BPS-MAC: Backoff Preamble Based MAC Protocol with Sequential Contention Resolution

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Abstract. Contention resolution represents a performance critical task in dense wireless networks since many Medium Access Control (MAC) protocols solely rely on the carrier-sense capabilities of the transceivers. Typical transceivers require a large amount of time to detect a busy radio channel. Especially, in the case that the transceiver has been switched off or has to be switched from receive to transmit mode. It is thus not able to sense the media during the switching phase, which leads to a large number of collisions in dense networks with correlated event-driven traffic load. In this paper the Backoff Preamble Sequential (BPS) MAC protocol is introduced which uses a sequential contention resolution to reduce the number of competing nodes step by step.

Keywords: Random access, wireless, reliable, networks.

1 Introduction

Clear Channel Assessment (CCA) is a logical function that returns the current state of the wireless medium. It is provided by almost any low power transceiver for WSNs in order to support Carrier Sense Multiple Access (CSMA) functionality to the MAC layer. However, the transceivers require a certain amount of time to reliably determine the state of the medium. Moreover, the time that a transceiver requires to switch from receive to transmit mode represents a vulnerable period for protocols that rely on the CSMA functionality since transceivers are not able to detect any transmissions that start during the switching period.

The CCA delay becomes the dominating performance limitation factor [1] for low power transceivers. Transceivers, like the CC2400 and the CC2520 from Texas Instruments or ATMEL´s AT86RF231, have to listen to the medium for a duration of 8 symbol periods to reliably detect an ongoing transmission. They average the Received Signal Strength Indication (RSSI) over the last 8 symbols in order to decide whether the channel is assumed to be busy or idle.

The reliability of CSMA based protocols can be increased if a backoff algorithm is used to smooth the peak traffic load. Backoff algorithms may only reduce the collision probability to some extend since the possibility to reduce the peak utilization strongly depends on the overall traffic load. They have to be configured very carefully to achieve the desired trade-off between reliability

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and delay [2]. Event suppression techniques [3,4] could be implemented to reduce the average number of nodes that compete for the medium access. Some MAC protocols, like SIFT [5], need to know the number of competing nodes in advance in order to achieve their maximum performance.

The introduced protocol was originally designed for Structural Health Monitoring applications with periodic and event-driven traffic. The target application had high requirements in terms of reliability under varying traffic load which could not be achieved with standard CSMA based protocols due to high node density, correlated traffic, and limited sensing capabilities of the transceiver. For that reason, we decided to focus on a completely different approach which is based on preamble transmission and sequential backoff resolution mechanism.

This paper is organized as follows. In Section 2, we describe the access mechanism of the BPS-MAC protocol and analyze the collision probability in case of simultaneous medium access of several nodes. Moreover, the performance of the sequential contention resolution depending on the number of sequences and the applied backoff distribution is analyzed. An overview of related work is given in Section 3. Finally, we conclude with our future work in Section 4.

2 BPS-Mac

The BPS-MAC protocol is optimized for reliability in scenarios with a high node density and highly correlated event-driven data traffic. It does not require synchronization or a large amount of memory which makes the protocol most applicable for sensor nodes with low computational power and limited transceiver sensing capabilities. A collision occurs if two or more nodes try to access the medium within a time interval that is shorter than the CCA delay of the used transceiver. Backoff algorithms are only able to reduce the collision probability by spreading the traffic load. Nevertheless, a node can never know whether another node is starting its transmission due to the fact that it cannot listen to the air interface while switching from rx to tx mode.

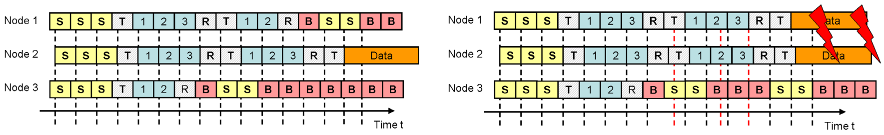
The introduced protocol follows a new approach in order to deal with the problem of CCA delay and the rx/tx switching. The basic idea of the protocol is to send a backoff preamble with variable length before transmitting the data. The length of the preamble has to be a multiple of the CCA delay to maximize the reliability of the protocol. The protocol uses a slotted contention resolution since the backoff preamble is a multiple of the CCA delay. In the case that two nodes send a preamble with different length, the node with the shorter preamble is able to detect the occupation of the medium by the other node.

