Protocol Options for Low Power Sensor Network MAC using Wake-up Receivers with Duty Cycling

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***Abstract*—Advances in miniaturization of sensor nodes enable a wide range of novel application scenarios. At the same time, however, this miniaturization drastically reduces the energy available for communication. We focus on wildlife monitoring applications for bats, which set a weight limit of 2 g for the sensor node including the battery. Here, the protocol design is complicated by the need to recharge a capacitor before each communication attempt. For communications with ground stations, wake-up receivers are used that inherently help mitigate synchronization demands and to provide a superframe structure. We study the not obvious choice of transmission slots within these synchronized superframes. Our findings clearly indicate that slotted access outperforms simple random channel access. Well-planned TDMA schedules only bring little gain compared to random slot selection.**

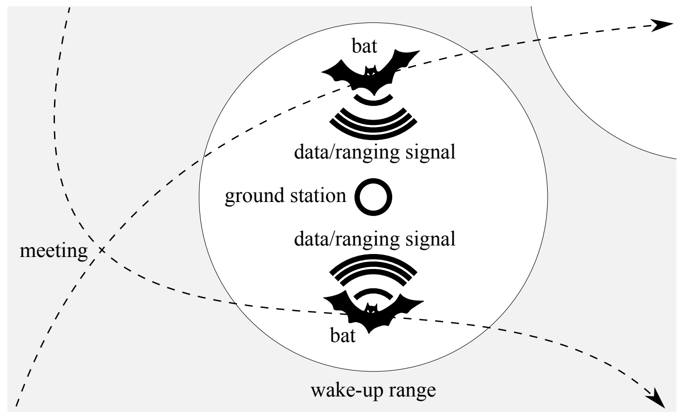

Figure 1. Scenario considered in this paper: wireless sensor nodes mounted on bats (*Myotis myotis*) in their natural habitat record meetings during flight; upon entering the wake-up range of a ground station they start transmitting a combined data/ranging signal for tracking and to offload recorded data.

I. Introduction

Wireless Sensor Networks (WSNs) have very distinct requirements on the MAC protocol compared to traditional wireless networks. The primary objectives for these protocols are self-adaptivity, low power consumption, and, eventually, long network lifetime [1], [2]. A wide range of MAC protocols have been developed for matching particularly these energy constraints [3]–[8].

In the BATS project, we attach sensor nodes to Mouse-eared bats (*Myotis myotis*) in order to study their social behavior which makes the network topology change rapidly [9]. These sensor nodes have to be extremely lightweight (maximal 2 g), since the bats themselves only weigh around 20 g. This implies an extremely low power budget. The technology is to be used for *(a)* tracking bats during flight maneuvers and *(b)* identifying social interactions by monitoring contact timestamps and durations between individuals.

The measurement data is to be downloaded from the mobile nodes to ground nodes deployed in the area under investigation (cf. Figure 1). In brief, the mobile nodes transmit a short beacon every second that is received by other bats nearby. From the reception of these beacons so called meetings are generated that contain information about which bat has been near the other for how long. In order to gather this information and to track the bats' positions, the ground stations send out a wake-up signal. When a mobile node is in range it wakes up and transmits its information to the ground station. We designed the physical layer protocol for this wake-up system so that it provides localization information during a downlink data connection [9]. For accurate tracking, we assume a message frequency of at least 10 Hz.

Recently, we presented a first hardware prototype for the mobile node that is able to provide the discussed capabilities [10]. In order to meet the discussed weight restrictions, we had to use a capacitor as the main energy source for the used microcontroller and radio chip. This is because the light-weight battery does not provide a high-enough current to continuously power the system. Out solution was to integrate a duty cycling (for recharging the capacity) with a wake-up receiver (for keeping the device off when not in communication range of a ground station).

In this paper, we address the problem of medium access control. Since traditional MAC protocols are not directly able to match the requirements in our challenging scenario, we have to question established concepts and identify options for the integrated use of duty cycling with wake-up receivers. The fast changing network topology and the low power budget does not allow to use common MAC protocols for sensor networks.

