Aloha with Preamble Sampling for Sporadic Traffic in Ad Hoc Wireless Sensor Networks

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***Abstract*— This paper presents an analysis of the performances of the Aloha protocol combined with the preamble sampling technique. This protocol is intended for low power sporadic communications in an Ad Hoc wireless network of sensors. The delay performances and the resulting power consumption and lifetime are computed analytically. The benefits of using CSMA instead of Aloha are indicated. The lifetime that can be expected by a node with a single alkaline LR6 battery is given for the different protocols in function of the interval between successful transmissions. Lifetime of years can be expected using Aloha with preamble sampling if the traffic is low. This protocol can be used to transmit sporadic data traffic or the signaling traffic needed to synchronize a network into a TDMA schedule.**

I. INTRODUCTION

Wireless sensor networks are a class of wireless Ad Hoc networks, for which the low power consumption is the main requirement. Because sensor nodes may be deployed in remote locations, it is likely that replacing their battery will not be possible. The lifetime of the sensor network is hence limited by the lifetime of the nodes’ battery. To be deployable in large quantities, the price of the sensors must be very low. The low cost requirement implies the usage of batteries of modest capacity. The low power consumption is hence a major requirement in the design of communication protocols for sensor networks. We consider that sensors shall target a lifetime of several years using a single alkaline LR6 battery. To reach such a target, the power consumption must be minimized at every layer: physical, medium access control and routing. In this paper, we will focus on the medium access control layer.

Medium access control protocols designed for wireless LANs have been optimized for maximum throughput and minimum delay. The low energy consumption has been left as a secondary requirement. For example, the CSMA/CA protocol used in the IEEE 802.11 wireless LAN standard requires that every node always monitor the channel [1]. There are large opportunities of energy savings at the MAC layer. Ye et al. have identified four sources of energy waste: protocol overhead, collisions, listening to a transmission destined to someone else (overhearing) and listening to an idle channel [2]. Techniques to prevent overhearing have been proposed by Singh [3] and Ye [2].

To reach lifetimes of years on a single alkaline battery, sensors will have to remain idle most of the time. The traffic on the medium is likely to be low. Therefore, we anticipate that the most important source of energy savings in a sensor network is to avoid idle listening. One way to avoid idle listening is to use the TDMA protocol. Sohrabi et al. have identified TDMA as a natural choice for the MAC layer [4]. The problems with a synchronized protocol are to initially synchronize the nodes, to repair broken links and to insert new nodes. For these signaling tasks, one need to use a contention multiple access protocol.

This paper will present and analyze a MAC protocol that combines the low power feature of the preamble sampling technique used in paging systems (e.g. ITU-R Radio Paging Code No 1 [5, 6]) with the classical Aloha contention multiple access protocol. The rest of the paper is organized as follow: Section II presents the topology and traffic assumptions, the models used for the transceiver hardware and the battery. In section III, the performances of Aloha and CSMA with preamble sampling are presented. Section IV gives the conclusions.

II. MODELS

A. *Topology and Traffic Models*

The topology of the wireless sensor network is assumed to be an Ad Hoc network. The nodes' location is random and can be described by the node density per square meter. Given the range of the transceiver, every node will have a random number of neighbors N. All curves will be drawn with N equal to 10. We will assume that all nodes generate traffic and have an infinite supply of packets to transmit. The packets will be transmitted following the protocol rules, i.e. transmissions following a Poisson process of rate g for Aloha and transmission attempts following a Poisson process of rate g for non-persistent CSMA. Depending on the probability of collisions, it will take a certain time D (called mean delay) to transmit a packet successfully. This is the time interval between two successful transmissions. We will compare the lifetime of the nodes using the different protocols in function of this mean delay.

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The size of all data and control messages is assumed to be equal to 15 bytes. This gives space for 2 bytes synchronization word (to detect the start of the message out of the noise), 4 bytes addressing, 8 bytes data and 1 byte CRC. At 24 kbps, the message transmission time is hence $T_M = 5 \text{ ms}$.