2.1 Protocol Description

First, a closer look is taken on the contention resolution as used by the standard BP-MAC protocol [6]. In the following, the term slot is used instead of CCA delay duration since it is more related to the context of contention resolution. Moreover, the term collision probability represents the probability that two or more nodes start their data transmission simultaneously after backoff transmission which represents an unsuccessful contention resolution. A node senses the medium for duration of three backoff slots if it wants to transmit a packet. The transceiver is switched from rx to tx in the case that the medium is free for three consecutive slots in order to transmit the backoff preamble. The duration of the preamble is chosen according to a uniform distribution between two and a maximum backoff window. The preamble covers the function of a reservation signal. Thus, a longer preamble increases the probability of gaining access to the medium.

The node senses the medium after the transmission of the preamble. If the medium is busy after the transmission, the node waits between two and maximum backoff window number of slots until it restarts the access procedure described above. Otherwise, the node is allowed to access the medium. Thus, it switches its transceiver from rx to tx mode which takes duration of one backoff slot. As a consequence, the medium is idle for duration of two slots after the transmission of a backoff preamble. For that reason, a node senses the medium for the duration of three slots in order to be sure that there is no ongoing contention resolution.

In [6] it was shown that the average number of transmissions which are part of a collision in a single backoff preamble sequence is given by the fraction of n and m where n is the duration of the preamble in number of slots while m corresponds to the number of nodes that start their preamble transmission simultaneously. This fact encouraged us to think about a new sequential backoff resolution called BPS-MAC which is described and analyzed in the following paragraphs of this section. Short consecutive backoff preambles are able to reduce the number of competing nodes step by step. Therefore, just a small number of nodes will compete in the last backoff preamble sequence for the medium access. The proposed sequential contention resolution procedure is shown in Figure 1.



(a) Synchronous Access

(b) Collision Example

Fig. 1. Sequential Contention Resolution

Competing nodes switch their transceivers to rx after the transmission of the first backoff preamble. If they sense a busy channel, the nodes abort their current medium access process and wait between zero and EBW slots before sensing the medium again. In the case of an idle channel, the nodes switch their transceivers back to tx and transmit the next backoff preamble. Thus, collisions may only occur if two or more nodes start their medium access procedure within one CCA delay interval and choose the same number of backoff slots in every backoff sequence. The maximum duration of each backoff preamble sequence and the number of sequences defines the maximum medium access delay for a single contention resolution.

Let y be the medium access delay in number of backoff slots and s the number of sequences. The EBW of sequence i is denoted as n_i. Furthermore, it is assumed that a node has to sense the medium for three slots before it switches its transceiver to tx mode - which requires an additional duration of one slot - in order to start the preamble transmission. The maximum access delay can be calculated according to Equation 1 provided that the gap between two consecutive backoff preambles is two slots.

$$y \leq 4 + \sum_{i=1}^{s} n_i + 2s \tag{1}$$

The minimum medium access delay is achieved if a node chooses the first backoff slot in every backoff sequence while no other node is competing for the medium access. Therefore, the lower bound of the access delay is given by Equation 2.

$$y \geq 4 + 3s \tag{2}$$

Many applications for WSNs need guarantees in respect to maximum medium access delay since the generated data is often mission critical. In the following it is assumed that a certain number of nodes have to transmit a small amount of data if they recognize an event. Thus, the maximum allowed medium access delay in number of backoff slots can be calculated if the amount of data per node, the transmission rate, and the maximum number of nodes that respond to an event are known in advance. The BPS-MAC protocol can be easily optimized for a particular application in the case that the maximum allowed medium access delay is known. First, the boundaries of the number of backoff sequences have to be specified according to the maximum allowed delay. The boundaries of the number of backoff sequences can be calculated according to Equation 3 provided that the smallest allowed value of the EBW is two slots.

$$1 \leq s \leq \frac{y}{4} - 1, s \in N \tag{3}$$

The next question that has to be answered is that of defining the length n_i of each individual backoff sequence. The length of the individual backoff sequences n_i has to be chosen such that $\prod_{i=1}^{s} n_i$ is maximized since the average number of collisions per backoff sequence is given by the fraction of competing nodes m and the length of the backoff sequence n_i. Therefore, the duration of each backoff sequence should be selected as short as possible to maximize the product. The highest probability of a successful contention resolution is achieved if n is a multiple of four. Due to the gaps between two consecutive backoff sequences, a length of four slots represents the best trade-off between overhead and success probability. In the following it is assumed that n is always a multiple of four.

