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BP-MAC: A High Reliable Backoff Preamble MAC Protocol for Wireless Sensor Networks

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ABSTRACT: Many Media Access Control (MAC) protocols for Wireless Sensor Networks (WSN) use variations of the popular Carrier Sense Multiple Access (CSMA) protocol due to its simplicity and its high performance in low traffic scenarios. However, CSMA does not always represent a good choice for WSNs since typical low power transceivers require a significant time to switch between receiving and transmitting and vice versa. Sensor nodes are not able to detect a busy channel during the switching. Thus, the collision probability in WSNs is very high in case of correlated event-driven traffic. In this paper we introduce the BP-MAC protocol that uses a backoff preamble with variable length in order to mitigate the effect of Clear Channel Assessment (CCA) delay.

1 INTRODUCTION

Most protocols for Wireless Sensor Networks are optimized in respect to energy in order to prolong the lifetime of the network. This is necessary since the nodes are often placed in areas which are hardly accessible. Low power microcontrollers and transceivers are used to reduce the energy consumption and to achieve a long lifetime. However, the low power consumption is often paid by the price of other limitations.

Popular low power transceivers, like the CC2420 from Texas Instruments and ATMEL´s AT86RF231, provide Carrier Sense Multiple Access - Collision Avoidance (CSMA-CA) functionality and are able to transmit data with a rate of up to 250 kb/s. The CCA signal is usually based on the measured Received Signal Strength Indication (RSSI). Both transceivers allow the specification of a threshold for the RSSI. A busy channel is reported to the microcontroller if the measured RSSI value is above the defined threshold. Furthermore, the RSSI value is averaged over 8 symbol periods. Thus, the transceiver has to listen for a minimum duration of 128 µs to reliably detect a busy channel. Bertocco et. al. showed that the reaction time of the CCA signal can be slightly reduced if the RSSI threshold is set right above the noise level. However, a too low threshold will increase the number of false positives which reduces the throughput and increases the delay.

MAC protocols that are based on the CSMA-CA protocol rely on the capability of the transceiver to detect a busy channel. Due to the limitations of low power transceivers, the CSMA-CA protocol does not represent a good choice - even for one hop scenarios - since a node is not able to reliably detect an ongoing transmission if the transmission has started within the last 128 µs. A CCA delay of 128 µs is only acceptable for low traffic scenarios where the traffic load is uniformly distributed. The traffic in WSNs often has burst characteristics since nodes sleep most of the time until they wakeup synchronously to respond to a certain event, like pressure loss, light detection, humidity, temperature, stress, strain, acceleration, or broadcast polling.

The probability of simultaneous transmissions can be reduced by using backoff algorithms to smooth the traffic load and to resolve the problem of contention as shown by Tay et. al. Their approach is based on non-uniform backoff slot selection in order to minimize the collision probability. The optimized distribution decreases the packet loss in a significant way if the number of competitors is known in advance. Nonetheless, the efficiency of CSMA-CA protocols strongly depends on the utilization of the media, the traffic pattern, and the number of contending nodes. Furthermore, it has to be kept in mind that backoff algorithms, like the popular Truncated Binary Exponential Backoff Algorithm (TBEBA), reduce the collision probability by taking a higher delay into account. Thus, they have to be configured carefully. Another problem in WSNs is represented by the amount of time that a transceiver requires to power up or to switch from rx to tx and vice versa.

Typical durations for switching between the two states are 128 and 192 µs.

A node is not able to detect the transmission of another node during this time interval. As a result, a collision will occur if two nodes start their transmissions within a 128 µs time interval. We encountered the problem described above in one of our projects in which we attached sensor nodes to a metal plate in order to measure the stress of the plate. The nodes were configured such that they transmit their sensed values to a central node for a short amount of time if the sensed values exceeded a certain threshold. The nodes started to transmit almost synchronously if the plate was stressed due to the fact that they were placed within a small area. Furthermore, we relied on the CSMA capabilities of the transceiver such that the nodes were allowed to access the media if the CCA pin was indicating a free media.

As a consequence of the synchronous transmission approximately 15 percent of the packets where part of a collision which was quite surprising since the overall traffic load was less than 5 percent. A packet loss of 15 percent is not acceptable for mission critical data. Therefore, we decided to implement a TBEBA to reduce the collision probability. It turned out that the TBEBA algorithm was only able to reduce the collision probability to roughly 1 percent in the low traffic scenario.

In the next step we increased the sampling frequency of the nodes in order to measure the performance of the WSN under a higher traffic load. The packet loss increased to almost 5 percent in scenarios with a utilization of approximately 40 percent. We tried to increase the reliability by further increasing the Start Backoff Window (SBW) and the End Backoff Window (EBW) of the CSMA-TBEBA. However, the reliability did not increase significantly as expected. After checking different error sources, like interferences from other wireless technologies and the software on the microcontroller, we located the cause of the packet loss in the CCA delay and in the time that the transceiver requires to switch between rx and tx. Typical backoff algorithms are only able to reduce the problem since they spread the traffic load which decreases the probability that two or more nodes transmit at the same time. Nevertheless, a node can never know whether another node is starting its transmission during the next CCA time interval due to the fact that it cannot listen to the air interface while switching from rx to tx mode. However, collisions will occur if two or more nodes try to access the medium within a time interval that is shorter than the CCA delay of the transceiver. Due to the fact that a high packet loss is not acceptable for real-time monitoring applications, we started to develop a new MAC protocol which is introduced in the following section.

This work is organized as follows. In Section 2, we describe the MAC protocol and analyze the collision probability in case of simultaneous media access. The performance of the BP-MAC protocol is compared with the CSMA-TBEBA protocol in a large number of different scenarios in Section 3. Related Work is introduced and discussed in Section 4. Finally, we conclude in Section 5.