B. Hardware Model

To compute the power consumption of the protocols, and to be able to compare the consumption of different protocols with different transceivers, we will use the set of variables shown in Table I. This set of variable includes the power consumed during transmission and reception, the time needed to change from the power down state to transmit or receive states, the time to reverse the transceiver between transmit and receive states (turn around time) and the mean power consumed during the state changes. T_{Sense} is the time needed to integrate the Received Signal Strength Indicator signal provided by the transceiver chip, to decide whether the channel is busy. With binary modulation, the length of a radio symbol is $1/B$, where B is the bit rate. We assume that it will be sufficient to integrate the RSSI during a radio symbol's duration to detect a signal out of the noise.

In order to run simultaneously a contention protocol and TDMA, a transceiver will need to support at least two channels. For this reason, we need to consider a low power transceiver with multiple channels capability such as the one described in [7] and [8]. Based on this technology, one can expect to reach the following power consumption and wake-up time performances:

$$P_{RX} = 1.8 \text{ mW},\ P_{TX} = 9 \text{ mW},\ T_{SeRx} = T_{SeTx} = T_{TaRxTx} = T_{TaTxRx} \approx 1 \text{ ms}$$

The assumed bit rate is $B = 24 \text{ kbps}$ and the sensing time $T_{Sense} = 1/B = 42\ \mu s$. The power consumed during the state change phases can be assumed to be the power consumed when receiving. This statement is motivated by the assumption that, during the state change phases, all the radio electronics is powered on at the exception of the final stage power amplifier used when transmitting. This is somehow a worst-case situation without hardware optimization.

TABLE I
TRANSCEIVER PARAMETERS

Symbol	Description
P_{RX}	Power consumed when receiving
P_{TX}	Power consumed when transmitting (at 0 dBm)
T_{SeRx}	Settling time into RX mode.
T_{SeTx}	Settling time into TX mode
T_{ReRxTx}	Reversal time from RX mode into TX mode
T_{ReTxRx}	Reversal time from TX mode into RX mode
P_{SeRx}	Mean power consumed during settling into RX mode
P_{SeTx}	Mean power consumed during settling into TX mode
P_{ReRxTx}	Mean power consumed during reversal from RX mode to TX mode
P_{ReTxRx}	Mean power consumed during reversal from TX mode to RX mode
T_{Sense}	Received Signal Strength Indicator integration time
B	Raw bit rate

These numerical values will be used to draw the curves shown in the next section.

C. Battery Model

Although Ni-Mg batteries have a longer lifetime with a constant output voltage, we will consider only the use of alkaline batteries because of their lower price. The leakage current will be modeled as follow: we assume a constant leakage power equal to 10% of the full energy E during one year:

$$P_{Leack} = \frac{0.1 \cdot E}{24 \cdot 365},$$ where the unit of E is Wh.

With a mean power consumption P, the battery will be empty at time T as given by the following expression:

$$T = \frac{E}{P + P_{Leack}} = \frac{E}{24 \cdot 365 \cdot P + 0.1 \cdot E} \text{ [years]} \tag{1}$$

The total energy E in Wh of a battery is derived from the capacity in Ah by considering that the voltage at the start of its life is 1.5V and 0.9V at the end. The mean voltage is hence $U = 1.2 \text{ V}$. For a typical LR6 battery with 2.6 Ah capacity, the energy over the lifetime T will be

$$E = UIT = 1.2 \cdot \frac{2.6}{T} T = 3.12 \text{ Wh} \tag{2}$$

This model is very simple but will suit our needs. We do not want to mix the complexity of the battery with the complexity of the protocols.

III. LOW POWER MULTIPLE ACCESS PROTOCOLS

A. Regular Aloha (RA)

To allow comparisons of preamble sampling Aloha with a well-known protocol, we will consider the regular Aloha protocol [9]. We assume that every node is transmitting its messages towards some other node in unicast. Messages are transmitted according to a Poisson process and repeated until received without collision. The feedback channel saying whether the message has been successfully received is instantaneous and has zero power cost, which is the classical assumption when studying Aloha. The mean inter-arrival time of the Poisson process is $1/g$. Every node is transmitting messages with rate g packets per second. A node, having N neighbors, will be exposed to the interference from N nodes when receiving a message from one of the neighbor. The number N includes $N-1$ other neighbors and itself, as it cannot know when someone is transmitting to itself.

