Performance Study of a Preamble based MAC Protocol in Multi-Hop Wireless Networks

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***Abstract*—The majority of Medium Access Control (MAC) protocols that are designed for Wireless Sensor Networks (WSN) solely rely on the carrier-sense capabilities of the transceiver. Typical low-power transceivers require a large amount of time to detect a busy channel and to switch from receive mode to transmit mode. Moreover, the switching phase represents a vulnerable period for random access MAC protocols since the transceivers are not able to sense the medium during the switching phase. These issues can be addressed by MAC protocols which make use of preamble transmissions to schedule the access to the medium. However, the transmission of preambles induces additional protocol overhead which might be a performance limiting factor in multi-hop networks. In this paper a preamble based MAC protocol in combination with a directed diffusion based routing protocol is simulated and compared with the performance of Zigbee in multi-hop wireless networks.**

***Index Terms*—Medium Access Control, contention resolution, wireless, preamble, sequential**

I. Introduction

Wireless communication gains more and more interest in the avionic industry since the latest generation of wireless devices achieve a high reliability and long lifetime. In addition, they support a high data rate which allows building large networks while maintaining a low delay. Therefore, WSNs for intra-aircraft communication have become a competitive solution under economical aspects for their wired counterparts. The applications range from low-data rate networks for smoke and fire detection to Structural Health Monitoring (SHM) applications which require a high-data rate and reliable communication due to their mission critical data. Applications for passenger and cargo monitoring are also considered by the flight industry. Passenger monitoring has especially high demands on the MAC protocol since the number of nodes and the node density are very high for this kind of application. Furthermore, the nodes have to be placed such that they are not recognized by the customers. Thus, the placement of the node has a negative affect on the transmission range which makes multi-hop communication necessary.

Typical state-of-the-art low power transceivers have specific characteristics that greatly affect the performance of WSNs. They are able to transmit data between 32 kB/s and 256 kB/s which limits the possibilities of MAC and routing protocols to exchange information since the number of nodes and the node density are usually very high in WSNs. Therefore, the majority of the MAC protocols that are designed for WSNs rely solely on the sensing capability of the transceiver in order to support random access by using the carrier sense functionality of the chip. However, the sensing capabilities of low-power transceivers are very limited, especially in the case that small chip antennas are used [1], [2]. As a consequence of the limited sensing capabilities the packet loss rate in WSNs is very high compared to other wireless networks like IEEE 802.11 [3].

Two communication issues are mainly responsible for the low performance of WSN MAC protocols in respect to reliability. The first issue is represented by the amount of time that low power transceivers require to switch between receiving and transmitting and vice versa. Thus, the switching time which is in the following referred to as turnaround time, specifies the time between the arrival of a packet and the beginning of the corresponding response [4]. During this time interval the transceiver is not able to detect the start of other transmissions. The second issue is called Clear Channel Assessment (CCA) delay. The CCA delay specifies the amount of time that a transceiver requires to detect a busy medium provided that the transceiver is already in receive mode. Typical low power transceivers, like ATMELs AT86RF231 [5] and the CC2420 [6] from Texas Instruments provide Carrier Sense Multiple Access (CSMA) functionality to the MAC protocol by measuring the Received Signal Strength Indication (RSSI). The transceivers average the RSSI value over the last 8 symbol periods. For that reason, both transceivers have to listen for a minimum duration of 128 μs in order to reliably detect a busy radio channel. As a result, the transceivers are not able to reliably detect the transmission of another node if the transmission has been started within an interval that is shorter than the CCA delay. A busy channel is reported to the micro controller if the measured RSSI value exceeds a predefined threshold. The detection time can be reduced if the threshold is slightly above the noise level [7]. However, it is clear that a too low threshold results in a large number of false positives which increases the delay and reduces the throughput of the network.

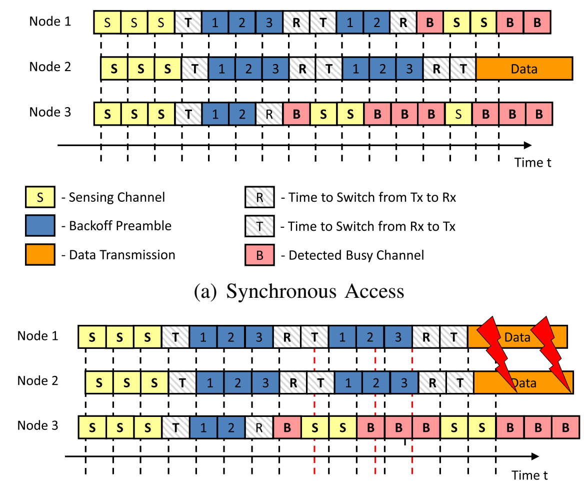
In [8] a new MAC protocol, which directly addresses the problem caused by the turnaround time and the CCA delay, is introduced. The protocol uses short consecutive preambles with variable length which cover the function of a reservation signal. In addition, the protocol may use a sequential contention resolution in order to reduce the number of competing nodes step by step. Furthermore, they showed that the BP-MAC protocol achieves a very high reliability in one hop wireless networks while maintaining a low delay. Nevertheless, it has to be kept in mind that the transmission range of wireless sensor nodes is very limited due to the low transmission power and the small layout of the chip antennas [1], [9], [10]. Thus, it is often necessary to build a multi-hop wireless network which has additional requirements on the MAC protocol.