We investigated the problem of medium access and performed an extensive simulation parameter study to identify possible options. The choice is non-trivial in our scenario as we have to keep track of conflicting optimization goals. The solution space ranges from very simple random access (à la classical ALOHA) to slotted approaches where additional synchronization effort is needed. We particularly investigated slotted ALOHA as the most simple form as well as Time Division Multiple Access (TDMA) schedules generated by the

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ground nodes. In all cases, this signal is transmitted periodically by the ground nodes at a rate of 1–10 Hz. The wake-up receiver helps solve the problem of synchronization among the nodes without the need for a complex protocol.

Our key contributions can be summarized as follows:

- We discuss protocol constraints for wake-up systems constraint to periodic recharging requirements due to tight hardware restrictions (Section III-A); and
- we study the solution space for MAC protocol options based on duty cycling integrated with a wake-up receiver (Section III-B);
- we performed an extensive simulation study to reveal very interesting performance characteristics and new insights into the operation of such protocols (Section IV).

II. Related Work

A. Wake-Up Receiver

Wake-up receivers can be grouped according to their hardware characteristics into passive and active. The former can be powered up by transforming the RF input signal. Unfortunately, these systems also suffer from poor radio sensitivity. Active wake-up receivers, in turn, can provide higher sensitivity, but there is a higher power consumption.

To solve the latency issue, an ultra-low power wake-up receiver, which can listen continuously, has been proposed in [11]. It consists of a filter, an amplifier, a detector, and a mixer with LO signal generator for down conversion of higher operation frequency. However, while it solves the latency problem and achieves higher sensitivity, the power consumption of the receiver still suffers by the always-on receiver. Modern wake-up systems use a multi-stage receiver to further reduce the power consumption.

To further reduce the power consumption of the receiver A good example is a 2-stage duty cycled wake-up receiver has been introduced [12]. At the first stage, a duty cycling scheme is applied on the ultra-low power receiver, which can only process the input signal with low data rate. To obviate the condition that the receiver misses the detection from the wake-up signal, the sampling rate needs to be aligned to the wake-up signal from the transmitter. As soon as the wake-up signal is confirmed, the second stage is activated which turns on the system permanently in order to process additional information, such as ID and data, with higher data rate.

We proposed a similar system combining duty cycling for recharging a capacitor as well as a wake-up receiver for activating the system only when in communication range to a set of ground nodes [10]. In this paper, we concentrate on MAC protocol design for such system relying on this system's hardware constraints.

B. MAC for Low Power Sensor Networks

In the last years, many MAC protocols for wireless sensor networks have been developed. These protocols aim to maximize the lifetime of a sensor network by minimizing the energy consumption [2], [3]. One option to achieve this goal is duty cycling. This allows the nodes to remain in an energy saving sleep state for most of the time where the main transceiver is turned off. In order to retain connectivity, such a MAC protocol must provide a synchronization method to ensure that sender and receiver are awake at the same time. One of the first of such energy efficient MAC protocols was S-MAC [4], [13], which synchronizes the sleep/wake schedules among nodes. Another duty cycling based protocol is TRAMA [5] which uses a slotted TDMA based mechanism to avoid collisions in an energy efficient way. The system benefits in terms of power consumption of the receiver, but increases the latency of detection and also implies higher energy consumption of the transmitter.

WiseMAC [6], on the other hand, uses separate data and control channels. Each node sends a preamble before each data packet to alert the receiving node. By learning the sleep schedules of direct neighbors the energy consumption can be reduced. In addition, WiseMAC can handle variable traffic conditions by adapting the preamble length.

In order to compensate the latency issue, wake-up receivers help wake up the receiving node only before an upcoming transmission. For example, CMAC [7] uses a wake-up receiver not only for waking up neighboring nodes but also as a control channel. Transmissions over the main transceiver are controlled via *Request* and *Confirm* messages that are similar to RTS/CTS messages known from 802.11. The hidden node problem is further coped with as a node that is currently receiving data on the main transceiver gets a request from a third node via the wake-up receiver it signals this node that it is currently busy (via a *Wait* signal). By using a wake-up receiver for asynchronous duty cycling and as a second channel for control messages, CMAC can provide low energy communication without curtailments of latency or throughput.

