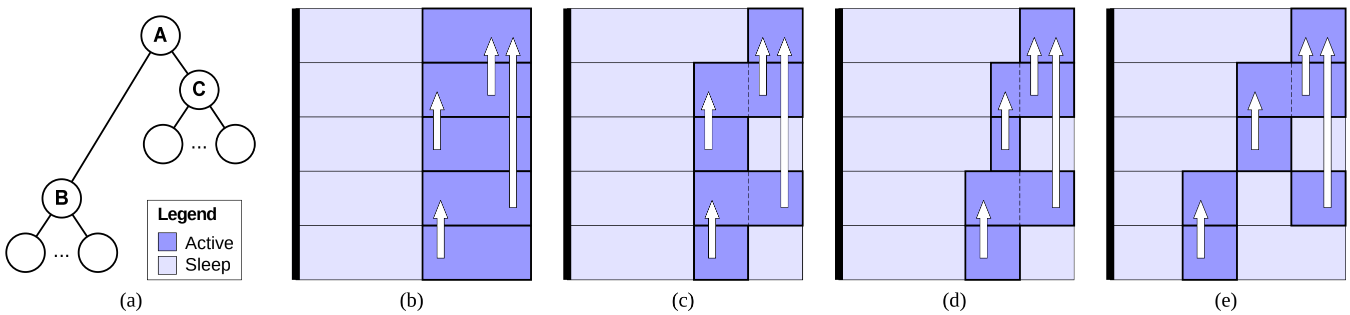


Figure 1. Sample routing tree (a) and different sleep/wake-up schemes: fully synchronized (b), fixed staggered (c), adaptive staggered (d), and ZigBee (e)

for multi-hop WSNs.

A. IEEE 802.15.4 MAC protocol

IEEE 802.15.4 [2] is a standard for low-rate, low-power, and low-cost Personal Area Networks (PANs). The basic components of a IEEE 802.15.4 network are: the *PAN coordinator*, which manages the entire network; one or more *coordinators*, which manage a cluster of nodes; and *ordinary* nodes. Ordinary nodes need to associate to a coordinator in order to participate in the network operations. Besides the simple star network, IEEE 802.15.4 also support multi-hop topologies, such as cluster-tree and mesh.

As for the channel access, the standard defines two different functions: a *beacon enabled mode* and a *non-beacon enabled mode*. The beacon enabled mode provides a power management mechanism based on duty-cycle, and implemented through a superframe structure bounded by beacons, i.e., special synchronization frames generated periodically by coordinator nodes. The time between two consecutive beacons is called Beacon Interval, $BI = 15.36 \cdot 2^{BO}$ms for $0 \leq BO \leq 14$, where BO is the *Beacon Order* parameter. Each superframe consists of an *Active Period* and an *Inactive Period*. In the Active Period nodes communicate with the coordinator they are associated with, while during the inactive period they enter a low power state to save energy. The Active Period is denoted by the Superframe Duration, $SD = 15.36 \cdot 2^{SO}$ms, for $0 \leq SO \leq BO \leq 14$, where SO is the *Superframe Order*. The SD can be further divided into a *Contention Access Period* (CAP) and a *Collision Free Period* (CFP). During the CAP, a slotted CSMA/CA (Carrier Sense Multiple Access with Collision Avoidance) algorithm is used for channel access, while in the CFP, communication occurs in a TDMA (Time Division Multiple Access) style by using a number of *Guaranteed Time Slots* (GTSs), pre-assigned to individual sensor nodes. In the non-beacon enabled mode there is no superframe, and there is no power management implemented at the MAC (although a higher layer policy can be used).

The beacon enabled mode uses a slotted CSMA/CA algorithm for channel access, i.e., all operations are aligned to backoff period slots with a duration of 320 μs. Upon receiving a data frame to be transmitted, the slotted CSMA/CA algorithm performs the following steps.