Figure 2 shows the probability of successful contention resolution depending on the number of competing nodes and the number of backoff sequences. The results shown in Figure 2 are very promising, especially in the case that

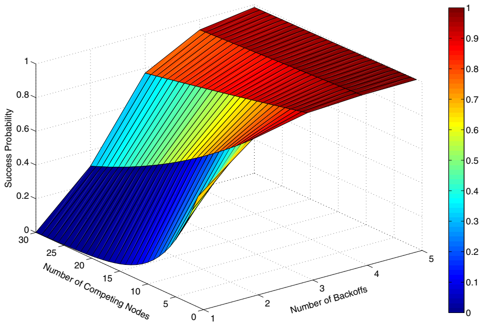


Fig. 2. Uniform Distribution - Probability of Successful Contention Resolution depending on the Number of Competing Nodes

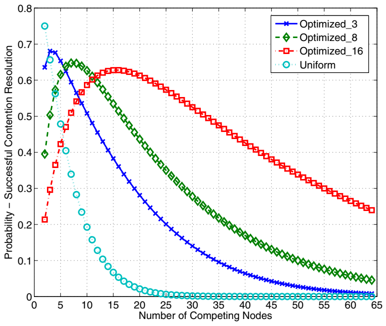


Fig. 3. Probability of Successful Contention Resolution for a four Slot Backoff Procedure depending on the Number of Competing Nodes

three or more backoff sequences are available. However, in some cases it is only possible to use up to two sequences in order to maintain within given medium access delay boundaries. A solution for this problem is given by Tay et al. [10] which evaluated the performance of non-uniform distributions for slotted contention resolution. They introduced an algorithm which calculates the optimum distribution for a given number of backoff slots provided that the number of competing nodes is known in advance. Their optimized solution only achieves a high success probability if the number of competitors does not differ much from the assumed number of competitors. Thus, they recommend using a truncated geometric distribution which performs similar to the optimized distribution but is less affected by the number of competitors. Figure 3 shows the probability of successful contention resolution for a single backoff sequence with maximum backoff duration of four slots depending on the used distribution from Table 1 and the number of competitors. The results of Figure 3 point out that the uniform distribution represents the best choice if only two nodes compete for the medium access. Nonetheless, the probability of successful contention resolution decreases rapidly with the increasing number of competitors. Therefore, the

Table 1. Distributions - Backoff Slot Selection

Distribution / Probability	Slot 1	Slot 2	Slot 3	Slot4
Optimimized_3	0.534	0.217	0.148	0.101
Optimimized_8	0.766	0.086	0.078	0.070
Optimimized_16	0.884	0.040	0.039	0.037
Uniform	0.250	0.250	0.250	0.250

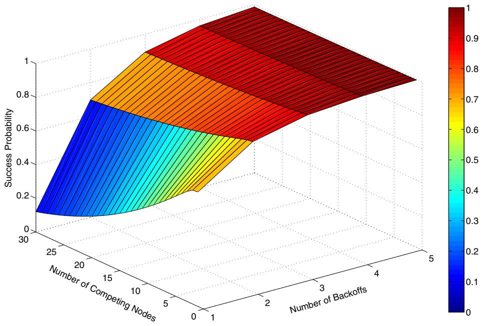


Fig. 4. Optimized_3 - Probability of Successful Contention Resolution depending on the Number of Competing Nodes and the Number of Backoff Sequences

uniform distribution is not the first choice for networks with high node density and correlated traffic. The truncated geometric distribution can be optimized for a fix number of competitors. However, the optimization of the distribution for more than three nodes is not really practical since the performance degrades significantly if the number of competing nodes is overestimated. This behavior becomes clear by taking a look at the different distributions shown in Table 1.