The probability of successfully transmitting (or receiving) a message is hence

$$P_S = e^{-2NgT_M} \tag{3}$$

As a node is transmitting g messages of length T_M per unit time, the throughput per node is given by

$$S = gT_M P_S \tag{4}$$

The probability to transmit the message successfully at the K^{th} attempt will be given by $P(K=k) = (1-P_S)^{k-1}P_S$. The mean time between two attempts is by definition of the Poisson process $1/g$. Therefore, the mean time until a successful transmission occurs can be computed as

$$D = \sum_{k=1}^{\infty} k\frac{1}{g}(1-P_S)^{k-1}P_S = \frac{1}{gP_S} \tag{5}$$

With this protocol, every node is listening all the time, except when transmitting a message. To compute the mean consumed power, we need to know the fraction of the time during which the transceiver is transmitting a message. The easiest way to find this result is to observe that the probability with which the transmitter is idle at some point in time is the probability that no arrival has occurred during the last T_M seconds. This event has a probability e^{-gT_M}. The probability that the transmitter is busy (which is also the fraction of the time when the transmitter is busy) is hence given by

$$b_1 = 1 - e^{-gT_M} \tag{6}$$

The mean power consumed by Aloha is given by

$$P^{RA} = b_1 P_{TX} + (1-b_1)P_{RX} \tag{7}$$

In this expression, the reversal between RX and TX mode is assumed to be instantaneous and has zero power cost.

With very low traffic ($b_1 \to 0$, no transmission) the mean power tends to P_{RX} and with very high traffic ($b_1 \to 1$), the mean power tends to P_{TX}.

B. Genie Aided Aloha (GAA)

The main problem of Aloha, and of most protocols designed for wireless computer networks, is that the receiver must be always on. As the power consumed when listening to an idle channel is the same as the power consumed when receiving data, this method is very power-inefficient. The goal of a low power protocol will be to avoid, as possible, to listen when the channel is idle. In order to see what are the theoretical limits of such protocols, we introduce the concept of Genie Aided Aloha. In this protocol, as genie tells to each node when the channel is busy. The node hence doesn't spend any time listening to an idle channel. This concept helps to measure what could be hopefully approached by feasible methods attempting to replace the Genie. The mean power consumed by a node will hence be the power consumed for reception when the channel is busy because of the transmissions of the N neighbors, plus the power consumed when transmitting itself. We have

$$P^{GAA} = b_1 P_{TX} + (b-b_1)P_{RX} \tag{8}$$

where

$$b = 1 - e^{-g(N+1)T_M} \tag{9}$$

is the proportion of the time when the medium is busy, under the load of $N+1$ nodes (N neighbors + the central node). b_1 is given in equation (6). The power consumed by the processor when the transceiver is powered off is neglected. It can be considered to be counted for in the battery power leakage.

C. Aloha with preamble sampling

The goal of the preamble sampling technique is to let the receiver sleep most of the time when the channel is idle. It consists in transmitting a preamble of length T_P in front of every packet. A receiver wakes up periodically every T_P seconds and checks for activity on the channel. If the channel is found idle, the receiver goes back to sleep. If a preamble is detected, the receiver stays on and continues to listen until the packet is received.

If we combine the property of preamble sampling with Aloha, we can reduce the time spent in listening to an idle medium. The price to pay will be an increased transmission and reception length, and an increased probability of collision due to the longer transmissions. Each message is preceded by a preamble. On successful reception of a message, after the time needed to reverse the transceiver from RX to TX, the destination node will send an acknowledgment message back. This is shown in Fig. 1.

The duration of the ACK message will be assumed to be

$$T_A = 0.5 \text{ ms} \tag{10}$$

To compute the probability of error, one has to observe that a packet will be destroyed only if another packet is transmitted during the DATA or ACK phases. A collision in the preamble only is not harmful. The dangerous packets are those starting between the two extreme positions shown in the bottom of Fig. 2. The first packet on the left is not followed

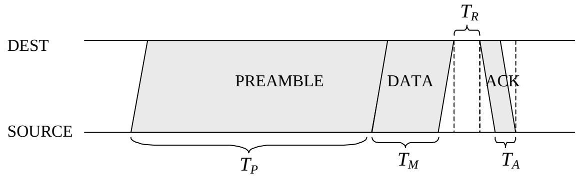

Fig. 1. Data - Ack transaction with Preamble.