1) The contention window size ($CW = 2$), the number of backoff stages ($NB = 0$), and the backoff exponent (which is set to the default minimum value, i.e. $BE = macMinBE$) are initialized as state variables.
2) A backoff timer is initialized by using a random backoff time uniformly distributed in the range $[0, 320 \cdot (2^{BE} - 1)]$ μs.
3) The status of the wireless medium is checked through a *Clear Channel Assessment* (CCA).
4) If the medium is busy, the state variables are updated as follows: $NB = NB + 1$, $BE = \min(BE + 1, macMaxBE)$ and $CW = 2$. If the number of backoff stages exceeds the maximum allowed value (i.e., $NB > macMaxCSMABackoffs$), the frame is dropped. Otherwise, the algorithm falls back to Step 1.
5) If the medium is free, then $CW = CW - 1$. If $CW = 0$ the frame is transmitted. Otherwise the algorithm falls back to Step 3 to perform a second CCA.

In the non-beacon enabled mode, an unslotted version of the CSMA/CA algorithm is used. Hence, operations are not aligned to the backoff period slots. In addition, the CCA operation is performed only once to check if the channel is busy or not (i.e., $CW = 1$).

In both cases, the CSMA/CA algorithm supports an optional retransmission scheme based on acknowledgements. When retransmissions are enabled, the destination node must send an acknowledgement just after receiving a data frame. Unacknowledged messages are retransmitted up to $macMaxFrameRetries$ times, and then dropped.

B. Sleep/wakeup scheduling in multi-hop WSNs

In order to effectively use a duty-cycle scheme in multi-hop WSNs there is a need to define a coordinated sleep/wakeup scheme so that nodes in the network can communicate efficiently and with a low energy expenditure. There are different approaches suitable to multi-hop WSNs [9], and their specific features depend on the network topology and the traffic model. In the following, we will assume that the network is organized as a tree, according to many solutions available in the literature [3], [4], and that the traffic flows from sensor nodes to the sink, which is one of the most common cases in WSNs. We also assume that the sleep/wakeup scheduling is defined in terms of the *Communication Period* (CP), i.e., the base interval during which nodes collect and report data (also known as *epoch*). CPs periodically repeat, and nodes can be either awake or sleeping during part of it. We define as *Active Period* the interval during which a node is awake.

In the following, we consider the sleep/wakeup strategies outlined below (refer to [4], [10] for a comprehensive overview), and illustrated in Figure 1, with reference to the routing tree depicted in Figure 1a.

- *Fully Synchronized*. The duty-cycle is the same for all nodes in the network. In addition, all nodes wake up and go to sleep at the same time, independent from their position on the routing tree (Figure 1b).
- *Fixed Staggered*. Nodes wake up and go to sleep according to their position in the routing tree, and active periods are organized as a pipeline (Figure 1c). The duration of the active periods is the same for all nodes in the network[1]. In addition, nodes at the same level in the routing tree share the same active periods, i.e., they wake up and go to sleep at the same time.
- *Adaptive Staggered*. This scheme is an extension of the fixed staggered approach. Specifically, each parent node can have a different duration for its active period (Figure 1d), depending on the traffic/channel conditions. As a consequence, nodes at the same level in the routing tree can wake up and go to sleep at different times.
- *ZigBee*. This scheme is similar to fixed staggered. However, the active periods of parent nodes are scheduled in TDMA, so that only a single parent and its children are active at the same time in the network (Figure 1e). This scheduling strategy is compliant to the one defined in the ZigBee standard [3] for cluster-tree WSNs.

Clearly, each sleep/wakeup scheme impact on the level on contention and collisions, depending on the way active periods are arranged among nodes. Staggered schemes reduce contention, since nodes do not relay the messages immediately, but they rather forward them according to the routing tree, i.e., only during the active period shared between a node and its parent [10].

III. Simulation setup

We used the ns2 simulation tool [11]. In all experiments we assumed that the IEEE 802.15.4 MAC protocol is operating on top of the 2.4 GHz physical layer with maximum bit rate of 250 Kbps. The radio propagation model was two-way ground; the transmission range was set to 15 m, while the carrier sensing range was set to 30 m, according to the settings in [7]. We enabled MAC layer acknowledgements.