2 BP-MAC

The BP-MAC protocol is a highly reliable MAC protocol which uses preambles with variable length to schedule the media access of the nodes. The usage of preambles increases the reliability of the protocol such that more than 98 percent of the packets are received even in high traffic scenarios without using retransmissions while maintaining a low delay.

2.1 *Media Access Description*

The basic idea of the protocol is to use a backoff preamble with variable length which covers the function of a medium reservation signal on the one hand and the function of a busy signal on the other hand. The duration of the reservation signal is a multiple of the CCA delay which results in a slotted contention resolution. In the following the term slot is used instead of CCA delay duration since it is more related to the context of contention resolution. If a node wants to transmit a data packet, it senses the media for three slots. In the case that the media is still free after the third slot, it switches from rx to tx and starts to transmit the backoff preamble. The duration in number of slots of the backoff preamble is chosen uniformly distributed between one and a maximum backoff window.

After the transmission of the backoff preamble is completed, the node switches from tx to rx to sense the media. If there is an ongoing transmission, the node may switch off its transceiver and waits between two and maximum backoff window number of slots before it senses the media again. The node switches from rx to tx to start its data transmission in the case that the media is free after the transmission of the backoff preamble. Thus, the time between the end of the backoff preamble transmission and the start of the data transmission is two slots. For that reason, a node senses the media for the duration of three slots before it starts to transmit a backoff preamble in order to be sure that there is no ongoing contention resolution.

The usage of a backoff preamble with varying duration reduces the collision probability in a significant way. However, collisions can still occur if two or more nodes start to transmit their backoff preamble within one slot and choose the same preamble duration. As a consequence, the nodes will start their data transmission at the same time since they are not able to detect the transmission of the other nodes. The contention resolution in case of synchronous media access is shown in Figure 1. Three nodes start to sense the media within one slot duration.

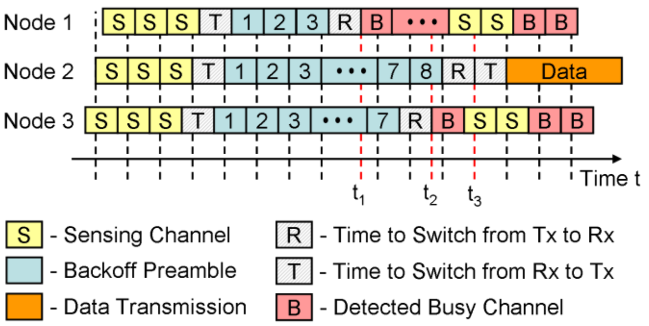

Figure 1. BP-MAC - Synchronous Access Example

Due to the fact that the media is free for the following three slots, all nodes switch their transceivers to tx mode and start to transmit their preamble.

Node 1 has chosen the shortest backoff preamble with duration of three slots. After the transmission of its preamble, the node switches to rx mode and senses the media. The time that is required to switch the transceiver mode and to sense the media is one slot duration. If a node recognizes a busy channel the next slot is marked as busy. Node 1 recognizes a busy channel. Thus, it waits a uniformly distributed number of slots until it senses the media again. Node 3 recognizes a busy channel after its preamble transmission, too. Therefore it follows the same procedure as Node 1. Node 2 senses a free medium after its backoff preamble transmission which allows it to start its data transmission.

Collisions may still occur, as mentioned earlier in this section. However, collisions only occur if two or more nodes start to access the medium within one slot and chose the same backoff preamble duration. An example of an unsuccessful contention resolution is shown in Figure 2.

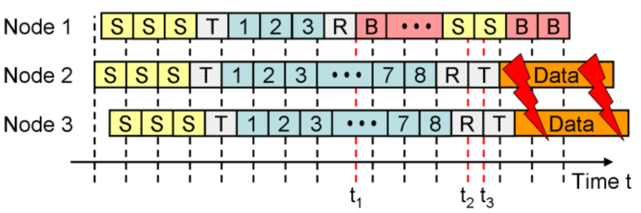

Figure 2. BP-MAC – Collision Example

2.2 *Analysis of the Contention Resolution*

The probability that two or more nodes access the media within one slot duration depends on the traffic load and the traffic pattern. For that reason, every scenario has to be analyzed individually if the reliability of a WSN has to be calculated in advance. Nevertheless, it is possible to calculate the collision probability if the number of nodes that transmit synchronously and the maximum backoff preamble duration is known. Thus, the achievable reliability can be calculated for worst case scenarios if we assume that all nodes in the WSN start the media access procedure at the same time.

First of all, we have to specify a collision from probability calculus point of view. A collision of two or more transmissions occurs if two or more nodes select the same number of backoff slots provided that they have selected the highest number of slots in this contention resolution phase.

The discrete random variable C which represents the number of nodes that are part of a collision can be calculated as follows. Let the number of nodes that access the media at the same time be m while the maximum number of backoff slots is n. The number of nodes that are part of a collision is c which corresponds to the value of the random variable C. Thus, we can formulate the distribution function of random variable C according to Equation 1

$$P(C>2)=1-P(C=1)=1-\sum_{i=1}^{n-1}\frac{m\cdot i^{m-1}}{n^{m}}\,. \tag{1}$$

The probability that the contention is successfully resolved is given by P(C=1). Equation 1 can be simplified to Equation 2 in the case that the backoff slots are selected according to a uniform distribution.

$$P(C=c)=\begin{cases}\dfrac{m!}{c!\,(m-c)!}\left(\dfrac{1}{n}\right)^{m}\sum\limits_{i=1}^{n-1} i^{m-c} & 1\le c<m\\[2ex] \left(\dfrac{1}{n}\right)^{m-1} & c=m\\[2ex] 0 & \textit{otherwise}\end{cases} \tag{2}$$

In the following we assume that the backoff slots are chosen according to a uniform distribution. The probability that the transmissions of two or more nodes are part of a collision during one backoff can be calculated according to Equation 4 by using the completeness axiom from Equation 3

$$\sum_{c=1}^{\infty} p(c) = 1 \quad , \tag{3}$$

$$P(C=c) = \frac{m!}{c!\,(m-c)!} \left(\sum_{i=1}^{n-1} p(i+1) \right)^{c} \left(\sum_{k=1}^{i} p(k) \right)^{m-c} . \tag{4}$$

To give a better impression of the impact that the duration of the backoff and the number of synchronously transmitting nodes have on the collision probability, we show the results of Equation 1 for typical values in Figure 3.

