A Blind Adaptive Tuning Algorithm for Reliable and Energy-Efficient Communication in IEEE 802.15.4 Networks

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Abstract—**Previous studies have shown that the IEEE 802.15.4 CSMA/CA with default parameter values suffers from a severe unreliability problem, which is undesirable in many wireless sensor network applications. For time-varying and unknown operating conditions, how to autonomously adjust parameters for reliability guarantees with low energy consumption is a significant challenge, especially when the acknowledgement (ACK) mechanism is disabled in order to reduce extra overhead and waiting time in control or alarm applications. In this paper, we propose a lightweight distributed algorithm called *Blind ADaptive Access Parameter Tuning* (BADAPT) for reliable and energy-efficient communication in IEEE 802.15.4 networks without using the ACK mechanism. Unlike previous adaptive algorithms that require a costly ACK to notify a sensor node whether a packet is successfully transmitted or not, the BADAPT allows sensor nodes to merely use the locally measured busy channel probabilities to estimate individual reliability under unknown operating conditions. Simulation results show that the BADAPT is effective both in stationary and dynamic scenarios.**

Index Terms—**Wireless sensor networks, IEEE 802.15.4, CSMA/CA, reliability.**

I. INTRODUCTION

IEEE 802.15.4 [1] is a well-known short-range wireless technology for a variety of recourse-constrained wireless sensor networks (WSNs) in industrial control, environmental surveillance and medical care. In this paper, we focus on its medium access control (MAC) protocol for the contention access period (CAP), in which each sensor node employs a Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) algorithm to access the channel. In addition to a major concern on energy efficiency, many WSN applications also strictly require different levels of reliability [2]. However, it has been shown in [3] that the IEEE 802.15.4 CSMA/CA with default parameter values suffers from a severe unreliability problem even when a limited number of sensor nodes contend for channel access simultaneously. Definitely, this problem would deteriorate further if acknowledgements (ACKs) and retransmissions are disabled. Hence, due to time-varying operating conditions in real-life scenarios, there is a natural interest in investigating how to adaptively set appropriate parameters for reliability guarantees with low energy consumption.

Several adaptive algorithms for IEEE 802.15.4 CSMA/CA have been proposed in the literature [4], [5]. However, there is relatively less attention on the reliability issue. Park *et al.* in [6] proposed a model-based approach by the derived optimal parameter setting. However, the model therein requires a priori knowledge of the network size and traffic pattern. To address this infeasibility in real-life scenarios, Francesco *et al.* in [7] proposed a heuristic algorithm, called the ADAPT, which allows sensor nodes to dynamically increase or decrease one of the CSMA/CA parameters only according to experienced packet delivery ratio. Simulation results shown that the ADAPT can achieve the specified reliability value under varying traffic demands. Furthermore, built on top of the ADAPT, JIT-LEAP [5] exploits the past history to find a more stable and accurate parameter setting, but with extra computational and storage resource. Notice that the ACK mechanism is needed in both ADAPT and JIT-LEAP to obtain the reliability estimation. This requirement incurs extra overhead, waiting time and energy cost.

To overcome the limitations in [5]–[7], this paper proposes a heuristic algorithm, called *Blind ADaptive Access Parameter Tuning* (BADAPT) for IEEE 802.15.4 networks without using ACKs. Our central idea is to merely utilize locally measured busy channel probabilities to estimate the individual reliability, and then activate the tuning phase when needed. It is fully distributed, can work under unknown network conditions, does not need ACKs, and does not require any modification of the existing standard. It will be shown that our approach is able to provide a target reliability level with low energy consumption.

The remainder of this paper is organized as follows. Section II describes the IEEE 802.15.4 CSMA/CA. A simple approach to derive the reliability is given in Section III. We describe the proposed BADAPT algorithm in Section IV and present simulation results in Section V. Conclusion remarks are provided in Section VI.

II. IEEE 802.15.4 CSMA/CA

In the following, we briefly introduce the IEEE 802.15.4 CSMA/CA. More details on physical layer related information can be found in [1].

This paper focuses on the beacon-enabled mode of the IEEE 802.15.4 MAC protocol, in which each sensor node schedules its transmission following a superframe structure, and the PAN coordinator transmits a beacon frame at the beginning of each superframe. The interval between two consecutive beacons (BI) is determined by the beacon order (BO): $\mathrm{BI} = 15.36 \cdot 2^{\mathrm{BO}}$ms; and the superframe duration (SD) is determined by the superframe order (SO): $\mathrm{SD} = 15.36 \cdot 2^{\mathrm{SO}}$ms, where $0 \leq SO \leq BO \leq 14$. A superframe consists of a contention access period (CAP) and a contention free period (CFP). During the CAP, sensor nodes access the channel by using a slotted CSMA/CA algorithm; while in the CFP, sensor nodes access the channel by using the assigned guaranteed time slots.