Furthermore, predictive solutions have been studied in the literature and show promising results when it comes to data communication patterns instead of physical contacts. In PW-MAC [8], the sender makes use of the wake-up time algorithm to predict the next wake-up of the receiver. This allows the sender to stay in sleep mode as long as possible and wake-up right before the receiver in order to conserve energy.

III. MAC Protocol Options

A. Protocol Constraints

The very low weight of the sensor nodes limits the available energy, which imposes tight constraints for the used protocols. The used battery cannot deliver sufficient current to power the microcontroller and the transceiver, which is why we use a buffer capacitor with 330 μF. The battery charges the capacitor, which then powers the sensors electronics until it goes to sleep mode or the voltage falls below the minimal threshold as illustrated in Figure 2. This limits the maximum active period for the sensor node and the maximum duty cycle. The exact timing specifications and the trade-off between the charging interval and the active period has been studied in detail in [10]. Our simulation model includes this charging and discharging of the capacitor to simulate failed transmissions caused by an insufficient charging state of the capacitor.

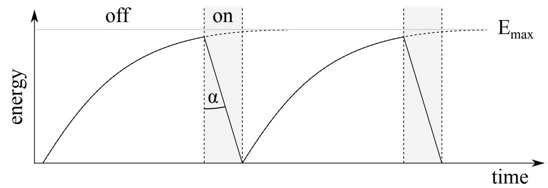


Figure 2. Qualitative overview of charging and discharging of the capacitor.

Another constraint for a suitable MAC protocol is the short interaction time between the mobile and ground nodes and the high dynamic of the network topology. These are caused by the fast movement of the bats. As studied in [14], most contact times are less than 3 s. This makes the usage of traditional rendezvous based MAC protocols impractical, if not impossible, because there is not enough time for the synchronization phase. Even if a communication schedule could be established between the mobile and the ground nodes, this schedule would immediately become outdated since many bats already have moved out of the communication range. Also, a lot of synchronization effort would be necessary to maintain connectivity in such a highly dynamic network, which conflicts with the requirement of ultra low energy consumption.

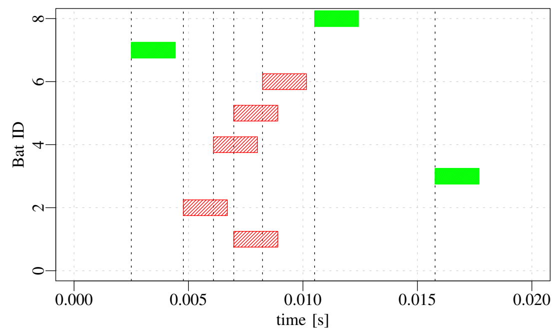
B. Exploring the Solution Space

When flying in the observation area, from time to time the bats come within communication range of the ground nodes. The ground nodes continuously broadcast a wake-up signal that is received by the mobile nodes. Starting a transmission immediately after receiving the wake-up signal, would lead to synchronized collisions. However, since all nodes in communication range receive this signal at the same time, this point in time can be used as a synchronization point for the medium access and is called $t = 0$ from here on. The time between two consecutive wake-up messages is called a *superframe* and has duration t_{SF}. Without loss of generality, we use a wake-up frequency of 10 Hz which results in a superframe length of $t_{\mathrm{SF}} = 100\,\mathrm{ms}$.

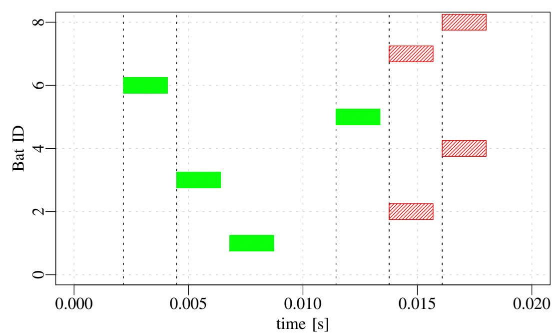
In the following, we explore three different options for medium access within the superframe: random, i.e., following the classical ALOHA approach as well as using time slots to reduce the probability for collisions. This could be a random choice of the time slot, i.e., slotted ALOHA or a TDMA scheme controlled and coordinated by the ground nodes.