The optimized distributions achieve a high success probability of the contention resolution due to their skewness. As a consequence of the skewness, the majority of the competing nodes choose one of the first slots while the minority of the nodes competes in the rest of the available slots. This explains the high success probability of the optimized distributions even in the case that the number of competitors is under estimated. Nevertheless, the skewness reduces the success probability if the number of nodes is smaller than the number for which the distribution is optimized. It has to be kept in mind that the number of competing nodes always decreases from a maximum - which depends on the node density and the traffic pattern - to one. For that reason, an optimized distribution for three competing nodes represents the best choice for most scenarios. An underestimation of the number of competitors only has a small impact on the packet loss in contrast to an overestimation which increases the collision probability in a significant way. The success probability of the Optimized_3 distribution for an EBW of four depending on the number of competing nodes and the number of backoff sequences is shown in Figure 4. The results of Figure 4 point out that the success probability for the Optimized_3 distribution for the first two backoff

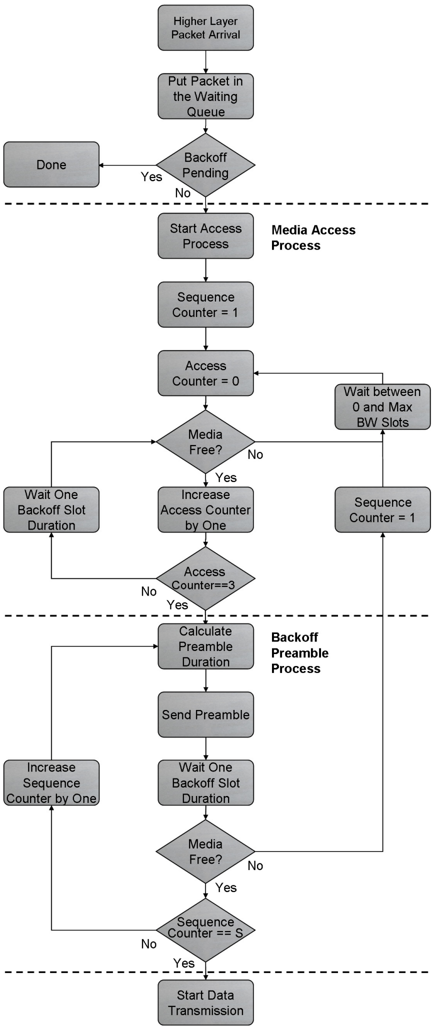


Fig. 5. Flow Diagram of the Medium Access Process of the BPS-MAC Protocol

sequences is much higher compared to the uniform distribution shown in Figure 2. However, the difference becomes smaller with an increasing number of backoff sequences. The uniform distribution even represents a slightly better solution if the number of sequences exceeds four and the number of competing nodes is less than 32. This behavior is the consequence of the stepwise reduction of the number of competing nodes. The probability that only two nodes compete in a single backoff sequence increases with an increasing number of backoff sequences. Due to the fact that the uniform distribution is the optimum distribution for the case of two competing nodes, its performance increases more with the number of backoff sequences than the performance of the Optimized_3 distribution.

2.2 Medium Access Process

In the following the medium access process of the BPS-MAC protocol shown in Figure 5 is described in detail. Higher layer packets are put into the waiting queue if a backoff is already pending. In the case that no backoff is pending the medium access process is started. The protocol initializes a sequence counter and an access counter. The access counter is used to count the number of free consecutive backoff preamble slots while the sequence counter represents the number of transmitted backoff preambles. Furthermore, the access counter starts with an initial value of zero in contrast to the sequence counter which starts with an initial value of one. After the initialization of the counters is completed, the protocol switches the transceiver to receive mode and starts to sense the medium. If the medium is busy, the node waits between zero and EBW slots before the medium is sensed again. In addition, the access counter is set back to zero. The transceiver might be switched off during the waiting period depending on the energy constraints of the node. The access counter is increased by one if the medium is idle and checks whether the counter is equal to three which indicates that the medium has been idle for duration of three consecutive backoff slots. If the value of the access counter is smaller than three the protocol waits one backoff slot until it follows the procedure described above. The protocol calculates the preamble duration depending on the sequence counter and starts to send the backoff preamble after the medium has been idle for duration of three backoff slots. This mechanism allows the modification of each backoff sequence e.g. a different EBW size or a different backoff distribution. Then it switches the transceiver back to receive mode which requires the duration of one backoff slot. If the node senses a busy channel after the preamble transmission, it resets the access and the sequence counter and waits between 0 and EBW slots before it senses the medium again in order to restart the access process. In the case that the medium is idle after the backoff transmission, the node checks whether the sequence counter has reached the maximum number of backoff sequences S. If the value is smaller than S, the counter is increased by one and the preamble process is started again. The node is allowed to start its data transmission if the medium is idle after the transmission of S backoff preambles.

