# An Adaptive Algorithm for Dynamic Tuning of MAC Parameters in IEEE 802.15.4/ZigBee Sensor Networks

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*Abstract - Recent studies have highlighted that IEEE 802.15.4 based wireless sensor networks (WSNs) suffer from a severe unreliability problem due to the default MAC parameters setting suggested by the standard, although with a more appropriate choice it is possible to achieve the desired reliability and better energy efficiency. However, such setting is strictly related to the operating conditions which, in general, vary over time and thus cannot be predicted in advance (i.e., before the deployment). In this paper, we propose an ADaptive Access Parameters Tuning (ADAPT) algorithm for dynamically adjusting the MAC parameters, based on the desired level of reliability and actual operating conditions experienced by the sensor nodes. Simulation experiments demonstrate that the ADAPT algorithm is able to provide the desired reliability with a very low energy expenditure, even under operating conditions that dynamically change with time.*

***Keywords:*** *Sensor Networks, IEEE 802.15.4, MAC Protocol, Reliability, Energy Efficiency, Scalability.*

## I. INTRODUCTION

Wireless sensor networks (WSNs) are widely deployed for diverse real-life applications. Based on recent studies [1, 2], it is expected that such deployments will grow dramatically in the near future, especially in the fields of logistics, automation and control. This positive trend is due to the adoption of two standards, recently released by the IEEE and the ZigBee Alliance. Specifically, the IEEE 802.15.4 standard [3] defines the physical and medium access control (MAC) layers of the protocol stack, while the ZigBee specifications [4] cover the networking and application layers.

Recent studies have also highlighted that IEEE 802.15.4 based WSNs suffer from a severe unreliability problem, due mainly to the default MAC parameters setting suggested by the standard. For instance, according to [5] and [6], the message drop probability can be extremely high, especially when the number of nodes and the message size are high. Similar conclusions are drawn in [7] and [8], where a larger exponential backoff delay is suggested to alleviate the problem. It has also been shown in [9] that, with a more appropriate MAC parameters setting, it is possible to achieve the desired level of reliability as well as better energy efficiency. Specifically, the solution in [9] exploits different sets of fixed parameters, which do not change over the network lifetime. However, setting the appropriate parameters is strictly related to the operating conditions which, in general, vary over time and hence cannot be predicted in advance, for example before the deployment. In [10], an adaptive mechanism for IEEE 802.15.4 based WSNs has been introduced in terms of a service differentiation strategy. The proposed strategy consists of different MAC parameter sets and queuing policies, in order to prioritize specific classes of traffic. Since the focus in [10] is on message prioritization, relatively less attention is devoted to the reliability and energy expenditure. This motivates our work.

In this paper, we propose an *ADaptive Access Parameters Tuning* (ADAPT) algorithm for dynamically adjusting the MAC parameters, based on the desired level of reliability and the actual operating conditions experienced by the sensor nodes. The ADAPT algorithm is fully distributed such that it is suitable for multi-hop WSNs. Moreover, it is lightweight because it requires only little computational and storage demands at each node. In addition, ADAPT does not require any modification to the MAC protocol itself, since it relies on the management functions available in the IEEE 802.15.4 standard.

The rest of the paper is organized as follows. Section II gives an overview of the IEEE 802.15.4 MAC protocol. Section III presents the ADAPT algorithm and its main components. Section IV describes the simulation setup, while Section V presents simulation results. Finally, Section VI concludes the paper.

## II. IEEE 802.15.4 MAC PROTOCOL

IEEE 802.15.4 [3] is a standard for low-rate, low-power and low-cost Personal Area Networks (PANs) which supports three different network topologies: *star* (single-hop), *cluster-tree* and *mesh* (multi-hop). The standard defines two different channel access methods: *beacon enabled* and *non-beacon enabled* modes. The beacon enabled mode provides a power management mechanism based on the duty cycle. In this paper, we will consider only the beacon enabled mode, which uses a superframe structure bounded by *beacons*, i.e., special synchronization frames generated periodically by the 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[1]. Each superframe consists of an active period and an inactive period. In the active period, nodes communicate with the coordinator

[1] Throughout the paper, we assume that the sensor network operates in the 2.4 GHz frequency band.

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 further be 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, the communication occurs in a TDMA (Time Division Multiple Access) style by using a number of *guaranteed time slots* (GTSs), pre-assigned to the individual sensor nodes. It is worth pointing out that in the non-beacon enabled mode, there is no superframe, and nodes are always active.