In the ALOHA variant, each node starts transmitting at a time chosen uniformly in the interval $[0, t_{\mathrm{SF}} - t_{\mathrm{d}}]$, where t_{d} is the packet duration time. This can lead to a high collision probability if many nodes are in the same collision domain as depicted in Figure 3a. This figure shows failed transmissions (red, dashed) and successful transmissions (green, solid) after the reception of a wake-up frame at time $t = 0$. One can see that many transmissions from different mobile nodes overlap and can therefore not be received at the ground node.

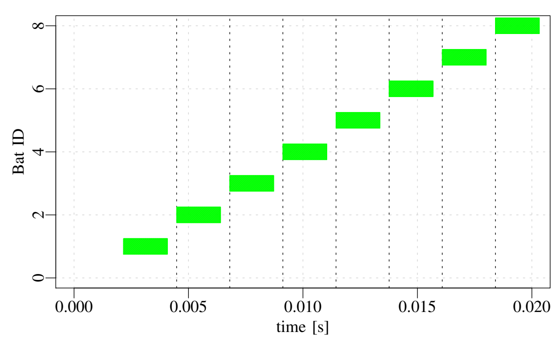
This problem can be addressed by using a slotted MAC scheme, where each node is only allowed to start sending at predefined points in time. In the slotted ALOHA variant of our



(a) ALOHA protocol option



(b) Slotted ALOHA protocol option



(c) TDM protocol option

Figure 3. Example of received frames within a superframe.

protocol, we divide each superframe into multiple sub frames, called slots. Upon the reception of a wake-up signal each node chooses one of the available slots and waits until this slot to send its data. Figure 3b shows that collisions can still occur if two mobile nodes choose the same slot.

Beside the problem of collisions, another problem can occur when using random transmission times or slots. In our system, the transceiver and the microcontroller of the mobile nodes are powered by a capacitor. During the inactive periods this capacitor is recharged again. If a mobile node sends its data at the end of a superframe followed by another transmission right at the beginning of the next superframe, the interval between both transmissions might bee too small. In such a case, the available energy of the capacitor would not be sufficient to successfully transmit the second packet.

As a third variant, we use a TDMA scheme to control the channel access. Like in the slotted ALOHA variant, each superframe is divided into multiple slots. The number of slots is denoted as s. Each mobile node has a unique ID which is used to determine the slot to be used. Since we assume that the number of time slots and the ID is known to each mobile node the slot can easily be calculated as ID $\bmod s$. Assume we have $s = 5$ slots, then bats 1 and 6 would choose slot 1 and bats 2 and 7 would choose slot 2. As long as there are no two bats with the same slot within the same collision range, collisions can be prevented completely. This is shown in Figure 3c, where there are 8 slots for 8 mobile nodes.

IV. Performance Evaluation

A. Simulation Model

We used the OMNeT++ simulation toolkit for our simulation in combination with the MiXiM framework for modeling physical layer radio communication [15]. As depicted in Figure 1, our scenario consists of multiple stationary ground nodes and mobile nodes that are attached to the bats. The communication between the nodes takes place over an 868 MHz channel. To model the wireless channel, we used a free-space path-loss propagation model with additional log-normal shadowing. The ground nodes are deployed in an irregular grid with a inter-node distance of 50 m. The size of the simulation is 300 m $\times$ 300 m with a total of 25 ground nodes. The mobility model for the bats is derived from the Lévi flight model and resembles the foraging behavior of the bats [14]. The area is divided into 9 hunting areas. Each bat chooses one these areas where it then “hunts” for a certain duration.