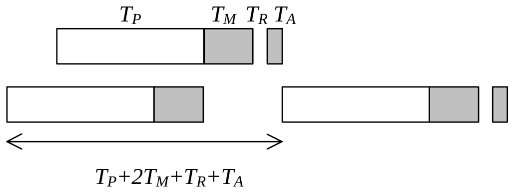

Fig. 2. Packet collision in Aloha with Preamble Sampling.

by an ACK. The reason is that, either the destination of the packet hasn't sent the ACK because it was jammed, or the ACK will not be received because the destination is a hidden node. A packet will hence be transmitted successfully if no other packet has been transmitted in a period of duration $T_P + 2T_M + T_R + T_A$.

The probability of success is hence

$$P_S^{PSA} = e^{-Ng(T_P+2T_M+T_R+T_A)} \tag{11}$$

The mean delay until a packet is successfully transmitted and acknowledged is still given by (5).

When computing the mean consumed power, one has to consider the message transmissions, the message receptions, and the preamble sampling as shown in Fig. 3.

When in RX mode, the transceiver should stop listening as soon as the channel becomes idle again. To simplify the computations, we will consider that the node will continue to listen until the end of the sampling interval. Under this assumption, the mean fraction of busy sampling intervals is equal to b^{PSA}, the mean fraction of busy instants on the medium.

Similarly as in last section, the fraction of the time when the medium is busy, in the case of preamble sampling Aloha, will be given by

$$b^{PSA} = 1 - e^{-(N+1)g(T_P+T_M+T_R+T_{Ack})} \tag{12}$$

The fraction of the time when the transceiver of a node is sending data, in the case of preamble sampling Aloha, will be given by

$$b_1^{PSA} = 1 - e^{-g(T_P+T_M+T_R+T_{Ack})} \tag{13}$$

The mean power consumption will be

$$P^{PSA} = b_1^{PSA} P_{TX} + (b^{PSA} - b_1^{PSA}) P_{RX} + \frac{P_{SeRx} T_{SeRx} + P_{RX} T_{Sense}}{T_P} \tag{14}$$

The preamble sampling technique is one way to implement the Genie telling when the channel is busy. Another way, described in [10], would be to have a second "wake-up" receiver that is constantly listening. This second receiver shall be very simple and therefore consume very little power (a few µW), allowing its constant usage. When traffic is detected on the medium, the main receiver is waken-up. On the transmitter side, a message transmission must be preceded by a wake-up wave so that the main receiver can be waken-up for the start of the message.

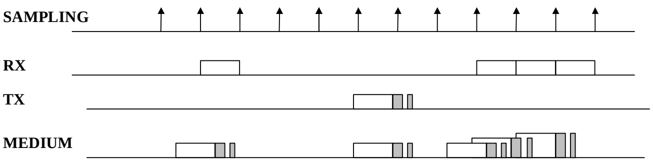

Fig. 3. Activities of a node.

D. Performances of Aloha based protocols

The classical performance curves for Aloha are the throughput and the delay in function of the offered load. Fig. 4 shows the throughput curves for Regular Aloha, Genie Aided Aloha (same curve) and for Preamble Sampling Aloha with a preamble length equal to 5, 10 and 20 times the message length. The X signs on the top of the curves show the maximal throughput point that is reached with the optimal value of g. The optimum depends on the number of nodes and of the protocol. These points will be plotted on the following curves as well. The X-axis in this graphic is the load offered to the channel by each node in packets per second. The Y-axis is the throughput per node in bit per second following formula (4), multiplied by the bit rate B. The bits in the preamble that are transmitted without collision are not counted in the throughput. This is the reason why preamble-sampling Aloha has a much lower throughput.

Fig. 5 shows the delay performances. We see that the preamble has a large impact on the minimum delay. For low values of the offered load (when collisions are rare), all protocols become equivalent.

As we are interested in the lifetime of the nodes, we need to know what is the mean power consumed by the protocols for different values of the offered load. We can see in Fig. 6 that when the offered load tends to infinity, all protocols consume permanently P_{TX}. Every transmitter is constantly transmitting. For an offered load that tends to zero, the power consumed by Regular Aloha tends to P_{RX}. With the other protocols (Genie Aided and Preamble Sampling Aloha), the consumed power tends to zero, which will give opportunities for very long lifetimes.

When implementing the preamble sampling Aloha protocol in sensors, one has to select a value for *g*. Algorithms could adapt the value of *g* to the perceived traffic to keep an optimal protocol. If a fixed value of *g* is chosen, it must be chosen to be optimal for a given number of nodes in range.