In the beacon enabled mode, the CSMA uses a slotted scheme such that all operations are aligned with backoff period slots of 320 µs duration. Upon receiving a data frame to be transmitted, the CSMA/CA algorithm performs the following steps.

0. A set of state variables is initialized: the contention window size (*CW* = 2), the number of backoff stages carried out for ongoing transmissions (*NB* = 0), and the backoff exponent (set to the default minimum value, *BE* = *macMinBE*).
1. A random backoff time, uniformly distributed in the range $[0, 320 \cdot (2^{BE} - 1)]$ µs, is generated to initialize a *backoff timer*.
2. A *clear channel assessment* (CCA) is performed to check the state of the wireless medium.
3. 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 (*NB*) exceeds the maximum admissible value (*macMaxCSMABackoffs*), the frame is dropped. Otherwise, the algorithm falls back to Step 1.
4. If the medium is free, then *CW* = *CW* – 1. If *CW* = 0, the frame is transmitted. Otherwise, the algorithm falls back to Step 2 to perform a second CCA.

The CSMA/CA algorithm supports an optional retransmission scheme based on the acknowledgements. When the retransmissions are enabled, the destination node must send an acknowledgement just after receiving a data frame. Unacknowledged messages are retransmitted for at most *macMaxFrameRetries* times, otherwise they are dropped.

## III. ADAPT ALGORITHM

The proposed algorithm ADAPT is implemented as a module exploiting a cross-layer architecture. More specifically, ADAPT obtains the desired level of reliability – expressed as the target (typically less than 100%) delivery ratio – from the application. Then it estimates the current delivery ratio and changes the MAC parameters autonomously, in order to satisfy the specified reliability constraint. ADAPT makes use of the management functions provided by the standard, so it is fully compliant to it, and does not require modifications in the MAC protocol itself. In addition, ADAPT is fully distributed, so each node can tune its own MAC parameters independent of others.

In the following, we will assume that the messages flow from the sensor nodes to the sink. In addition, we will refer to a periodic reporting application where sensor nodes report data to the sink every *communication period* (CP). The operations of ADAPT are based on two different elements: a control scheme for estimating the delivery ratio and enforcing the requested reliability level; and a strategy for tuning the MAC parameters accordingly. These two elements will be discussed in the subsections below.

### A. Delivery ratio control scheme

The delivery ratio control scheme is performed at each communication period. The actual (measured) delivery ratio, $d_i^{meas}$, referred to every *i*-th CP, is calculated as the ratio between the number of messages acknowledged by the destination ($n_i^{ack}$) and the number of messages sent by the source ($n_i^{sent}$). In order to make ADAPT less sensitive to sudden variations in the measured delivery ratio, a smoothing technique is used to obtain the estimated delivery ratio, $d_i^{est}$. More specifically, an exponential moving average is applied to derive $d_i^{est}$ as follows:

$$d_i^{est} = \alpha \cdot d_{i-1}^{est} + (1-\alpha) \cdot d_i^{meas}$$

where $\alpha$ is a memory factor in the range [0,1].

In addition, on the basis of the level of reliability $d^{des}$ requested by the application, ADAPT derives two thresholds, $t^{min}$ and $t^{max}$. The motivation behind the definition of the thresholds is as follows. At any time, the delivery ratio should be at least equal to $d^{des}$. To better react to the decrease in the delivery ratio, we define a lower threshold $t^{min} > d^{des}$ so that the adaptation can be triggered before the actual delivery ratio drops below $d^{des}$. On the other hand, we define a higher threshold $t^{max}$ to avoid excessive energy expenditure, given the desired level of reliability. The main goal is to keep the actual delivery ratio over $d^{des}$ and within the *reliability region* defined by the two thresholds whenever possible, as illustrated in Figure 1. In addition, ADAPT should quickly react to variations in the operating conditions due to transient phases. In order to have a more flexible solution, we define the two thresholds as follows:

$$t^{\min} = d^{des} \cdot (1+\sigma)$$

$$t^{\max} = d^{des} \cdot (1+\sigma+\gamma)$$

based on the parameters $\sigma$ and $\gamma$, respectively representing the distance from $d^{des}$ and the width of the reliability region. Clearly, the choice of $\sigma$ and $\gamma$ is critical, so that a proper setting is needed. To this end, we performed a preliminary simulation study and found that suitable values for $\sigma$ and $\gamma$ lie in the range [4%, 8%].