B. Energy Model Validation

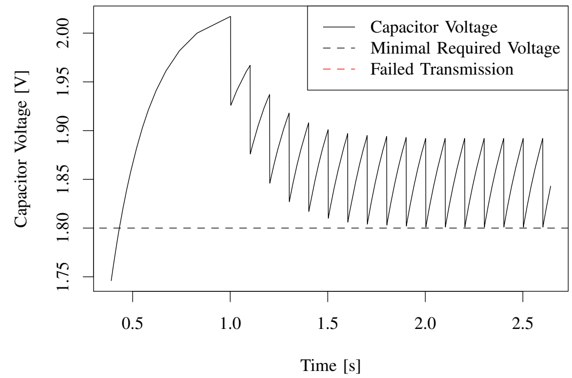
Before running the MAC protocol simulations, we evaluated our new energy simulation model. Our mobile nodes are not directly powered by the battery but indirectly using a buffer capacitor (cf. Figure 2).

When using the ALOHA variant, a node waits for a random time after receiving the wake-up signal. The resulting capacitor voltage over time is shown in Figure 4b. As can be seen, the graph is irregular. As shown by the red, dashed lines, this behavior can cause failed transmissions. If the time between two consecutive transmissions is not sufficient to recharge the capacitor, the voltage drops under the minimal voltage during the second transmission.

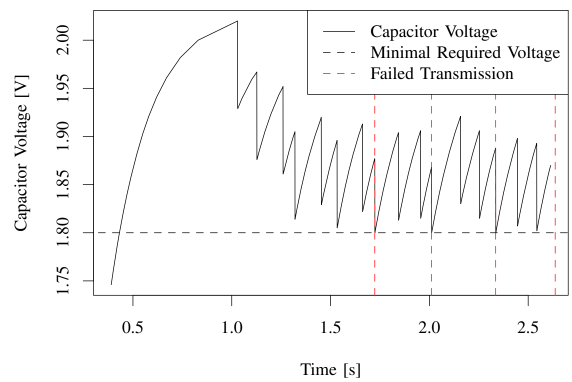
A similar effect can be observed in Figure 4c for the slotted ALOHA approach. Here only one transmission failed due to capacitor outages.

Finally, Figure 4a shows the voltage of this buffer capacitor of one mobile node over time when using the TDMA variant. Since the wake-up signals come in a regular interval of 100 ms and the mobile node always uses the same slot, the pattern is regular. All transmissions were successful since the voltage did not drop under the minimal voltage of 1.8 V.

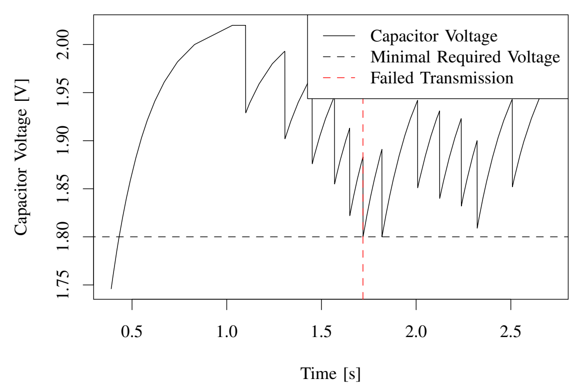
At the end of the node’s lifetime (that is, at low battery levels) the effect of the capacitor is different. When using the TDMA variant, the time between two successive transmissions from one node is always the length of one superframe, regardless of



(a) TDMA protocol option: All transmissions are successful. If the battery voltage was even lower, no packets could be send anymore



(b) ALOHA protocol option: Due to the irregular inter-packet times four transmissions fail because of an insufficient capacitor load