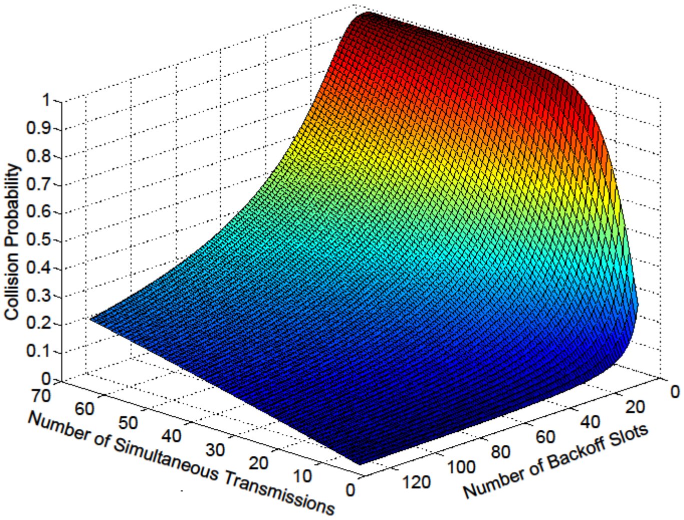

Figure 3. Collision Probability depending on the Number of Competing Nodes and the Number of Backoff Slots

Figure 3 shows that BP-MAC contention resolution is able to reduce the collision probability in case of simultaneous medium access in a significant way depending on the number of backoff slots. However, it has to be kept in mind that the contention resolution reduces the possible overall throughput since no data can be transmitted during the preamble transmission. Thus, the utilization of the air interface and the traffic pattern have to be taken into account when choosing the maximum number of slots.

If the difference of the signal strength of two simultaneous transmissions is larger than 3db, the transmission with the higher signal strength is received correctly while the other packet is lost due to bit errors. Nevertheless, we focus on the worst case scenario in which both packets are disturbed such that the bit errors can not be corrected. In order to calculate the mean packet loss we introduce a new discrete random variable T which represents the number of lost packets during one contention resolution. The random variable T is calculated as described in Equation 5

$$\begin{aligned} E[T] &= \sum_{t=1}^{\infty} tP(T=t) \\ &= \sum_{c=2}^{\infty} cP(C=c) \\ &= \sum_{t=1}^{m} tP(T=t) \\ &= \sum_{t=2}^{m-1} t \frac{m!}{t!\,(m-t)!} \left(\frac{1}{n}\right)^{m} \sum_{i=1}^{n-1} i^{m-t} + m \left(\frac{1}{n}\right)^{m-1} \\ &= \frac{m}{n} \quad . \end{aligned} \tag{5}$$

Thus, we are able to calculate the mean of the packet loss due to collisions during the contention resolution according to Equation 6

$$P(T=t) = \begin{cases} \frac{m!}{t!\,(m-t)!} \left(\frac{1}{n}\right)^{m} \sum_{i=1}^{n-1} i^{m-t} & 2 \le t < m \\ \left(\frac{1}{n}\right)^{m-1} & t = m \\ 0 & \text{otherwise} \end{cases} \quad . \tag{6}$$

All traffic sources in the network access the medium at the same time in a worst case scenario. In such a particular scenario variable m corresponds to the number of traffic sources. In order to reduce the collision probability, a larger number of backoff slots n can be used to resolve the contention problem. Nonetheless, the duration of the backoff should not exceed certain duration since a longer backoff will result in a higher delay. Furthermore, a longer backoff increases the probability that more nodes try to transmit during a single backoff which might decrease the reliability. For that reason, we are simulating the impact of the backoff duration and the CCA delay in Section 3.

Nodes in WSNs are usually not synchronized to maintain simplicity since the clock drift of the micro controller makes synchronization a serious task. Therefore, the time during the media access is divided into time slots to achieve a minimum of synchronization. The behavior of the protocol upon higher layer packet arrivals is shown in Figure 4.