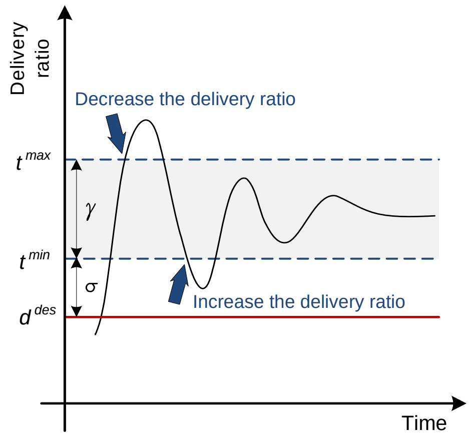


**Figure 1. Threshold-based adaptation of the delivery ratio.**

Now to satisfy the reliability constraint $d^{des}$, ADAPT compares the estimated delivery ratio $d_i^{est}$ against the two thresholds and applies a tuning strategy in order to compensate the variations in the delivery ratio, i.e.,

**if** ( $d_i^{est} < t^{min}$ )
*apply tuning strategy to increase the delivery ratio*
**else if** ( $d_i^{est} > t^{max}$ )
*apply tuning strategy to decrease the delivery ratio*

*B. MAC parameters tuning strategy*

The tuning strategy exploited by ADAPT consists of changing the MAC parameters in order to increase or decrease the delivery ratio, so that it remains in the reliability region specified by the control scheme.

In theory, different tuning strategies can be applied. We exploited the results in [9], and defined a policy that can adapt the delivery ratio while keeping a low enegy expenditure. Regarding the impact on the MAC parameters, the following remarks hold [9].

- In an ideal communication environment, nearly all undelivered packets are dropped by the MAC protocol because they exceed the maximum number of backoff stages (i.e., *macMaxCSMABackoffs*). So it is better to tune the maximum number of backoff stages rather than the maximum number of retransmissions (i.e., *macMaxFrameRetries*), whose impact on the delivery ratio is almost negligible.
- Both the maximum and the minimum backoff window sizes (i.e., the parameters *macMinBE* and *macMaxBE*) have a significant effect on the communication reliability, especially when jointly tuned together with the maximum number of backoff stages.

The tuning strategy is defined based on the above-mentioned results. More specifically, ADAPT keeps *macMaxBE* to a fixed value $maxBE^{def}$ and dynamically tunes the parameters *macMinBE* and *macMaxCSMABackoffs*. Additional thresholds – in terms of minimum and maximum allowed values – are also defined in order to limit the range of values achievable for both *macMinBE* and *macMaxCSMABackoffs*. Note that a high and fixed value of *macMaxBE* is not detrimental, since it becomes relevant only after several backoff attempts. In addition, it gives room to meaningful variations of *macMinBE*. In detail, the tuning strategy is defined as follows:

// Strategy for increasing the delivery ratio
**if** (*macMinBE* < $macMinBE^{max}$)
*macMinBE++*
**else if** (*macMaxCSMABackoffs* < $maxCSMABackoffs^{max}$)
*macMaxCSMABackoffs++*
// Strategy for decreasing the delivery ratio
**if** (*macMaxCSMABackoffs* > $maxCSMABackoffs^{min}$)
*macMaxCSMABackoffs--*
**else if** (*macMinBE* > $macMinBE^{min}$)
*macMinBE--*

The strategy to improve the delivery ratio is to increase *macMinBE* until the maximum value is reached. Only after this point, *macMaxCSMABackoffs* is increased up to its maximum value. The increase of *macMinBE* is preferred with respect to *macMaxCSMABackoffs*, since the last parameter has a higher impact on the energy expenditure. The strategy for decreasing the delivery ratio is similar. First *macMaxCSMABackoffs* is decreased, until its minimum value is reached. Then *macMinBE* is decreased by up to its minimum value.

Clearly, the tuning strategy is very simple and lightweight, since it stores only a few parameters. In addition, it does not require control messages; each node autonomously estimates its own delivery ratio and tunes MAC parameters accordingly.