We considered a network where 100 sensor nodes are placed in a 100×100 m area. In order to organize sensor nodes in a logical tree, we implemented a simple tree formation algorithm based on the minimum hop count[2]. The sink acts as the PAN coordinator and the non-leaf nodes as cluster routers/coordinators. All other devices act as ordinary nodes associated with its cluster coordinator. All messages are always sent by all nodes to the sink (uplink traffic). We used a CP of 125.8 s in all cases, and an active period of 15.7 s for all scheduling schemes[3] except for adaptive staggered, which tuned the duration of active periods autonomously. All schemes except for ZigBee are implemented on top of the non-beacon enabled IEEE 802.15.4 mode, due to issues related to superframe scheduling [12]. So the duty-cycle mechanism is enforced by the sleep/wakeup scheduling policy on top of the MAC protocol. The ZigBee scheme, instead, exploits the beacon-enabled mode of IEEE 802.15.4, since it directly maps the active periods to the corresponding ones in the superframes [3] (i.e. by using $BO = 13$ and $SO = 10$ in the considered scenario).

In our analysis we considered the following performance metrics:

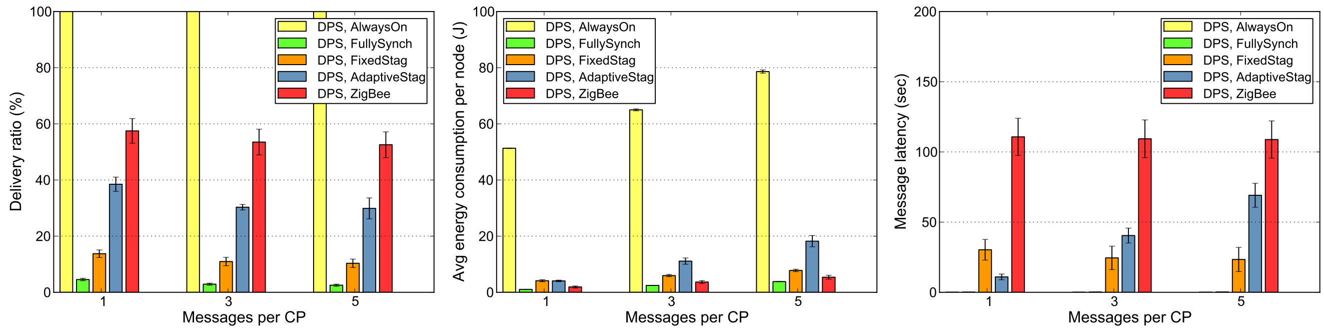
- *Delivery ratio*: the ratio between the number of messages correctly received by the sink and the number of messages sent by all sensor nodes.
- *Average energy consumption*: the average energy consumed by a single node in the network.
- *Average latency*: the average latency measured from the instant a message is sent by the source node and the instant the same message is correctly received at the sink.

In the following simulation analysis we evaluate the different sleep/wakeup schemes in the scenario introduced above, where each node generates a variable number of messages per CP after waking up. We also consider the *always-on* scheme, which does not use any duty-cycle (i.e., nodes are always active), as a reference. According to the conditions usually assumed in the literature [5], we use a Poisson message arrival process for the always-on scheme for comparison purposes. As for the energy consumption, we used the model in [5], which is based on the Chipcon CC2420 radio [13]. In our experiments, for each considered scenario, we performed 5 independent replicas. In the results

[1]Actually, the active period also depends on the role of the nodes, i.e., if they are leaves or not in the routing tree. For clarity, in the following we will refer as active period to the one defined for nodes which have the same role in the routing tree.

[2]The routing protocol produces a tree with 7 levels on the average for the considered scenario.

[3]We have verified by preliminary simulations that such an active period is long enough to accommodate all messages to be transmitted by the nodes in the network.