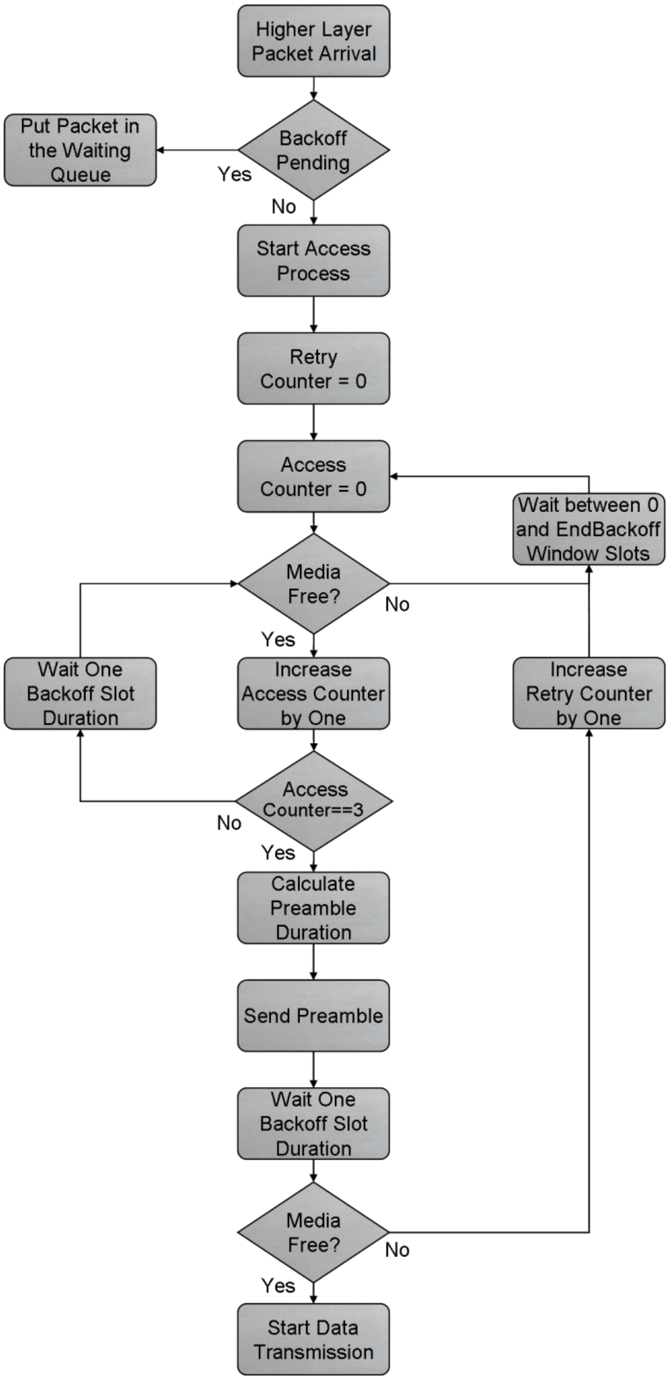

Figure 4. Media Access Process – Flow Diagram

Higher layer packets are put into the waiting queue if a backoff is already pending. In the case that no backoff is pending the media access process is started. The protocol initializes a retry counter and an access counter. Note that the retry counter and the access counter have different functions. The access counter is used to count the number of free consecutive backoff preamble slots while the retry counter represents the number of transmitted backoff preambles.

After the initialization of the counters is completed, the protocol switches the transceiver of the node to receive mode and starts to sense the media. If the media is busy, it waits between zero and EBW slots before the media is sensed again. In addition, the access counter is set to zero. The transceiver might be switched off during the waiting period in order to save energy.

The protocol increases the access counter by one if the media is idle and checks whether the counter is equal to three which indicates that the media 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 retry counter and starts to send the backoff preamble after the medium has been idle for duration of three backoff slots. Then it switches the transceiver back to receive mode which requires the duration of one backoff slot. If the node senses an idle channel after the preamble transmission, it starts to transmit all packets in its waiting queue. Otherwise, it increases its retry counter by one and resets the access counter before restarting the procedure.

3 RESULTS

The performance evaluation of a MAC protocol is always a challenging task since many factors, e.g. the number of competing nodes, the utilization of the air interface, and the traffic pattern, have an impact on the reliability and the delay. Due to the fact that our protocol is designed for WSNs, we focus on networks with data-centric traffic pattern and highly correlated traffic. We simulate the performance of the protocol under various traffic loads and a varying number of traffic sources.

In all scenarios the sensor nodes are in transmission range of each other and the signal strength between the sources and the sink differs by less then 3 dB. Therefore, all packets of simultaneous transmissions are lost which represents the worst case for collisions. The nodes are placed according to a uniform distribution within a square of 10 by 10 meters. In order to give a better impression of the performance of the BP-MAC protocol we compare its performance with the CSMA protocol. The CSMA protocol uses a TBEBA to resolve contention on the channel. The duration of a CSMA backoff slot is set to 30.51μs which corresponds to the 32 kHz clock cycle of the micro controller. The TBEBA uses a SBW and an EBW to calculate the number of backoff slots. The number of backoff slots is then chosen uniform distributed between zero and two to the power of the current backoff window. The algorithm increases the backoff window if the media is busy after the current backoff which indicates an unsuccessful media access.

Table 1. Traffic Pattern

Pattern Name	Parameter	Distribution	Range / Values
Burst (Sources)	Burst IAT	uniform	[9.9995;10.0005]s
	Pct p. Burst	constant	3
	Packet IAT	uniform	[0.0000; 0.0010]s
	Packet Size	constant	1024 bit
	Sources	-	[10;20;30;40;50; 60;70;80;90;100]
Burst (Load)	Burst IAT	uniform	[0.4995; 0.5005]s
	Pct p. Burst	constant	[2;4;6;8;10;12; 14;16;18;20;22]
	Packet IAT	constant	0.0250 s
	Packet Size	constant	1024 bit
	Sources	-	10
Low	Packet IAT	uniform	[0.9500; 1.0500]s
	Packet Size	constant	1024 bit
	Sources	-	10
Medium	Packet IAT	uniform	[0.0950; 0.1050]s
	Packet Size	constant	1024 bit
	Sources	-	10
High	Packet IAT	uniform	[0.0450; 0.0550]s
	Packet Size	constant	1024 bit
	Sources	-	10
CCA Delay	Packet IAT	uniform	[0.0950; 0.1050]s
	Packet Size	constant	1024 bit
	Sources	-	10

The backoff duration of the BP-MAC protocol is set to the duration of the CCA delay. If not further mentioned, the CCA delay is set to 128 µs which represents the RSSI average time of eight symbol periods. In addition, the data rate of the transceiver is set to 256 kb/s. The settings described above are used in all scenarios if not further mentioned again in the following subsections. The duration of each simulation run is 1100 seconds. Statistics are collected after a 100 second transient phase. The results are calculated from 20 simulation runs with different seeds which are quite sufficient since the results of different simulation runs are almost equal. The delay results represent the average of the 99 percent quantiles of the delay while the reliability results are calculated as the average of the simulation runs.