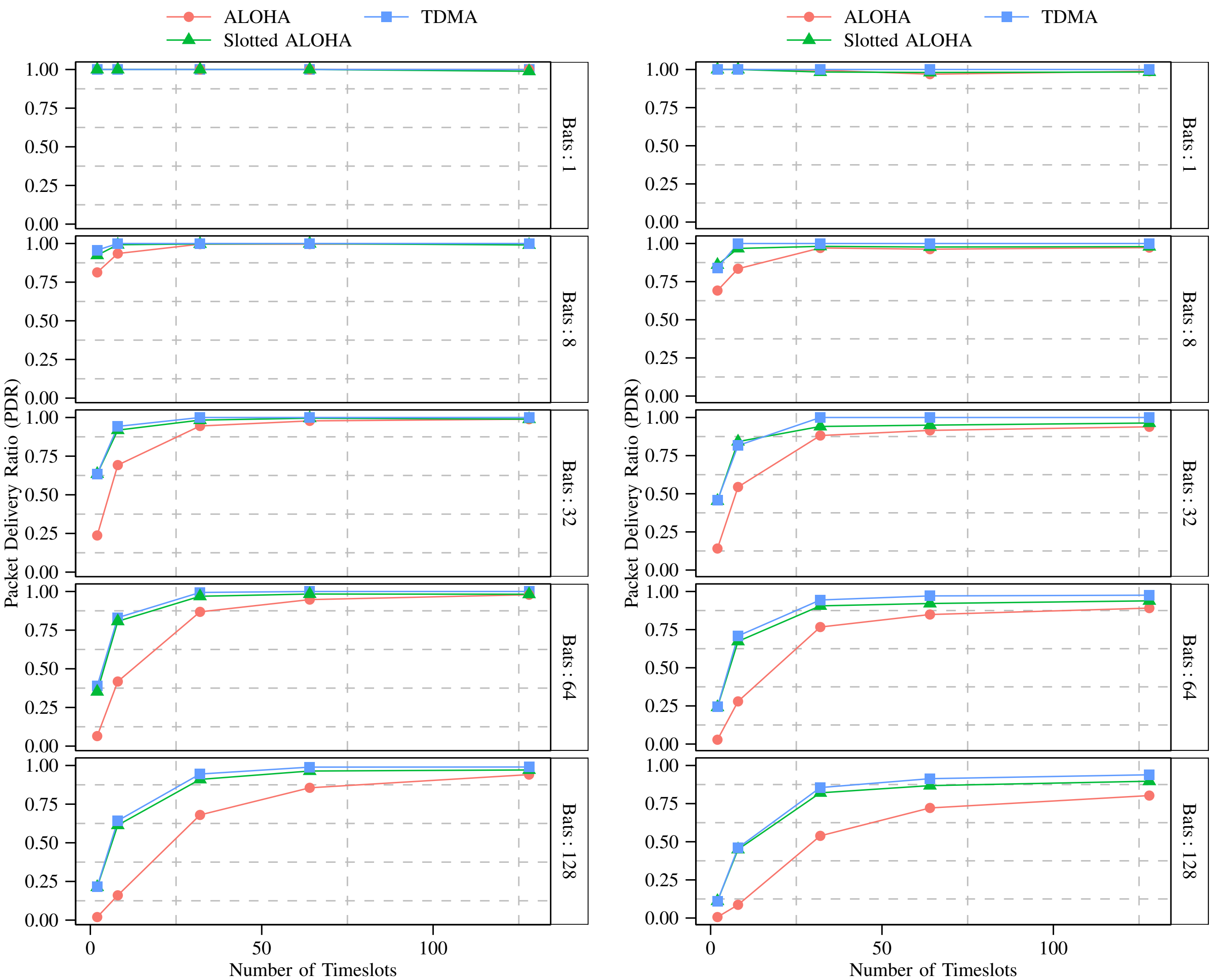
(c) Slotted ALOHA protocol option: In one case the transmission fails because of an insufficient capacitor load

Figure 4. Voltage of the buffer capacitor over time.

the chosen time slot. If the voltage of the battery gets too low to recharge the capacitor within 100 ms to a sufficient level, the TDMA variant will always fail to transmit. For the random protocols the time between two successive transmissions can be larger than one superframe, which would allow at least some transmissions to succeed.

C. Protocol Performance

To evaluate the performance of the proposed protocol schemes, we ran an extensive set of simulations using the



(a) Packet size of 12 bit

(b) Packet size of 48 bit

Figure 5. Packet Delivery Ratio (PDR) of different MAC variants over number of time slots and the total number of bats in the scenario.

model described in Section IV-A. We fixed the number and positions of the ground nodes. The number of bats in the scenario was increased from 1 to 128. They start at the same position but then choose random hunting fields. That means that if having 128 bats in the scenario, they will not all compete for medium access for the whole time since they fly to different hunting fields. Another parameter of our simulation is the number of time slots. To achieve fairness between the ALOHA variant and the slotted variants, the time in which the random protocol can send was adapted accordingly.