(a) (b) (c)

Figure 2. Performance with DPS: delivery ratio (a), energy consumption (b) and latency (c).

Table I
IEEE 802.15.4 MAC PROTOCOL PARAMETERS [2]

Parameter	Allowed values
$macMaxFrameRetries$	Range: 0–7 (Def: 3)
$macMaxCSMABackoffs$	Range: 0–5 (Def: 4)
$macMaxBE$	Range: 3–8 (Def: 5)
$macMinBE$	Range: 0–$macMaxBE$ (Def: 3)

below, we show the average values, as well as the associated standard deviations.

IV. SIMULATION RESULTS

In the following, we first present the performance of data collection in multi-hop WSNs based on IEEE 802.15.4. We then highlight issues related to the reliability of communication, and propose and evaluate possible solutions.

A. Performance with the default MAC parameters

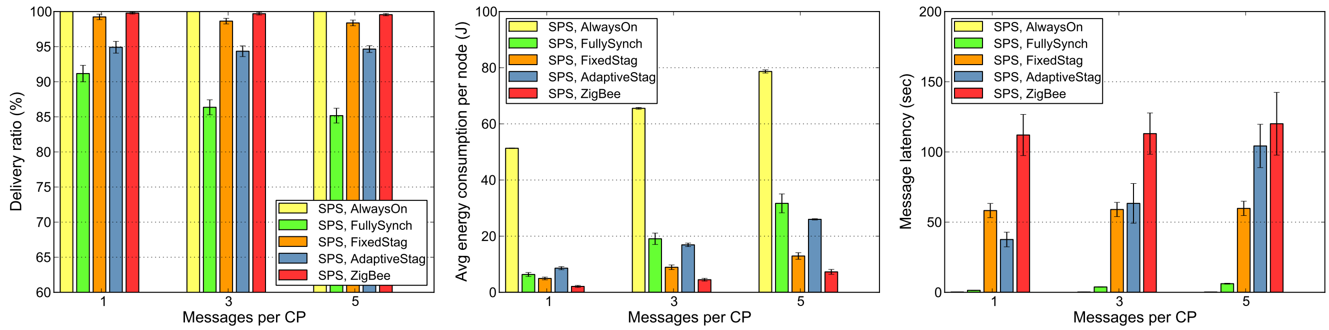
The IEEE 802.15.4 standard suggests the default values for the MAC parameters which regulate the operations of the channel access algorithm. These MAC parameters and the related allowed (and default) values defined in the standard [2] are summarized in Table 1. We define as *Default Parameters Set* (DPS) the set of the default MAC parameter values defined by the IEEE 802.15.4 standard. DPS is the reference configuration, since WSNs based on IEEE 802.15.4 are usually deployed without any intervention on the (default) MAC parameter values. So we will start our investigation on how different sleep/wakeup strategies impact on multi-hop WSNs.

Figure 2a shows the delivery ratio as a function of the number of messages sent by each node in each CP. We can see that, when nodes are always active nearly all messages are correctly received by the sink. This is due to the fact that messages are generated according to a Poisson process along all the CP, which is rather large (i.e, about 2 minutes), so that the probability of simultaneous transmissions is very low. However, the situation is much different when sleep/wakeup strategies are used, since the active periods are much shorter than the CP (in the order of a few seconds). Depending on the specific algorithm, the delivery ratio can be even below 20% (i.e., for the fully synchronized and the fixed staggered schemes), and does not exceed 60% in the best case (represented by ZigBee). In addition, the impact of the number of messages per CP is not very apparent, since the network is already loaded with one message per CP. Anyway, we can see that there is a serious unreliability issue, mainly related to contention and collisions, and due to the combined effect of using IEEE 802.15.4 and sleep/wakeup scheduling.

Figure 2b shows the energy consumed by the different sleep/wakeup strategies as a function of the number of messages per CP. We can clearly notice that, despite having the highest delivery ratio, the always-on scheme is actually unfeasible as for its energy consumption. The different sleep/wakeup strategies perform much better (i.e., there is one order of magnitude reduction in the energy consumption), even though they are sensitive to the number of messages per CP.