3.1 *Impact of the CCA Delay*

The configuration of the CSMA-TBEBA and the BP-MAC protocol can be optimized for low traffic and high traffic scenarios. However, before we take a look on the performance of both protocols under different traffic loads with different configurations, we compare their performance with an optimized configuration depending on the CCA delay in a scenario with a medium traffic load.

The CCA Delay scenario consists of 10 sources that generate 10 packets per second on average according to the uniform distribution shown in Table 1. Thus, the overall traffic load is approximately 40 percent. Typical transceivers for WSNs, like the CC2420 or the AT86RF231, have a typical CCA delay between 128 and 192 µs. For that reason, we decided to simulate the delay and the reliability of the protocols by increasing the CCA delay from 32 µs up to 256 µs in steps of 32 µs. The SBW and the EBW of the CSMA-TBEBA protocol are set to 9 which represent the best trade-off between reliability and delay for this scenario. The configuration was determined from measurements and a large number of simulations with comparable traffic pattern. A detailed description of the CSMA-TBEBA configuration and its impact on the performance is given in the following subsection. The BP-MAC protocol is configured such that it sends a preamble with duration of up to 32 backoff slots. Note that the duration of a BP-MAC slot corresponds to the CCA delay while the CSMA-TBEBA backoff slot duration is constant. The reliability and the delay of the protocols depending on the CCA delay are shown in Figure 5 and Figure 6. The results of Figure 5 reveal that the reliability of the CSMA-TBEBA protocol is greatly affected by the duration of the CCA delay. The slope of the graph shows that the reliability of the CSMA-TBEBA is reciprocally proportional to the CCA delay. However, the result is no real surprise since the performance of the protocol mainly depends on the sensing capabilities of the transceiver.

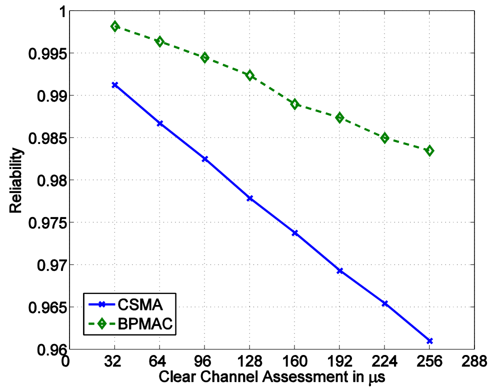

Figure 5. Reliability depending on the CCA Delay

The reliability of the BP-MAC protocol is less affected by the CCA delay. The small decrease of the reliability with increased CCA delay is caused by the higher media access delay due to longer backoff slots. As a consequence of the higher delay more nodes compete for the media access within one contention resolution. Thus, the probability that two or more nodes start their preamble transmission at the same time and choose the same number of backoff slots increases. Nonetheless, the decrease is much less compared to the reliability decrease of the CSMA-TBEBA protocol.

Figure 6 indicates that the delay of the CSMA-TBEBA protocol is not greatly affected by the higher CCA delay. A very small decrease of the delay can be mentioned which results from the lower utilization due to the increased packet loss.

In contrast to the CSMA-TBEBA the delay of the BP-MAC protocol increases almost linearly with the CCA delay as long as the utilization remains on a medium level. The linear increase reflects the increase of the duration of the backoff slots. Furthermore, the results of Figure 6 show that the BP-MAC protocol performs better than the CSMA-TBEBA of the CCA if the delay is less than 224 µs. The difference between the two protocols becomes larger for shorter CCA delays. Thus, the BP-MAC protocol represents a good choice for future WSNs since new technologies will be able to shorten the CCA delay further than 128 µs for low power transceivers.

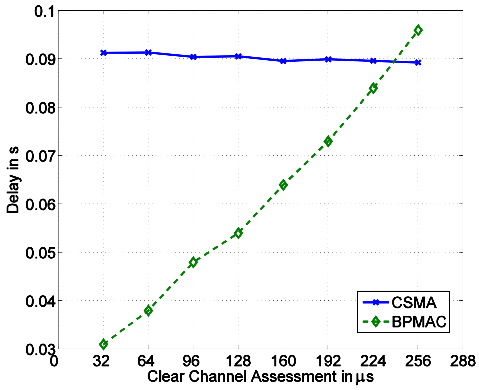

Figure 6. Delay depending on the CCA Delay

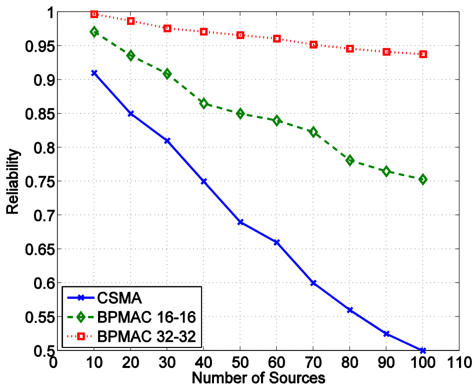

Figure 7. Reliability depending on the Number of B-Sources

3.2 *Impact of the Number of Sources and the Traffic Load*

Many MAC protocols use random access mechanisms due to their simplicity in contrast to time scheduled access mechanisms. However, the price of simplicity is often paid by higher delay or unfairness which results from the required contention resolution. The following two scenarios are used to simulate the performance of the protocols while increasing the traffic load and the number of sources. Furthermore, a traffic pattern with burst characteristics is used to simulate typical event-driven traffic.