In our application scenario of monitoring bats in the wild, the mobile nodes only send packets if they have a certain amount of new data available. To remove this influence and evaluate the MAC protocols under heavy load, we assume that a node always tried to send data to the ground node if a wake-up signal is detected. Since our wake-up receiver based protocol does not produce any additional overhead, the required energy does not depend on the used variants. Still, failed transmissions lead to wasted energy. In Figure 5, we plot the Packet Delivery Ratio (PDR) as an indirect metric for energy efficiency.

Figure 5a shows the simulation results when data packets of 12 bit were sent. If there is only one bat in the scenario, there is no possibility for collisions and all protocol variants are equally good. As soon as more bats are in the scenario, the collision probability increases if there are not enough time slots available, which leads to a reduced PDR. The graph clearly shows that the slotted protocol variants are superior to the ALOHA variant. For a large number of bats the collision probability of the ALOHA variant gets too high, which causes a low PDR and therefore a lot of wasted energy.

These effects are even more distinct if the data size of the transmitted packet is increased as shown in Figure 5b for

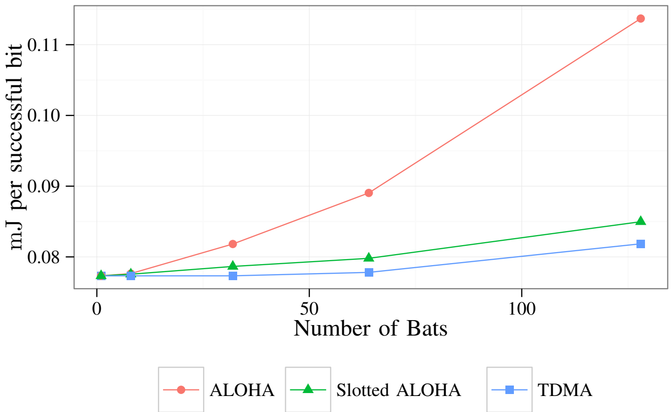


Figure 6. Required energy to successfully send a bit for an increasing number of bats. The lower the value, the more efficiently a protocol uses the available energy.

a packet size of 48 bit. As can be seen, this increases the transmission time and therefore the collision probability.

D. Energy Performance

Finally, we investigate the efficiency using the ratio of energy per successfully transmitted bit. Figure 6 shows this ratio over the number of bats in the scenario. In this figure, we fixed the number of time slots to be 32, which we selected as a representative sample for our application scenario. The graph clearly shows that the ALOHA protocol variant is less efficient than the slotted ones. As discussed before, the number of transmitted bits is equal for all protocol variants. The differences in the efficiency are therefore induced only by the amount of collisions causing transmissions to fail.

V. Discussion and Conclusion

In conclusion, it can be said that the optimal choice of the medium access method strongly depends on a number of system parameters. First and foremost, this is the expected maximum number of mobile nodes in communication range within the ground station. A next parameter is the packet size, which controls the transmission time of a single packet. Together, both parameters define the necessary number of time slots within a superframe and indirectly the maximum frequency for transmissions. For precise tracking, we aim for at least 10 Hz, which allows for about 32 time slots.

As can be seen from our simulation experiments, random access within the superframe is suboptimal for increasing numbers of nodes and increasing packet sizes. In both cases, the PDR is increasing. Slotted ALOHA as well as TDMA perform quite similar with respect to PDR and energy consumption per bit. In fact, TDMA slightly outperforms random slot selection.

At this stage, we could conclude that only TDMA provides the expected performance. Yet, TDMA requires a careful definition and assignment of time slots to mobile nodes. In our experiments, we used the address identifier modulo the number of available slots. This may be improved assuming the ground nodes exactly know, or at least rather accurately anticipate the mobile nodes in communication range. If this is not the case, slotted ALOHA may be able to support higher dynamics in the network.

Future work is therefore planned on addressing schemes supporting both the wake-up procedure (at the moment, all nodes are triggered when they enter the communication range of a ground node) as well as the slot assignment.

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