Figure 2c shows the latency obtained with the different sleep/wakeup strategies as a function of the number of messages per CP. The latency obtained with the always-on and the fully synchronized schemes is so low (i.e., in the order of a hundreds milliseconds) which cannot be appreciated in the plot. The fixed and the adaptive staggered schemes obtain much higher values, which is related to the fact that messages are queued at each parent node for the duration of the active period before they can be forwarded up to the tree. Adaptive staggered is more sensitive to the number of messages per CP, since the increased amount of messages triggers a longer duration of the active period. The same is not true for fixed staggered and ZigBee, where the duration of the active period is statically defined. ZigBee has the highest latency, which, however, does not exceed the duration of the CP.

On the basis of the poor results concerning reliability, we investigated means to improve the delivery ratio, and considered how they impact on other metrics such as energy



(a) (b) (c)

Figure 3. Performance with SPS: delivery ratio (a), energy consumption (b) and latency (c).

consumption and latency. The study in [7] highlighted that the reliability of IEEE 802.15.4 can be seriously compromised by an inappropriate choice of the MAC parameters setting. Furthermore, the default parameters chosen by IEEE 802.15.4 clearly appear inadequate to WSN scenarios. To this end, the authors proposed two different sets of MAC parameters, namely the *Standard Parameters Set* (SPS) and the *Non-standard Parameters Set* (NPS). SPS consists in the maximum values of the MAC parameters as allowed by IEEE 802.15.4 (cfr. Table I), while NPS uses some values beyond the maximum ones (i.e., $macMinBE = 8$ and $macMaxBE = macMaxCSMABackoffs = 10$). The impact of the different parameter sets on the performance of IEEE 802.15.4 was also evaluated. However, the main limitation of [7] is that only a single-hop scenario is considered. Actually, the applicability of single-hop WSNs is limited, since multi-hop WSNs are being deployed even in industrial scenarios [12].

In the following, we will consider the impact of the different MAC parameters sets on the performance of multi-hop WSNs based on IEEE 802.15.4. Since sleep/wakeup strategies are necessary for energy-efficient operations, we investigate below if the approach in [7] is still applicable in multi-hop WSNs.

B. Impact of MAC parameters

We start investigating the impact of SPS on the different performance metrics. Figure 3a shows the delivery ratio as a function of the number of messages per CP. We can see that the delivery ratio is significantly higher with SPS, rather than with DPS. Now all sleep/wakeup strategies achieve a delivery ratio above 85%. The best sleep/wakeup strategies get a delivery ratio which is higher than 94%. We have verified that moving from SPS to NPS does not significantly impact the delivery ratio, except for the fully synchronized scheme, which reaches the values of the other parameters. This is somewhat different from the results in [7], where NPS was found to be effective when the number of nodes is very high. The results clearly show the impact of the sleep/wakeup strategy on the reliability. In fact, the two staggered schemes and ZigBee show that they can help to reduce contention and collisions by scattering the active periods of nodes along the CP. Therefore, the reliability obtained with SPS is very good, and a further increase of the MAC parameter values is not beneficial. Hence, in the following (and when not otherwise specified) we will focus on SPS only.

Figure 3b shows the energy expenditure as a function of the number of messages per CP. We can see that SPS has a higher energy consumption than DPS (cfr. Figure 2b). This is especially true for the fully synchronized scheme, which is the one with the highest increase in the delivery ratio. The other schemes perform rather well, even though adaptive staggered seem to suffer more from SPS. As for the latency, we can see from Figure 3c that it increases as well, but it remains below the length of the CP. Fixed and adaptive staggered obtains interesting results, with the latter performing better when the load is light.