The trade-off that we have to make when choosing the value for *g* (either dynamically or once for all) will be between the mean consumed power and the mean delay. To better read the curves, it is useful to convert the consumed power into a lifetime with a single LR6 Alkaline battery using formula (1). The resulting lifetime-delay curves are shown in Fig. 7.

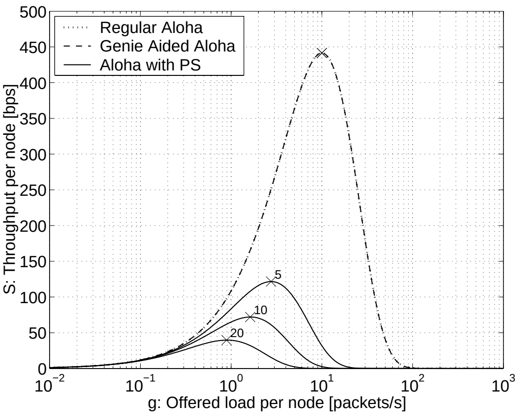

Fig. 4. Throughput of Aloha and PS-Aloha.

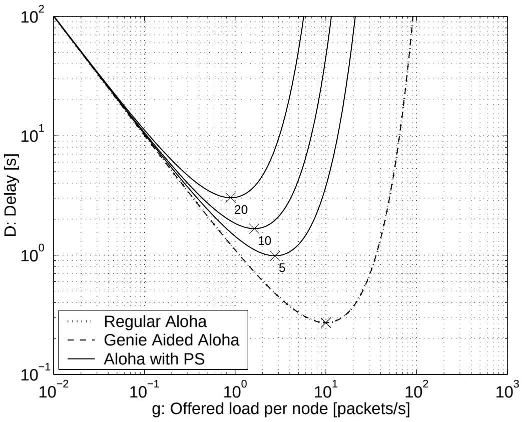

Fig. 5. Delay of Aloha and PS-Aloha.

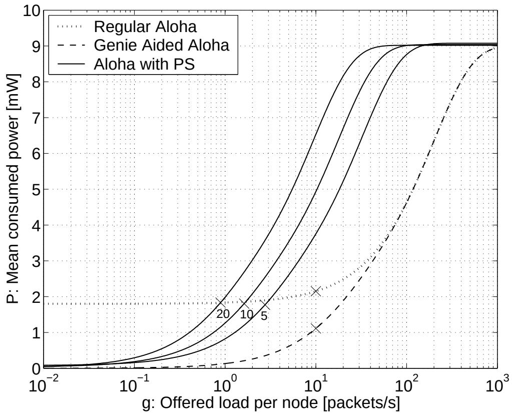

Fig. 6. Power consumed by Aloha and PS-Aloha.

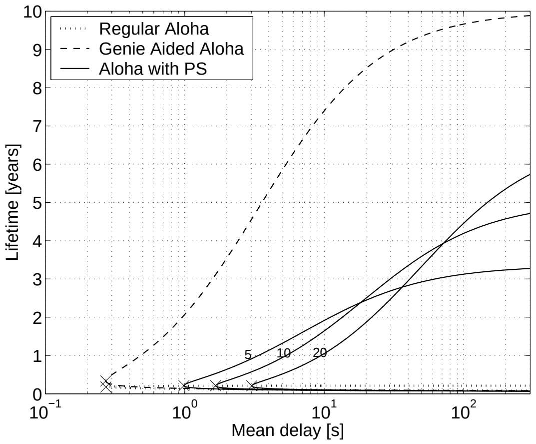

Fig. 7. Lifetime - Delay trade-off for Regular Aloha, Genie Aided Aloha and Preamble Sampling Aloha.

The curves in Fig. 7 are parametric with parameter *g*. For small values of *g*, the delay is large and the consumed power is small (long lifetime). Above an optimal point, the catastrophic behavior of Aloha introduces an increasing delay for an increasing power. We can see that, depending on the delay that can be accepted, other values of T_P will give the longest lifetime. When choosing T_P, we make a tradeoff between preamble sampling power (high for small T_P) and transmission/reception power (high for large T_P). For low traffic, one must choose a large T_P and for high traffic, a small T_P. If we need 10 s average delay, we can choose $T_P = 5T_M$ and obtain 2 years lifetime. If 100 s average delay is sufficient, we can choose $T_P = 20T_M = 100\text{ ms}$ and obtain more than 4 years lifetime. The lifetime of any protocol is limited to 10 years because of our battery model, which results is an empty battery after 10 years even without load.