Large WSNs may take a high advantage from spatial reuse. Nonetheless, the potential of spatial reuse strongly depends on the interference in the network and the utilization of the medium. Therefore, it is not clear whether the preamble based BP-MAC protocol outperforms CSMA based MAC protocols in dense multi-hop WSNs with event-driven data traffic. In this work, a solution is introduced which is based on the BP-MAC protocol and directed diffusion [11]. The performance of the solution is compared with Zigbee which adapts the MAC and physical layer of the IEEE 802.15.4 [12] standard. This paper is organized as follows. In Section II, the medium access procedures of the BPS-MAC protocol is described in detail. The simulation results are presented and analyzed in Section III. An overview of related work is given and discussed in Section IV. Finally, we conclude in Section V.

II. BPS-MAC Protocol

Random access based MAC protocols are not able to reliably exchange data in dense WSNs with correlated event-driven traffic if they solely rely on the sensing capabilities of the low power transceiver due to the fact that the transceivers cannot detect a transmission that has been started within an interval that is shorter than the CCA delay and the turnaround time. The BPS-MAC protocol addresses this problem by using backoff preambles with variable length before transmitting data. The duration of the preamble is a multiple of the CCA delay or the turnaround time of the transceiver. Thus, a node is able to detect a synchronous preamble transmission of another node provided that they choose a backoff preamble with a different number of slots. Furthermore, the slot duration has to be larger or equal than the CCA delay and the turnaround time in order to leave the nodes enough time to switch the transceiver mode and/or to sense the medium. An example of the medium access procedure with two backoff sequences is introduced in Figure 1.

The example shows a scenario in which three nodes compete for the medium access. As mentioned in the previous paragraph, the BPS-MAC protocol divides the time during the medium access into time slots. A node that wants to transmit data senses the radio channel for duration of three slots. If the medium has been idle during the three slots, the node switches its transceiver from receive to transmit mode which requires an additional slot. Then, the node chooses a backoff duration and starts to transmit the backoff preamble. After the transmission of the preamble is completed, the node switches its transceiver back to receive mode and senses the medium. If a node senses a busy medium after the preamble transmission, it restarts the medium access procedure after a random number of slots. In the case that the medium is free after the preamble transmission, the node switches its transceiver back to tx mode in order to proceed with the next sequence of the contention resolution. A node is only allowed to start its data transmission if it has sensed an idle medium after the transmission of the last backoff preamble. Note, the time between two consecutive preambles is two slots. For that reason, the nodes sense the medium for a duration of three slots at the beginning of the medium access process to assure that there is no ongoing data transmission.



(a) Synchronous Access

(b) Collision

Fig. 1. Sequential Contention Resolution

The introduced procedure reduces the collision probability in case of synchronous medium access in a significant way. However, collisions may still occur if two or more nodes start their preamble transmission at the same time and chose the same number of preamble slots in every backoff sequence. Figure 1b shows a collision example for a contention resolution with two backoff sequences. Dividing the preamble transmission into multiple sequences improves the contention resolution of the protocol while maintaining a low medium access delay. This becomes clear by taking a look on the average number of collisions. If the nodes choose the preamble duration uniformly distributed, the average number of collisions is given by the fraction of the number of nodes which start to transmit their preamble at the same time and the maximum number of backoff slots. Thus, a single backoff sequence with a maximum preamble duration of 16 slots provides the same performance than two backoff sequences where each sequence has a maximum duration of 4 slots.

Nonetheless, the backoff procedure represents protocol overhead which limits the maximum throughput of the protocol. Therefore, both parameters have to be chosen in respect to the node density and the traffic pattern. The sequential contention resolution represents an extension of the medium access procedure that is introduced in [8].

III. SIMULATION

The performance of MAC protocols for WSNs strongly depends on the characteristics of the network, e.g. the number of nodes, the node density, and the traffic pattern. Moreover, the data rate and the sensing capabilities of the transceiver have a large impact on the network performance. In the following, it is assumed that the transceiver achieves a maximum data rate of 250 kb/s. Furthermore, a CCA delay and a turnaround time of 128 μs is assumed which represent typical values for state-of-the-art low power transceivers. The OPNET Modeler [13] is used to simulate the performance of the protocols. Note that most simulation tools, like OPNET Modeler or ns-2 [14], simplify the physical layer in order to increase the simulation speed. Thus, their standard models simplify or even neglect important communication issues, e.g. the turnaround time of the transceiver and the CCA delay. For that reason, we modified the physical layer of the OPNET Modeler software such that it takes both communication issues into account. The transmission range is limited to 10 meters and the maximum interference range is set to 17 meters by modifying the so-called pipeline stages of OPNETs free space propagation model. These values reflect the average results from our first measurements with a small self-developed sensor board that uses a MSP430 micro controller and a CC2420 transceiver. The short range results from the fact that the nodes were placed inside the backrest of the seat. It is clear that these values may vary significantly depending on the position and orientation of the sensor node and the characteristics of the used antenna. Thus, the assumed values only fit to our particular example scenario.