2.3 Performance Analysis

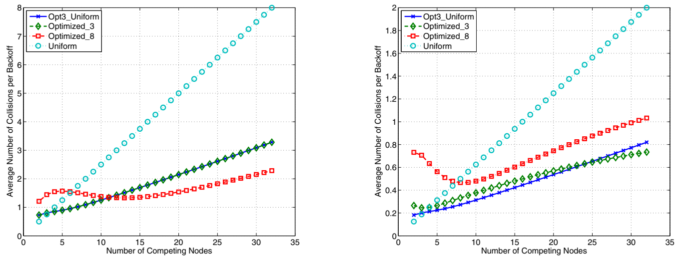
A closer look is taken on the average number of collisions per backoff. Note, a distribution may achieve a higher success probability than another distribution but it may have a higher packet loss if the average number of nodes that are part of a collision is higher. Thus, the question is, how many nodes are part of a collision in case of an unsuccessful contention resolution depending on the backoff distribution and the number of backoff sequences.

Let c_0 be the number of nodes that compete for the medium access in the first backoff preamble sequence and c_i the number of nodes that collide in the ith sequence. Moreover, n_i represents the number of backoff slots in the ith backoff sequence while s represents the number of backoff sequences. The function $p(var_1, var_2, var3)$ is an extension of probability mass function introduced in [6] whereas the parameters n, m, and c are freely configurable. Variable var_1 corresponds to the maximum number of backoff slots n while variable var_2 represents the number of competing nodes m. The number of nodes c that are part of a collision is indicated by var_3. Thus, the average number of nodes that are part of a collision after s backoff sequences can be calculated according to Equation 4 by using Equation 1.

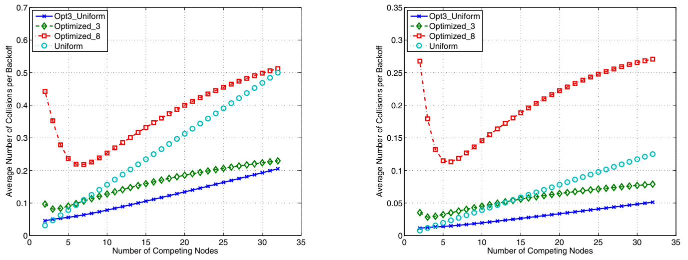
$$\begin{aligned}
E[C,1] &= \sum_{c_1=2}^{c_0} c_1 p(n_1, c_0, c_1) \\
E[C,2] &= \sum_{c_1=2}^{c_0} \sum_{c_2=2}^{c_1} c_2 p(n_1, c_0, c_1) p(n_2, c_1, c_2) \\
\vdots \quad & \quad \vdots \qquad\qquad\qquad \vdots \\
E[C,s] &= \sum_{c_1=2}^{c_0} \cdots \sum_{c_s=2}^{c_{s-1}} c_s p(n_1, c_0, c_1) \cdots p(n_s, c_{s-1}, c_s)
\end{aligned} \tag{4}$$

Figure 6 shows the average number of collisions per backoff for the optimized distributions for three and eight competing nodes as well as for the uniform distribution. The Opt3_Uniform graphs represent the results of a hybrid approach where the Optimized_3 distribution from Table 1 is used in the first backoff sequence while the uniform distribution is used in the consecutive sequences.