E. Non persistent CSMA with preamble sampling

Because we are in a collision environment, and because CSMA is known to perform better than Aloha, it is important to evaluate how much can be gained by using CSMA. There exist numerous variants of the CSMA protocol: persistent, non-persistent, p-persistent, exponential backoff [11]. We have considered the non-persistent CSMA protocol, mainly because computations are easier with this variant. P-persistent CSMA and CSMA with exponential backoff (as in the IEEE 802.11 standard) can provide lower delays when the channel is highly utilized.

The analysis of the performances of non-persistent CSMA is well known in a wireless network without hidden nodes [11, 12]. Using this method, one can compute the lifetime-delay curve of non-persistent CSMA with preamble sampling shown in Fig. 8. We can see that the delay that can be reached with NP-CSMA with PS is lower than when using Aloha with PS. This lower delay is unfortunately coupled with a very short lifetime. We must accept delays between 10 and 100 seconds to reach years of lifetime, for which the advantage of CSMA is smaller and smaller. In this region of the curve, *g* is small and the medium is mostly idle. Sensing does not help a lot. In addition, recall that the computations made for CSMA are valid only without hidden nodes. In an Ad Hoc network, a transmitter may sense the medium idle, while the destination of the message is currently receiving a message from a hidden node. The hidden-node effect will let the

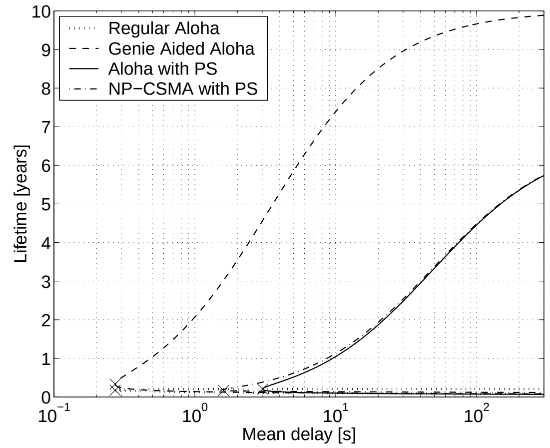

Fig. 8. Lifetime using NP-CSMA with Preamble Sampling, compared to Genie Aided and Preamble Sampling Aloha (with $T_P = 20T_M$).

performances of non-persistent CSMA approach the ones of Aloha even further, Aloha being a special case of non-persistent CSMA, where all the other nodes are hidden.

IV. CONCLUSION

This paper has presented a low power version of Aloha, targeted for low traffic ad hoc wireless sensor networks. The classical Aloha protocol has been combined with the preamble sampling energy saving technique. The throughput, delay and power consumption have been analytically derived. A brief performance comparison with non-persistent CSMA with preamble sampling was given.

The contention channel should be used rarely, permitting to select a long preamble size. The contention channel shall transport synchronization messages needed to insert a node into the synchronized schedule of a sensor network, or transport sporadic data traffic. With the hardware parameters considered (1.8mW in reception, 9mW in transmission, reversal time of 1ms, 1 LR6 Alkaline battery) and assuming 10 nodes in range, a node can last for 2 years with a mean message delay of 10 seconds (per hop) on the contention channel. If the delay for message transmissions can be relaxed to 100 seconds, the lifetime will over 4 years.

If the contention channel is used only for initial synchronization, one could be tempted to reduce these restrictions and transmit these few messages at a higher rate. As these message bursts are infrequent, the mean traffic remains low. If there are only one or very few nodes behaving like this in the same area and at the same time, this can work. However, if a large number of nodes need to transmit data on the contention channel, and all are sending data too fast, we will reach the catastrophic situation with no throughput and permanent listening (fully busy channel). Following the discipline of keeping a low transmission rate will guarantee a stable operation and a long network lifetime.

We have seen that Aloha performs about as well as CSMA in the operating region of interest, because the medium is anyway idle most of the time. Although CSMA is a little bit more complex to implement than Aloha, it should be preferred in an implementation. As CSMA provides a higher throughput, it offers a better robustness to unexpected momentary high traffic conditions. CSMA with exponential backoff should be preferred to NP-CSMA because of its lower latency and its automatic adaptation to the traffic conditions.

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