## IV. 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 a maximum bit rate of 250 Kbps. The radio propagation model was two-way ground; the transmission range was set to 15 m (according to the settings in [12]), while the carrier sensing range was set to 30 m (following the model in [13]). We used the IEEE 802.15.4 beacon enabled mode, where the beacon interval is set to $BI$ = 125.8 s for $BO$ = 13, and the active period is set to $SD$ = 3.93 s for $SO$ = 8. We verified that such an active period is large enough to let every node send its data messages, so that the enforced duty cycle does not harm the message transmission process. In addition, we mapped the communication period (CP) to the beacon interval, such that nodes generate messages just after receiving a beacon from the coordinator.

We considered a star network (single-hop scenario), where 30 sensor nodes were placed in a circle of radius equal to 10 m, centered at the sink node. Due to the considered radio model, where the carrier sensing range is twice the transmission range, all nodes are in the carrier sensing range of each other. Consequently, this excludes collisions due to the hidden node problem. The sink acts as the PAN (personal area network) coordinator and all other devices as ordinary nodes associated with it. All messages are sent to the sink by the ordinary nodes.

Our analysis considered the following performance metrics.

- *Delivery ratio*: the ratio between the number of messages correctly received by the sink to the number of messages generated by all sensor nodes.
- *Average latency*: the average time elapsed between the instant at which a message is transmitted at the source node, and the instant at which the same message is correctly received by the sink.
- *Average energy per communication period*: the average energy consumed by a single node in each CP.

To compare the performance of the ADAPT algorithm, we considered three non-adaptive schemes as a reference, for which the sets of parameters are as defined in [9].

- *Default Parameters Set (DPS)*: the default values specified by the IEEE 802.15.4 standard.
- *Standard Parameters Set (SPS)*: the maximum (and still compliant) values allowed by the IEEE 802.15.4 standard.
- *Non-standard Parameters Set (NPS)*: values beyond the maximum ones allowed by the IEEE 802.15.4 standard.

As for the energy consumption, we used the model in [14], based on the Chipcon CC2420 radio [15]. The values of simulation parameters are summarized in Table 1.

**Table 1. Parameters used for simulation.**

| Parameter | Value |
|---|---|
| $d^{des}$ | 80% |
| $\sigma$ | 6% |
| $\gamma$ | 7% |
| $maxBE^{def}$ | 10 |
| $macMinBE^{min}$ | 1 |
| $macMinBE^{max}$ | 7 |
| $maxCSMABackoffs^{min}$ | 1 |
| $maxCSMABackoffs^{max}$ | 10 |

## V. EXPERIMENTAL RESULTS

To study how effectively the ADAPT algorithm is able to dynamically adjust the delivery ratio, we defined an experiment where the traffic in the network is dynamically altered in terms of both the generation rate and the message size. In detail, at the beginning of the experiment, each node generated one 20 bytes-long message per CP (*low* traffic load). After the 200th CP, the nodes increased their generation rate to 10 messages per CP, while keeping the same message size as before (*medium* traffic load). After the 500th CP, the nodes increased the message size to 100 bytes, while keeping their generation rate constant (*high* traffic load). Finally, after the 800th CP, the traffic reverted back to the original condition (i.e., one 20 bytes-long message per CP). This experiment is intended to stress the ability of ADAPT to match the desired level of reliability, even with abrupt changes in traffic conditions. We have also replicated the experiment several times. However, due to space limitations, we show here only a single representative simulation run (the results are similar in other cases).

Let us first analyze the delivery ratio as shown in Figure 2. We observe that DPS is not at all suitable for the considered scenario, since it obtains a delivery ratio always below 40%, and even below 10% with the highest load. On the other hand, SPS and NPS perform much better, thus obtaining very high delivery ratios, namely almost 100% with NPS. Moreover, when the traffic is high, SPS is on the border of 80% delivery ratio, and below it for several CPs. We can also see that ADAPT effectively keeps the delivery ratio in the reliability region, with the exception of a few spikes corresponding to the sharpest variations in the operating conditions. This is unavoidable, however, since the traffic change is very sudden. On the other hand, the change in the delivery ratio is very limited in ADAPT, in comparison with other schemes.