The first thing that can be mentioned for the results of the single backoff sequence shown in Figure 6(a) is that the average number of collisions per backoff increases linearly with the number of competing nodes for the uniform distribution. The uniform distribution only offers the best performance for two competing nodes while the Optimized_3 distribution represents the best solution for three to 10 competing nodes. If the number of competing nodes exceeds 10 the Optimized_8 distribution shows a better performance. It is interesting to notice that the Optimized_8 distribution does not achieve the lowest packet loss for eight competing nodes though its success probability is optimal for 8 competing nodes. The answer is given by the Optimized_8 distribution function. Due to the high probability of the first slot there is a noticeable probability that all nodes choose the first backoff slot in one sequence. Therefore, the average number of collisions increases in a significant way. Figure 6(b) shows that the average number of collisions can be approximately quartered if the BPS-MAC protocol uses two consecutive backoff preambles to resolve the contention. This affect can be recognized for the uniform, Optimized_3 and Opt3_Uniform distributions. The performance of the Optimized_8 distribution does not represent a good solution for scenarios with less than 32 competing nodes. As a consequence of its heavy-tailed characteristic, the probability is high that less than 8 nodes compete for the medium access in the second backoff preamble sequence. Thus, there is a high chance that the remaining competitors collide in one of the first slots in the second backoff sequence.



(a) Single Backoff Sequence (b) Two Backoff Sequences



(c) Three Backoff Sequences (d) Four Backoff Sequences

Fig. 6. Average Number of Nodes that are Part of a Collision

If the BPS-MAC protocol uses three consecutive backoff preamble sequences the performance of the Optimized_8 distribution degrades even more which is shown by the results of Figure 6(c). The highest reliability for scenarios with more than three competitors is achieved by the Opt3_Uniform approach. The Optimized_3 distribution reduces the number of competing nodes in the first sequence such that uniform distribution becomes the best choice for the consecutive backoff sequences. The Opt3_Uniform approach should be used for these scenarios since it offers the highest reliability which is indicated by the results of Figure 6(d).

3 Related Work

A large number of different types of MAC protocols for WSNs were introduced in the past few years. Most of them are optimized in respect to energy consumption [14], delay or throughput. However, the majority of these MAC protocols requires synchronization and are too complex to be practical for WSNs. The performance evaluation of the protocols often neglect or simplify many issues of wireless communication. The assumptions that are made, e.g. bi-directional links or circular transmission area, may have a large impact on the results as shown in Kotz et al. [7] and Langendoen [8]. Moreover, technical aspects, like the CCA delay of low power transceivers, are usually disregarded. The problem of

CCA delay is only addressed by a small number of papers since standard models from network simulators, e.g. ns-2 or OPNET, simply assume a transceiver that does not need any time to sense the radio channel or to switch between rx and tx mode. The impact of CCA delay on IEEE 802.15.4 networks is described by Kiryushin et al. [1]. The focus of their work lies on real world performance of WSNs and describes the impact of different kinds of communication aspects. Bertocco et al. [9] have shown that the performance of a wireless network can be improved by minimizing the CCA threshold. Nevertheless, the minimization of the threshold requires great knowledge of the radio channel since a too small threshold will result in false positives. Another very interesting approach is followed by Tay et al. [10] which use optimized distributions to select the number of backoff slots in order to reduce the collision probability. The same research group introduced the SIFT [5] MAC protocol which uses non-uniform backoff distribution and achieves a very high performance provided that the number of competing nodes is known in advance. A small number of MAC protocols make use of preamble transmissions in order to wake up neighbor nodes [11] or to reserve the radio channel [12,13,14]. However, their contention resolution is based on standard CSMA mechanisms. Thus, their performance is affected by the CCA capability of the wireless transceiver which limits their performance in dense networks with event-driven traffic.

4 Conclusion

In this work we introduced the BPS-MAC protocol which uses a new sequential backoff preamble mechanism to minimize the number of competing nodes step by step. It is able to deal with a very high number of competing nodes due to the stepwise contention resolution. Its medium access procedure is independent from the CCA delay of the transceiver and can thus be applied on any platform.

Furthermore, the protocol will take more advantage out of next generation transceivers compared to CSMA based protocols since its performance in terms of medium access delay is directly affected by the duration of CCA delay. We are currently working on different Quality of Service (QoS) mechanisms in order to make the protocol attractive for heterogeneous networks and for those which require priority based medium access.

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