In the first scenario, the nodes send traffic according to the Burst(Sources) traffic pattern shown in Table 1. Thus, the nodes try to send three packets approximately every 10 seconds which results in peaks of the traffic load. This kind of traffic represents typical event-driven traffic from, e.g. Structural Health Monitoring applications, in WSNs.

The number of sources is increased from 10 to 100 nodes in steps of 10 nodes in order to simulate the impact of the correlated traffic load on the performance. The SBW and the EBW of the CSMA-TBEBA protocol are set again to 9. The first configuration of the BP-MAC protocol uses a SBW and an EBW of 16 while the second configuration uses a SBW and an EBW of 32. Figure 7 shows that the reliability of both protocols decreases almost linearly if the number of traffic sources is increased.

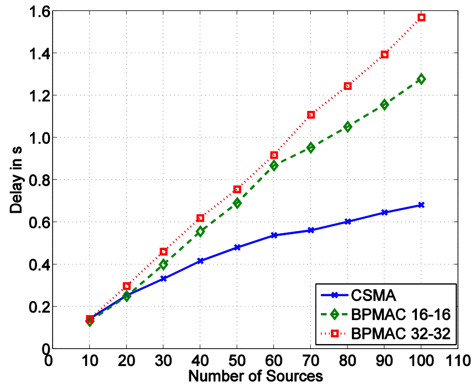

Figure 8. Delay depending on the Number of B-Sources

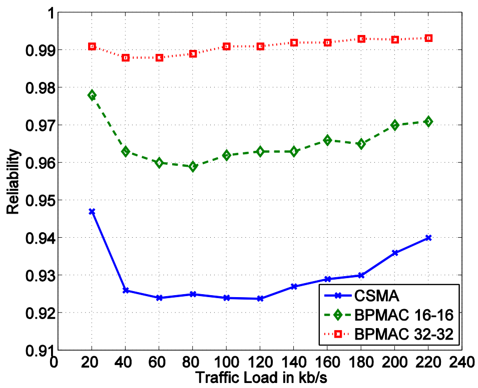

Figure 9. Reliability depending on the Traffic Load

Nevertheless, the reliability of the BP-MAC protocol remains on a very high level while the reliability of the CSMA-TBEBA protocol significantly decreases. It is not able to detect the start of simultaneous transmissions due to the CCA delay of 128 µs.

The delay depending on the number of sources is shown in Figure 8. The linear increase results from the protocol overhead and the utilization of the media. The increase is higher for both configurations of the BP-MAC protocol compared to the CSMA protocol if more than 20 nodes compete for the media access. However, the lower delay of the CSMA-TBEBA in high traffic scenarios follows from the lower reliability. Due to the lower reliability, the utilization of the media is reduced since two or more nodes transmit at the same time.

In the second scenario, the nodes use the Burst(Load) traffic pattern shown in Table 1. The nodes send bursts according to a uniform distribution between 0.4995 and 0.5005 seconds. Furthermore, the traffic generation of each node starts with a uniform distributed offset between 0 and 0.1 second in order to smooth the traffic peaks. Nevertheless, the traffic has still burst characteristics but with more variation due to the uniform distributed offset. The same configuration of the protocols as in the previous scenario is used to simulate the impact of the traffic load on the performance of the protocols. The traffic load of the network is increased from 20 to 220 kb/s by increasing the number of packets per burst from 2 to 22 in steps of 2 packets.

The results of Figure 9 show that the BP-MAC protocol achieves a high reliability for all traffic loads. Nevertheless, all protocols have the highest reliability if the traffic load is either very low or very high which is quite surprising since we assumed the highest reliability only for the scenario with the lowest traffic load. However, the traffic pattern in Table 1 and the results of Figure 10 give a clue for the reason of the slope of the reliability graph in Figure 9. The larger delay reduces the probability that a node accesses the media more than one time to send all packets from a single burst. Note that the packet inter arrival time is set to 25 milliseconds which results in a burst duration of up to 550 milliseconds.

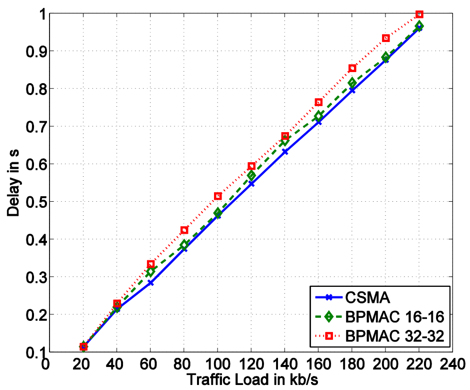

Figure 10. Delay depending on the Traffic Load

As a consequence of the data aggregation, the number of media access procedures are reduced which leads to a reduction of the number of collisions. The increase of the reliability for scenarios with more than 80 kb/s shows that the traffic load becomes the dominating factor.

Furthermore, the linear increase of the delay in Figure 10 indicates that the delay of the protocol scales with the traffic load in scenarios with typical WSN traffic pattern. The 99 percent quantile of the delay of the BP-MAC protocol is slightly higher than the delay of the CSMA protocol. However, the higher delay results from the higher reliability of the BP-MAC protocol. Thus, it represents a better solution for this kind of scenarios.

3.3 *Impact of the Backoff Configuration depending on the Traffic Load*

The focus of this section lies on the performance of the protocols depending on the traffic load and the size of the SBW and the EBW. Furthermore, we will answer the question whether the reliability of the protocols can be increased if a higher delay is taken into account. The evaluated scenarios consist of WSNs with 10 sources and a sink. All nodes are in transmission range of each other and are again placed uniformly distributed within a square of 10 by 10 meters.