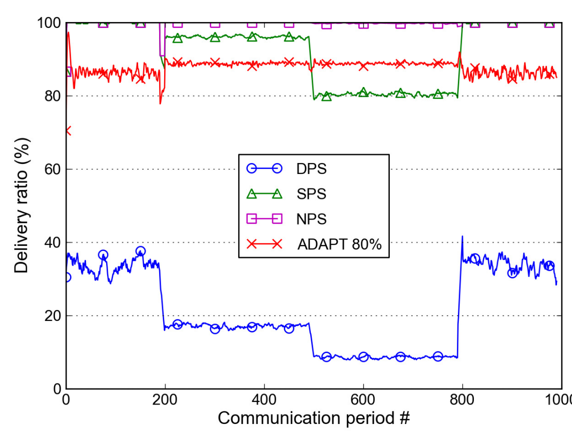


**Figure 2. Delivery ratio as a function of time.**

The average message latency as a function of time is depicted in Figure 3. We can see that the lowest latency is provided by DPS. This happens because the maximum duration of the channel access is bounded by the MAC parameters, and it is lower for DPS. In addition, the delivery ratio of DPS is low, and the latency is measured only in terms of messages successfully received by the sink, which decrease when the traffic increases. This also explains how the latency decreases when the traffic is higher. On the other hand, the other schemes have a high delivery ratio and the latency increases with traffic as expected. Indeed, SPS and ADAPT always perform better than NPS. More precisely, ADAPT has a lower latency than SPS when the traffic load is low or moderate, while it has a higher latency than SPS when the traffic load is high. This is mainly due to the chosen adopted tuning strategy, which optimizes energy expenditure rather than latency.

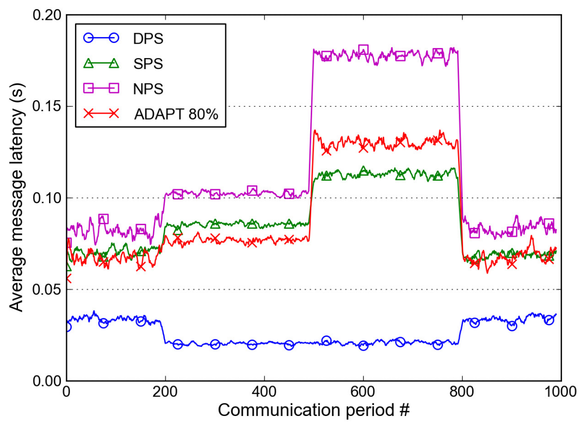


**Figure 3. Average latency as a function of time.**

Figure 4 shows the average energy consumed per node at each CP as a function of time. Observe that all different strategies exhibit similar results when the traffic load is low. At moderate traffic load, the energy expenditure per CP starts exhibiting a more significant trend. Furthermore, the three fixed schemes have higher energy expenditure than ADAPT. The trend is also similar when the traffic load is high, except for DPS. Thus, we conclude that ADAPT has a much lower energy expenditure than NPS and SPS. Even if the difference between ADAPT and SPS or NPS is apparently not so large, we need to take in consideration that this difference represents the energy saved by ADAPT in a single CP (i.e., 125.8 s). Therefore, considering that the network lifetime is typically in the order of several months, the total energy savings by ADAPT are significant.

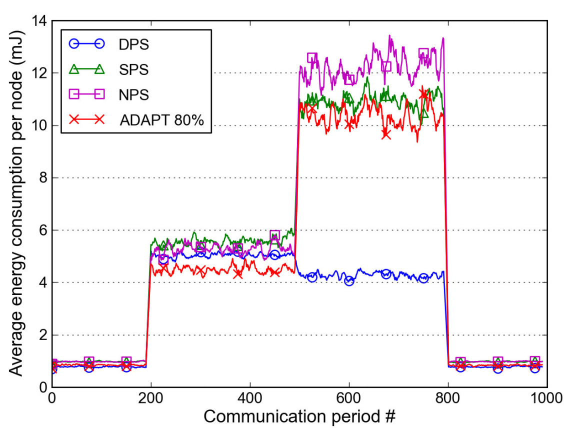


**Figure 4. Average energy consumed by each node.**

To better understand the long term impact of the different schemes on energy expenditure, we analyzed the difference (expressed as a percentage) between the amount of energy consumed by ADAPT and the static schemes. A positive value means that ADAPT consumes less energy with respect to the considered scheme, so that it can prolong the network lifetime. In contrast, a negative value means that ADAPT has higher energy expenditure. To this end, we averaged the results corresponding to the different traffic conditions. They are presented in Table 2. We can clearly see that ADAPT has a significant energy gain over SPS and NPS for all traffic conditions, ranging from about 5% to almost 20%. The advantage of ADAPT over these two schemes is more apparent when the traffic load is light. However, ADAPT has a higher energy expenditure than DPS, except for the medium traffic scenario. Again, this is due to the fact that DPS obtains a very low delivery ratio, so that the energy consumed does not give a significant estimation of the effectiveness of the different solutions in that case.