In the slotted CSMA/CA, each operation can only occur at the boundary of a backoff period with a duration of 320 μs. When a sensor node has a data packet awaiting transmission, the CSMA/CA initializes the values of two parameters: $NB = 0$ and $BE = macMinBE$ (default value = 3). Then the sensor node waits for a random number of backoff periods which is uniformly selected in the range $[0, 2^{BE} - 1]$, and performs clear channel assessments (CCAs) at the physic layer in

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two consecutive backoff periods. The algorithm starts counting down the number of backoff periods regardless of the channel state. The sensor node begins to transmit a data packet if these two CCAs both sense the channel to be idle. Once a busy slot is detected, *NB* and *BE* are both increased by one, and the transmission is delayed for a random number of backoff periods uniformly chosen from $[0, 2^{BE} - 1]$. Note that *BE* shall not exceed *macMaxBE* (default value = 5). If the *NB* value is greater than *macMaxCSMABackoffs* (default value = 4), the algorithm shall be terminated with a channel access failure, i.e., the packet is dropped. ACKs and retransmissions are not considered.

III. RELIABILITY ANALYSIS

A number of analytical models for IEEE 802.15.4 CSMA/CA have been developed in recent years. For example, in order to model the steady-state individual behavior under saturated traffic or random traffic, [6], [8]–[10] applied Discrete Time Markov Chains (DTMCs); and [11] applied the renewal theory with a contraction mapping technique. On the other hand, unlike these steady-state analyses, an approach based on recursive updating was proposed in [12] to capture the transient behavior under periodic traffic; and an approach based on event chains computation was proposed in [13] to model all the possible outcomes under event-driven traffic.

To achieve the desired level of reliability, local reliability estimation is an essential ingredient in adaptive algorithms. However, to our best knowledge, all previously known analytical models focus on how to derive the reliability by using various access parameters, such as the network size, the MAC parameters, and the traffic pattern. As some of the access parameters are locally unmeasurable, these methods are unsuitable to be directly used to estimate the individual reliability under unknown operating conditions. To cope with this issue, this section establishes a connection between the reliability and the adjacent-slot-pair-wise channel state, which allows a sensor nodes to obtain the reliability estimation merely relying on the local measurements in CCAs.

Before presenting the reliability analysis, let us first introduce the adopted system model. We consider a single-hop network with one sink node acting as a PAN coordinator and a number of sensor nodes. All the sensor nodes are within the interference range of each another, so there are no hidden terminals in the network, as shown in real experiments [14]. Such a topology is a common case in group-based monitor applications. We assume that the sensor nodes access the channel by the slotted IEEE 802.15.4 CSMA/CA without using ACKs. All transmitted packets are assumed to occupy the same fixed channel time of L slots, which can be achieved by the fragmentation or concatenation at the upper layer. A collision happens if multiple sensor nodes simultaneously begin transmissions. We do not consider channel errors so that all transmitted packets may be lost only due to collisions. We also assume that there is no queue overflow for each sensor node. Notice that all of the above assumptions have been widely adopted in previous studies on IEEE 802.15.4 [4].

We consider the delivery ratio R as a measure of a tagged sensor node's reliability, which is defined as the ratio between the number of data packets successfully transmitted by the tagged sensor node and the total number of packets generated by the tagged sensor node. In the slotted CSMA/CA without ACKs, we know that a packet is discarded at the MAC layer due to either channel access failure or collision. Hence, the delivery ratio R can be derived as:

$$R = (1 - \sigma)(1 - p_c) \tag{1}$$

where σ is the probability that the tagged sensor node fails to access the channel within the maximum allowed attempts, and p_c is the probability that the tagged sensor node experiences a collision when transmitting.

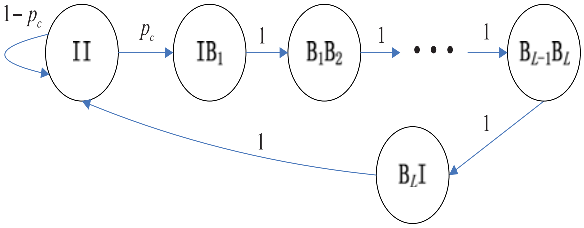


Fig. 1. Adjacent-slot-pair-wise channel state model.