We finally contrast the results related to the delivery ratio and the energy efficiency of the different MAC parameter sets. In the following, we will consider only the ZigBee scheme, since it is the one which provides the highest reliability. We start from Figure 4a, which shows the delivery ratio as a function of the levels of the tree where sensor nodes send five message per CP. We can see that with DPS the delivery ratio is not the same for all the levels. This highlights the unfairness of data collection, since for some nodes – i.e., the ones in the first and in the lowest two levels of the tree – the probability of correct message delivery is much lower than the average value (depicted with a dashed line in the figure). Instead, when using SPS or NPS, the delivery ratio is almost the same for all the levels in network.

Figure 4b shows the energy consumption as a function of the levels of the tree where sensor nodes send five message per CP. Clearly, DPS obtains the lowest energy consumption due to the lower number of transmission attempts. The difference between DPS and SPS/NPS decreases with the depth of the tree, since nodes at the periphery of the

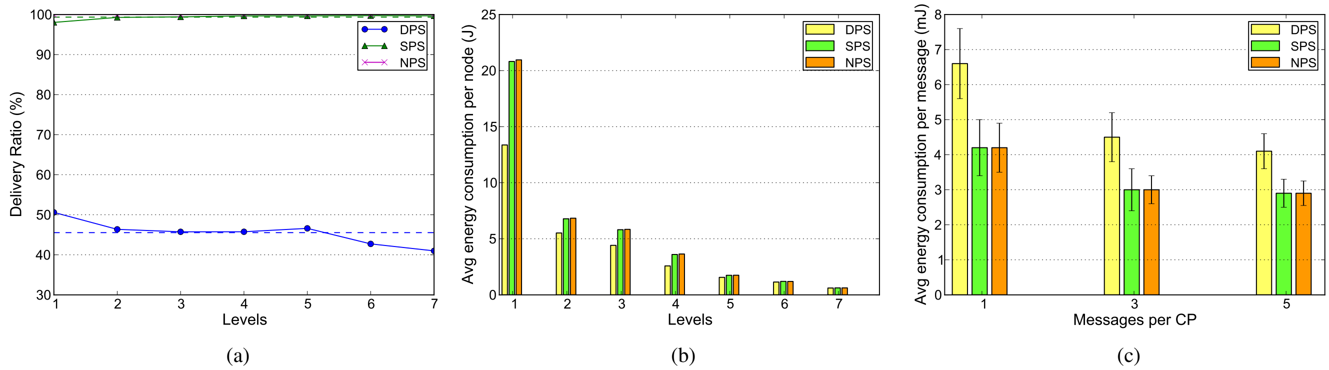


Figure 4. ZigBee scheduling: delivery ratio (a) and energy (b) as a function of the tree depth; and energy-efficiency (c) as a function of the number of messages per CP.

tree are less loaded than the others. In addition, SPS and NPS obtain almost the same energy consumption. Finally, Figure 4c shows the energy efficiency, i.e., the ratio between the average energy consumption and the average delivery ratio, for the different MAC parameter sets as a function of the number of messages per CP. We can clearly see that the increase in the average energy spent by the nodes (cfr. Figure 3b) is largely compensated by the increase in the delivery ratio for both SPS and NPS. As a result, the two MAC parameters sets result in effective, reliable and energy-efficient data collection.

V. Conclusions

In this paper we addressed the problem of reliable data collection in multi-hop Wireless Sensor Networks (WSNs) based on the IEEE 802.15.4 standard. We considered several sleep/wakeup strategies, and provided a comprehensive performance evaluation, also focusing on energy efficiency. We showed that by using the default values suggested by IEEE 802.15.4 the delivery ratio can be very low. Then, we investigated different MAC parameter settings, and evaluated their impact on the network performance. We found that by using different settings it is possible to significantly improve the reliability of communication, and, at the same time, the energy efficiency of the sensor network. Interestingly, the MAC parameters settings suitable to multi-hop WSNs exploiting sleep/wakeup scheduling are not the same as for single-hop scenarios. While here we investigated the usage of static MAC parameter sets, a future work would consist in dynamic adaptation of MAC parameters.

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