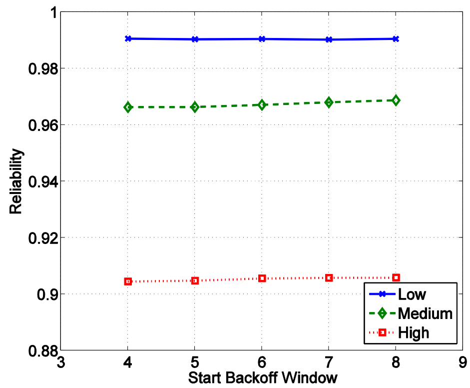

Figure 11. CSMA-TBEBA Reliability depending on the SBW (EBW=8)

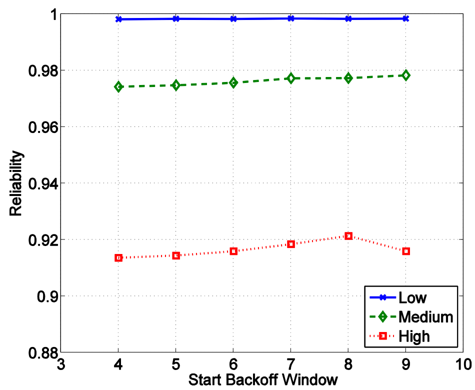

Figure 12. CSMA-TBEBA Reliability depending on the SBW (EBW=9)

Three scenarios with different traffic loads are simulated in order to evaluate the performance of the protocols with different configurations under different traffic loads. The sources generate traffic according to the Low, Medium, and High traffic pattern shown in Table 1.

In the following parameter study the SBW of the CSMA-TBEBA protocol is varied between 4 and EBW while the SBW of the BP-MAC protocol is varied between 2 and EBW. Furthermore, the CSMA-TBEBA is simulated for EBWs of 8 and 9. The performance of the CSMA-TBEBA is then compared with the performance of the BP-MAC protocol using an EBW of 16 and 32. The different SBWs and EBWs are simulated to find out whether the performance of the protocols can be increased by using a longer backoff.

The reliability of the CSMA-TBEBA depending on the EBW is shown in Figure 11 and Figure 12. The results point out that the reliability of the CSMA-TBEBA could not be increased by increasing the EBW. Thus, an EBW of 8 represents a better choice for the CSMA-TBEBA since the EBW should be chosen as low as possible to minimize the delay.

Figure 13 and Figure 14 show the reliability of the BP-MAC protocol depending on the used SBW and the EBW. The first thing that can be recognized is that the reliability of the protocol is increased if a longer backoff is taken into account.

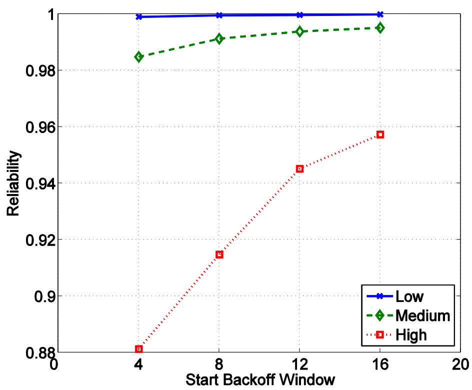

Figure 13. BP-MAC - Reliability depending on the SBW (EBW=16)

Furthermore, the reliability of the BP-MAC protocol is higher compared to the CSMA-TBEBA protocol for all scenarios. However, the results of Figure 13 and Figure 14 for the medium and the high traffic scenario show that the SBW of the BP-MAC protocol has to be chosen in respect to the traffic load and the maximum number of competing nodes. Otherwise, the performance of the protocol may drop down to the performance of the CSMA-TBEBA protocol. It is obvious that a too small SBW represents a worse decision in scenarios with temporary contention and a high node density. As a result, the collision probability for the first backoff slots would be very high which would lead to an overall performance decrease. In addition, the EBW has to be large enough to achieve high success probability even in the case that many nodes access the media at the same time. A high reliability can be achieved in worst case scenarios if the EBW is chosen in respect to the number of competing nodes which is reflected by the results of Figure 14.

The results of the previous scenario showed that the reliability of the CSMA-TBEBA could not be significantly increased by taking a longer backoff into account. This behavior is in contrast to the behavior of the BP-MAC protocol which achieves a higher reliability if the size of the EBW is increased. Thus, a closer look is taken on the delay of the protocols depending on the size of the EBW.

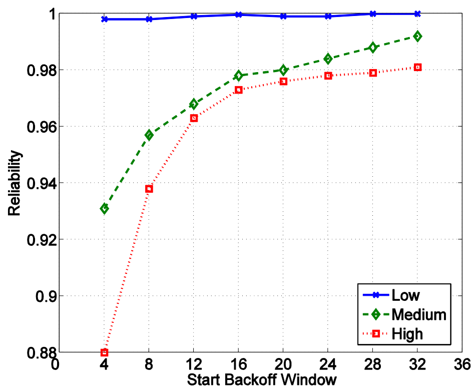

Figure 14. BP-MAC - Reliability depending on the SBW (EBW=32)

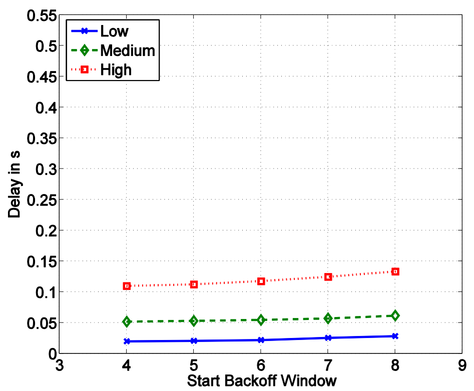

Figure 15. CSMA-TBEBA - Delay depending on the SBW (EBW=8)

Figure 15 shows the delay of the CSMA-TBEBA with an EBW of 8 depending on the SBW and the traffic load. The delay increases if the SBW is increased due to the fact that a higher SBW increases the duration of the first backoff. Nevertheless, the increase of the delay is reduced by the impact of data aggregation. The results of Figure 16 show the delay of the CSMA-TBEBA protocol for an EBW of 9. The delay doubles in the high traffic scenario if an EBW of 9 is used. Nonetheless, the larger EBW does not increase the success probability of the contention resolution. Thus, an EBW of 8 represents the optimum choice for the CSMA-TBEBA in the simulated scenarios. However, the delay is still on an acceptable level for most WSN applications even in the case that an EBW of 9 is used.