TABLE I
PARAMETERS USED FOR SIMULATION

Parameter	Value
bit rate	250 kbps
packet size	120 bytes
BO, SO	13, 10
target reliability (R^{des})	70%, 80%
memory factor (δ)	0.4
weighted distance μ, ν	8%, 3%
macMinBE$^{\text{min}}$, macMinBE$^{\text{max}}$	1, 7
macMaxBE$^{\text{max}}$	10
macMaxCSMABackoffs$^{\text{min}}$	1
macMaxCSMABackoffs$^{\text{max}}$	10
power consumption in RX, TX, idle, sleep	56.4, 52.2, 1.28, 0.06 mW

To further derive the relationship featuring p_c and the busy channel probabilities, we make use of a DTMC to model the adjacent-slot-pair-wise channel state when the tagged sensor node keeps silent, as shown in Fig. 1. Unlike the channel state model in [10] which assumed a random packet length, our model focuses on a fixed packet length. The II state corresponds to the channel state of idle-idle-slots pair, the IB_1 state corresponds to the channel state of idle-busy-slots pair, the $B_l B_{l+1}$ state corresponds to the channel state with the l-th and $l+1$-th slot of the current transmission for $l = 1, 2, \ldots, L-1$, and the $B_L I$ corresponds to the channel state of busy-idle-slots pair. The channel leaves the state II to become IB_1 with probability p_c, as one or more than one other sensor nodes begin to transmit, whereas it stays in the state II with probability $1 - p_c$. Once the channel state becomes IB_1, the channel state successively goes into $L - 1$ channel states of the busy-slots pair with probability 1, and then takes a transition to the state $B_L I$ with probability 1. Finally, as the sensor nodes are only allowed to begin transmission after sensing the channel to be idle in two consecutive CCAs, the channel leaves the state $B_L I$ to become II with probability 1. According to the described transitions, we can obtain the stationary channel state probability of II as follows:

$$P_{II} = \frac{1}{(L+1)p_c + 1} \tag{2}$$

From (2), it is interesting to observe:

$$p_c = \frac{1 - P_{II}}{(L+1)P_{II}}. \tag{3}$$

Let ϕ denote the probability that the tagged sensor node finds the channel busy either in the first CCA or in the second CCA. Obviously, we have $\phi = 1 - P_{II}$, and thus (3) can be rewritten as:

$$p_c = \frac{\phi}{(L+1)(1-\phi)}. \tag{4}$$

Further, substituting (4) into (1) yields:

$$R = (1 - \sigma)\Big(1 - \frac{\phi}{(L+1)(1-\phi)}\Big). \tag{5}$$

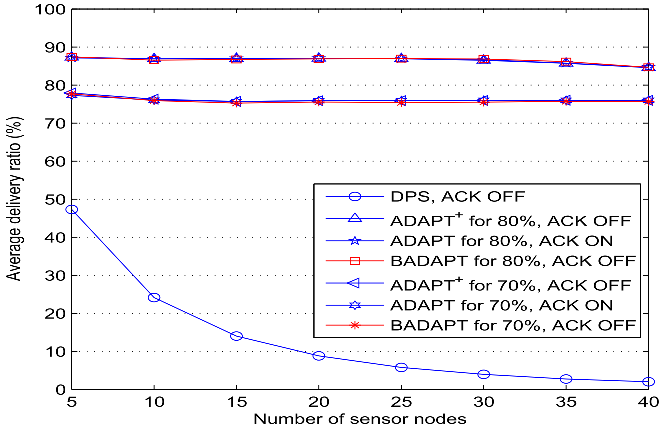


Fig. 2. Delivery ratio in stationary conditions.

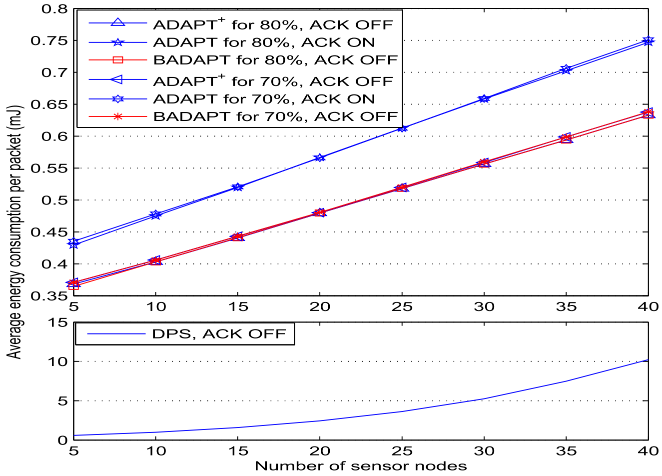


Fig. 3. Energy consumption in stationary conditions.