**Table 2. Energy gain of ADAPT 80% over other schemes.**

| Scheme | Low Traffic | Medium Traffic | High Traffic |
|---|---:|---:|---:|
| ADAPT vs DPS | -8.42% | 10.82% | -142.95% |
| ADAPT vs SPS | 13.63% | 19.28% | 4.95% |
| ADAPT vs NPS | 13.58% | 14.70% | 15.19% |

To prove our claim, we also performed the same analysis by considering ADAPT with a target delivery ratio of 70% (instead of 80%). The results are provided in Table 3. The difference between ADAPT and DPS is almost negligible when the traffic is low. In addition, the difference between ADAPT and DPS is much lower when the traffic is high. It is important to recall that in all cases ADAPT is able to enforce the requested delivery ratio, in contrast with DPS. Moreover, ADAPT even increases its energy gain over SPS and NPS, since it obtains values between 20% and 30%.

**Table 3. Energy gain of ADAPT 70% over other schemes.**

| Scheme | Low Traffic | Medium Traffic | High Traffic |
|---|---:|---:|---:|
| ADAPT vs DPS | -0.92% | 23.17% | -103.53% |
| ADAPT vs SPS | 19.83% | 30.46% | 20.37% |
| ADAPT vs NPS | 19.78% | 26.52% | 28.95% |

In addition to the experimental results obtained under dynamic conditions, we also evaluated the performance of ADAPT under stationary conditions. More specifically, we considered a variable number of nodes which generated one 100 bytes-long message per CP. Each experiment lasted for 1000 CPs, and was replicated 5 times. We also derived the related standard deviations, which were always below 1%, and hence not reported in the plots. Due to space limitations, we limit our discussion to the delivery ratio, as illustrated in Figure 5. First, ADAPT can effectively enforce the requested level of reliability (i.e., 80% delivery ratio) independent of the number of nodes. The same is not true with DPS, whose delivery ratio drops below 20% when the number of nodes is greater than 30. Also, the performance of SPS decreases with the number of nodes, even though less sharply than DPS. Moreover, the delivery ratio of SPS is below the one provided by ADAPT when the number of nodes is equal to 50, and it is going to fall below the desired level of reliability when the number of nodes is higher. On the other hand, NPS has a delivery ratio close to 100% independent of the number of nodes. Therefore, NPS can be used as a worst-case solution based on fixed parameters to achieve a high delivery ratio. However, its energy efficiency may also be unnecessarily high, especially if the worst-case operating conditions are overestimated (as also shown in Table 2 and Table 3).

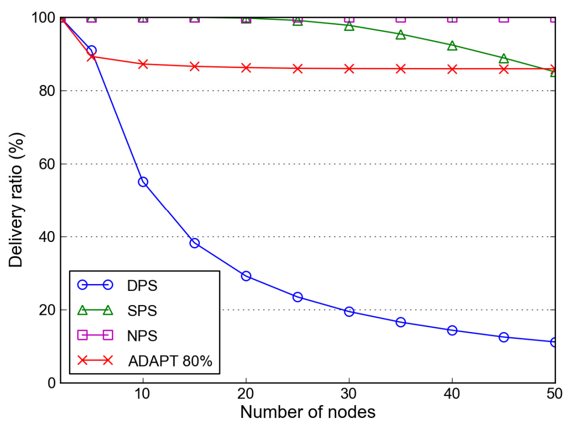


**Figure 5. Delivery ratio as a function of the number of nodes.**

## VI. CONCLUSIONS

In this paper we have proposed ADAPT, an adaptive algorithm for tuning the MAC parameters of the IEEE 802.15.4 standard in order to satisfy a target delivery ratio specified by the application, while minimizing the energy consumption. The ADAPT algorithm is simple yet effective, and does not require modifications to the IEEE 802.15.4 standard. ADAPT can not only successfully enforce the desired level of reliability, but also obtain a higher energy efficiency than other non-adaptive schemes designed to improve the communication reliability. We are currently testing an implementation of ADAPT on real sensor nodes; our preliminary experiments confirm the results obtained through simulation study. In addition, while in this paper we have limited our attention to single-hop wireless sensor networks, we also intend to evaluate ADAPT in multi-hop scenarios.

## ACKNOWLEDGEMENTS

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