In contrast to the CSMA-TBEBA protocol the backoff duration has a large impact on the performance of the BP-MAC protocol. The impact of the EBW on the delay of the BP-MAC protocol is shown in Figure 17 and Figure 18. The increase of the delay between the BP-MAC with an EBW of 16 and an EBW of 32 for the low traffic and medium traffic scenarios is negligible. Moreover, the delay of the BP-MAC is lower than the delay of the CSMA-TBEBA independent from the configuration in both scenarios. The delay of the BP-MAC protocol is more affected by the traffic load than the delay of CSMA-TBEBA protocol.

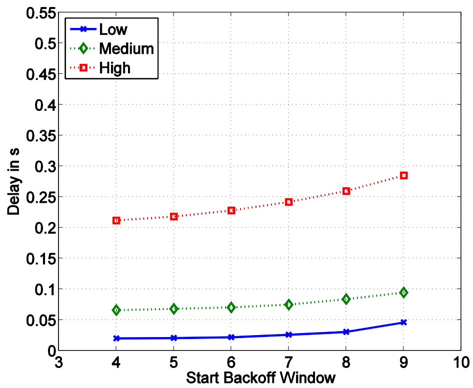

Figure 16. CSMA-TBEBA - Delay depending on the SBW (EBW=9)

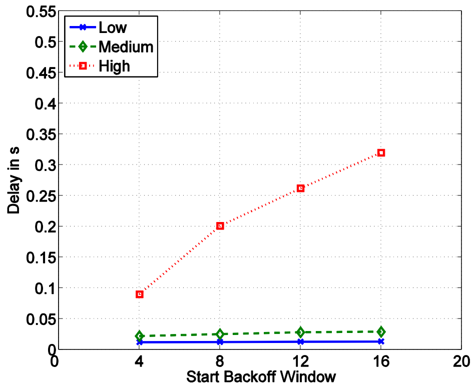

Figure 17. BP-MAC - Delay depending on the SBW (EBW=16)

For that reason, the delay of the BP-MAC is higher than the delay of the CSMA-TBEBA for the high traffic scenario. However, the retransmission of lost packets would affect the delay of the CSMA protocol more than the delay of the BP-MAC protocol due to its lower reliability. Nevertheless, the 99 percent quantile of the delay is far below one second which represents the maximum acceptable delay boundary for typical WSN applications.

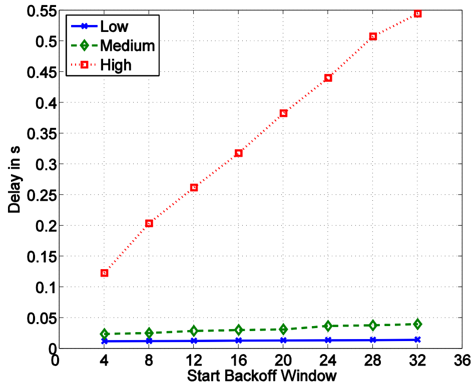

Figure 18. BP-MAC - Delay depending on the SBW (EBW=32)

4 RELATED WORK

The problem of CCA delay is not addressed in many papers due to the fact that most of the current research solely relies on simulation and analysis where the transmission area of the radio is assumed to be circular, all links are bi-directional and without any packet loss. Langendoen et. al. discuss the serious issues that are neglected if the previous assumptions are made. Besides the characteristics of the physical media almost all network simulators neglect the delay of the transceivers. Thus, the problem of CCA delay does not occur if unmodified standard simulation models, e.g. from ns-2 or OPNET are used. The work presented by Kiryushin et. al. shows the problem of CCA delay from a more detailed point of view since it describes the real world performance of CCA in IEEE 802.15.4 WSNs. Furthermore, Bertocco et. al. showed that it is possible to increase the network performance by optimizing the CCA threshold in order to minimize the CCA delay. Ramachandran and Roy introduce an intelligent cross-layer approach that modifies the CCA method dynamically depending on the current channel conditions and upper layer parameters. In addition, they compare different CCA methods in respect to energy consumption. A different approach is followed by Tay et. al. Instead of addressing the CCA problem they reduce the number of collisions by optimizing the contention resolution for event-driven WSN data traffic. They introduce a non-uniform distribution for the backoff selection which reduces the collision probability for a certain number of contenting nodes.

5 CONCLUSIOS AND FUTURE WORK

In this work we introduced the BP-MAC protocol which uses a backoff preamble with variable length to reduce the collision probability in WSNs. The described medium access mechanism can be used in any MAC protocol to overcome the problem caused by the high CCA delay of typical low power transceivers for wireless sensor nodes. The presented results showed that the protocol will take a greater benefit out of next generation low power transceivers compared to CSMA based protocols since its performance is more affected by the CCA delay. Thus, we are confident that the media access scheme of the BP-MAC protocol will present a more than attractive alternative to the ordinary backoff solution for high reliable WSNs in the near future.

We are currently working on a sequential backoff preamble access scheme with non-uniform backoff slot selection. The sequential contention resolution allows reducing the number of competing nodes step by step which increases the reliability of the protocol in WSNs with a very high node density.

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