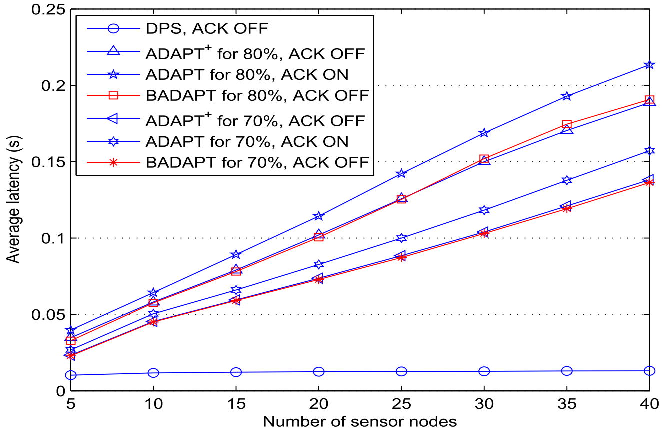


Fig. 4. Average latency in stationary conditions.

By noting that both σ and ϕ are locally measurable, (5) provides a theoretical tool that allows individual sensor nodes to merely exploit local measurements during CCAs to evaluate the reliability R.

It should be noted that (2) only holds in a network without hidden terminals and exposed terminals, and thus our reliability estimation is inapplicable to a multi-hop network. Nevertheless, this limit is difficult to address in the absence of ACKs, since that it is impossible to establish an accurate connection between the collision probability and locally observed channel states under unknown network conditions if there are hidden or exposed terminals.

IV. BLIND ADAPTIVE ACCESS PARAMETER TUNING

In this section, we describe the proposed BADAPT algorithm. We present a run-time reliability estimation grounded on the reliability analysis developed in Section III, and then introduce a heuristic tuning algorithm that is triggered only when needed.

A. *Run-Time Reliability Estimation*

At the end of every BI, we require each sensor node to first estimate σ and ϕ, and then compute the reliability R by using (5). Each sensor node can be aware of whether a packet is discarded due to channel access failure, and hence, in practice, σ in the i-th BI can be estimated locally by the ratio between N_i^{caf}, the number of packets that fail to access the channel in the i-th BI and N_i, the total number of packets generated in the i-th BI. On the other hand, ϕ in the i-th BI can be estimated locally by the ratio between N_i^{bcca}, the times of finding the channel busy in the i-th BI and N_i^{cca}, the total times of performing the first CCA in the i-th BI. Therefore, the estimated reliability $\hat{R}_i$ can be computed at the end of the i-th BI as follows:

$$\hat{R}_i = \left(1 - \frac{N_i^{caf}}{N_i}\right)\left(1 - \frac{N_i^{bcca}}{(L+1)(N_i^{cca} - N_i^{bcca})}\right).$$

To avoid sharp changes in the estimated value, we further apply an exponential moving average to update the estimate:

$$\text{estimated\_}R_i = \delta \cdot \text{estimated\_}R_{i-1} + (1-\delta) \cdot \hat{R}_i$$

where $\delta \in [0, 1]$ is a memory factor.

B. *Adaptive Tuning Algorithm*

It has been shown in [7] that the reliability increases monotonically with the value of either *macMinBE* or *macMaxCSMABackoffs*, and increasing *macMinBE* is more energy efficient. Following the contention control scheme in ADAPT [7] and JIT-LEAP [5], we also use these simple logic to design the tuning algorithm in the BADAPT.

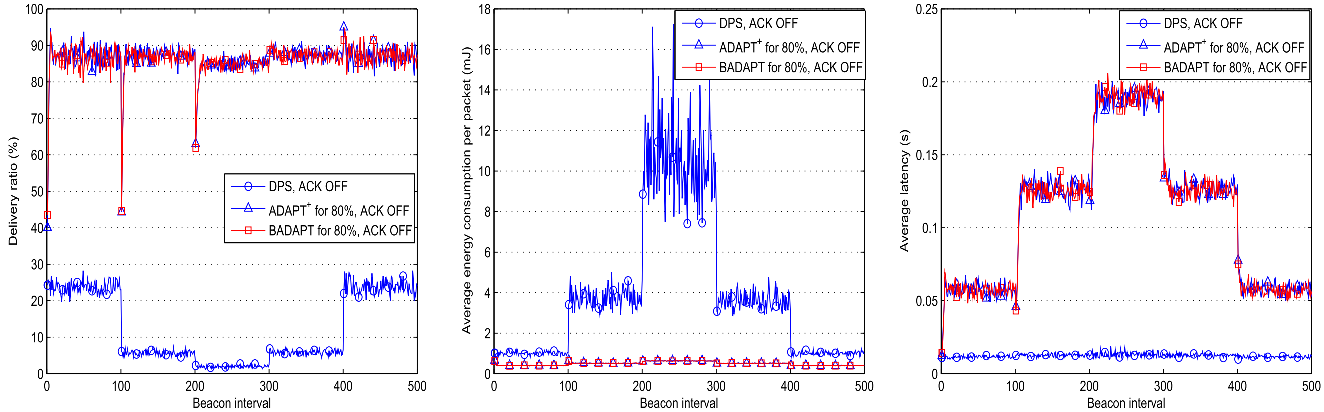
According to the required reliability R^{des}, we define two thresholds to avoid tardy adaptation or excessive energy consumption: $R^{low} = R^{des} \cdot (1+\mu)$ and $R^{high} = R^{des} \cdot (1+\mu+\nu)$ in which $\mu \in (0, \frac{1}{R^{des}} - 1)$ and $\nu \in (0, \frac{1}{R^{des}} - 1 - \mu)$.

By comparing estimated_R_i with R^{low} and R^{high} at the end of the i-th BI, each sensor node applies a simple tuning strategy as follows. If estimated_R_i is smaller than R^{low}, the *macMinBE* is increased until *macMinBE*^{max} is reached, and then *macMaxCSMABackoffs* is increased until *macMaxCSMABackoffs*^{max} is reached. If estimated_R_i is larger than R^{high}, the *macMaxCSMABackoffs* is decreased until *macMaxCSMABackoffs*^{min}, and then *macMinBE* is decreased until *macMinBE*^{min}.

Notice that it is difficult to theoretically analyze such a heuristic tuning algorithm. Instead, in the subsequent section, we show that the BADAPT is effective and energy-efficient via simulation results, as done in other similar studies [5], [7].

V. SIMULATION RESULTS

In this section, we use the ns2 simulator to evaluate the performance of BADAPT both in stationary and dynamic scenarios. According to [5], [7], we make the following simulation setup. We consider that sensor nodes are randomly placed 10 m away from the sink node,



(a) (b) (c)

Fig. 5. Delivery ratio, energy consumption and latency under dynamic conditions. (a) Delivery ratio. (b) Energy consumption. (c) Average latency.

TABLE II
IMPACT OF THE DATA RATE ON THE BADAPT

Parameter	$m = 10$	$m = 20$	$m = 40$
delivery ratio (%)	85.8	86.4	86.9
energy consumption (mJ)	0.573	0.509	0.479
latency (s)	0.092	0.097	0.101
transient time (BIs)	4	4	4
ratio of violations (%)	3.4	1.2	0.8

and all have transmission range 15 m, and carrier sensing range 30 m. We use the IEEE 802.15.4 beacon enabled mode and the Chipcon CC2420 radio transceiver [15] based energy model. It should be noted that we put the sensor nodes to sleep when they have no packets ready for transmission, and to idle when they are in backoff. We summarize the operating parameters in Table I. We also assume that each sensor node sends m data packets to the sink node per BI, and all these packets are passed down to the MAC layer at the beginning of each BI. Such a traffic pattern depicts a common IEEE 802.15.4-based monitor scenario [3] in which the sensor nodes experience a long inactive period and have several collected reports awaiting transmission at the end of the inactive period. Unless otherwise specified, we consider $m = 40$ in all cases.

To show the BADAPT is effective and energy-efficient, we consider default parameters setting (DPS) and ADAPT$^+$ for comparison purposes. Notice that ACKs are not used in these three schemes. Here, ADAPT$^+$ impractically assumes that sensor nodes know whether a packet is successfully transmitted or not without using ACKs, and adopts the same tuning algorithm as in the BADAPT. This ideal scheme is unfeasible in practice, and is only introduced as a benchmark in order to demonstrate the accuracy of the reliability estimation in the BADAPT. On the other hand, to show the advantage of not using ACKs, we also investigate the performance of ADAPT [7], which employs ACKs for reliability estimation, and additionally triggers the retransmission scheme when needed. For a fair comparison, in the experiments for ADAPT, we adopt the tuning parameters in Table I, and set the memory of the message loss estimator and sensitivity to message losses as 80% and 2.5%, respectively.

In addition to the reliability, we also consider the following two performance metrics: (i) *average energy per packet* defined as the average energy consumed by a sensor node per single successfully transmitted packet, and (ii) *average latency for a successfully received packet* defined as the average time interval from the instant a packet is at the head of the MAC queue, until the packet is correctly received by the sink node.

The results in stationary conditions are averaged over 1000 BIs, and the results in dynamic conditions are from a single representative simulation run for 500 BIs.

A. Analysis in Stationary Conditions

We start by evaluating the impact of the number of sensor nodes on the performance in stationary conditions. We from Fig. 2 observe that BADAPT is able to meet different reliability requirements regardless of the number of sensor nodes, whereas the DPS suffers from a sharp deterioration on reliability with the increasing network size. Due to autonomous tuning, one sees that the BADAPT offers a nearly constant average delivery ratio between d^{low} and d^{high}. This bounded region leads to a significant reduction on energy consumption compared with the DPS, as shown in Fig. 3. Regarding the latency, as shown in Fig. 4, the BADAPT inevitably has a larger latency than the DPS, since it requires sensor nodes to spend more time in backoff for reducing the contention level. Specifically, as expected, a higher required reliability incurs a larger latency in the BADAPT.

On the other hand, from the comparisons between the BADAPT and ADAPT$^+$ in Figs. 2–4, we find these two adaptive schemes enjoy almost the same performance. This phenomenon verifies that our reliability estimation ensures a satisfactory accuracy. Meanwhile, we find BADAPT outperforms ADAPT in terms of latency and energy consumption, although they have similar reliability performance. There are a 9.47%–17.6% reduction on latency and a 14.8%–15.5% reduction on energy consumption. This improvement obviously benefits from not using ACKs.

B. Analysis in Dynamic Conditions

We now focus on dynamic scenarios with time-varying number of active sensor nodes. In the considered 500 BIs, we assume that 10 sensor nodes are always active. At the 101-st BI, 15 more sensor nodes become active from inactive, and return inactive after 300 BIs. Another set of 15 sensor nodes activates at the 201-st BI, and deactivates 100 BIs later. We aim to examine the robustness of the BADAPT algorithm to such changes. It should be noted that some "violations" of the desired delivery ratio may occur due to suddenly changed network conditions or inappropriate tuning incurred by overestimation of the reliability.

For a clear demonstration, we only present the case of $R^{des} = 80\%$ for BADAPT, DPS and ADAPT$^+$ in Fig. 5.

Fig. 5(a) shows that the reliability of the BADAPT is above the required value almost all the time, whereas the reliability of the DPS is always below 30%. In detail, for the BADAPT, we observe that the transient time is at most 5 BIs for every sudden change in operating conditions, and the ratio of violations (including the transient time) is 2.6%. As for the ADAPT$^+$, we find the transient time is at most 5 BIs and the ratio of violations is 2.2%. This result shows that BADAPT and ADAPT$^+$ have similar convergence, and confirms the accuracy of our reliability estimation again. From Fig. 5(b) and (c), we also find BADAPT and ADAPT$^+$ enjoy almost the same energy consumption and latency performance under dynamic conditions.

Finally, to broaden our analysis, we record the impact of the data rate on the BADAPT in Table II. We consider that 20 sensor nodes send 10, 20, 30 and 40 packets per BI to the sink with $R^{des} = 80\%$, respectively. We observe that, increasing the data rate leads to a higher average delivery ratio, a lower average energy consumption per packet, a smaller ratio of violations and a larger latency, but has no impact on the transient time. This is because that a higher data rate would make the reliability estimation more accurate, and on the other hand, make the actual delivery ratio per BI more stable. Obviously, both of these can avoid unnecessary tuning. Overall, we find the BADAPT is effective even when the data rate is low.

VI. CONCLUSION

To address the unreliability issue in IEEE 802.15.4 based WSNs without using ACKs, we in this paper have proposed the BADAPT algorithm, by which each sensor node can adaptively achieve the required reliability level under unknown and time-varying operation conditions. Unlike ACKs-dependent or model-based adaptive algorithms, the BADAPT utilizes the busy channel probabilities measured in CCAs to estimate reliability in a single-hop network without requiring any input parameter. Simulation results have shown that the BADAPT is effective and energy-efficient in the considered scenarios.

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