The simulated scenario represents a typical middle-size airplane with six seats per row. A wireless sensor is placed in the backrest of each seat which monitors the state of the seat, e.g. whether the seat is occupied, the seatbelt is fastened, or the tray is secured. This information is reported periodically to a sink in the front of the plane. It has to be kept in mind that the simulated application is just an example application. There are currently a large number of applications under consideration to improve the existing flight cabin management system. A multi-hop network is required to enable connectivity between all nodes in the network due to the fact that large planes reach lengths of up to 60 meters. More powerful sensor nodes with routing capabilities are placed on the ceiling along alleyway approximately every 8 meters in order to connect the other sensors with the sink. An overview of the simulated scenario is shown in Figure 2.

The figure illustrates the high node density of up to 60 nodes.However, the large interference range has to be taken into consideration as well when specifying the application requirements. As a consequence of the high node density, the traffic pattern has a huge impact on the network performance in the simulated scenario. Data traffic is usually highly correlated in WSNs since it is often event-driven and data centric. Thus, we decided to simulate three different traffic patterns which are representative for a large number of popular intra-

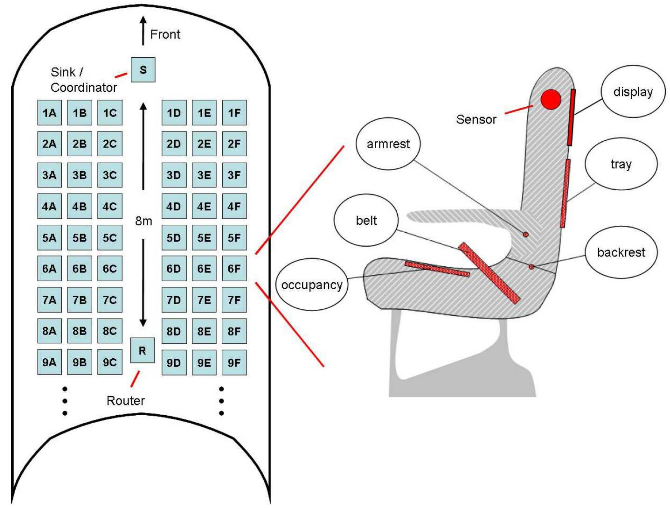


Fig. 2. Overview of the Simulated Scenario

aircraft applications. The simulated traffic pattern are shown in Table 1. The number of (seat) rows is increased from 8 to 40 in order to find out how many nodes are supported by the protocols in the intra-aircraft scenario depending on the application. The results represent the 90 percent confidence intervals of the average end-to-end delay and packet loss that are collected from 20 simulation runs with a duration of 1000 seconds and different seeds.

The traffic pattern start after 80 seconds since the Zigbee model requires some time to build a tree topology. In addition, the traffic generation stops at 980 seconds to allow the nodes to empty their waiting queues. Thus, the packet loss is given by the fraction of generated packets and the number of packets that are successfully received by the sink. Zigbee is set to non-beacon mode. Zigbee implies network layer functionality. Thus, a directed-diffusion [11] based routing protocol is used in combination with the BPS-MAC protocol to support comparable routing functionality. The directed-diffusion based routing protocol is modified such that only routers retransmit the interest which minimizes the routing overhead. The BPS-MAC protocol uses three consecutive backoff preambles with a maximum number of four slots.

A. Scenario A

The introduced passenger monitoring application does not require a large amount bandwidth since some of the monitored characteristics, e.g. seatbelt fastened or unfastened, are logical. However, advanced monitoring features such as temperature or humidity can be considered. Furthermore, the sensed values are not time-critical. In scenario A, the nodes follow the traffic pattern of application A which is introduced in Table I. It is assumed that the nodes only transmit a 256 bit packet approximately every 10 seconds. The packet inter-arrival time slightly varies uniformly distributed by 20 milliseconds. The traffic pattern starts with a uniformly distributed offset of ten seconds which results in an unsynchronized medium access of the nodes. Figure 3 shows the average end-to-end delay

Pattern Name	Parameter	Distribution	Range / Values
Application A	Packet IAT	uniform	[9.99; 10.01] s
	Packet Size	constant	256 bit
	Start Time	uniform	[80;90] s
	Number of Rows	-	[8;16;24;32;40]
Application B	Packet IAT	uniform	[9.99; 10.01] s
	Packet Size	constant	256 bit
	Start Time	uniform	[80;81] s
	Number of Rows	-	[8;16;24;32;40]
Application C	Packet IAT	uniform	[3.95; 4.05] s
	Packet Size	constant	1024 bit
	Start Time	uniform	[80;84] s
	Number of Rows	-	[8;16;24;32;40]

TABLE I
TRAFFIC PATTERN

between the nodes and the sink depending on the number of rows in the plane. The figure reveals that the end-to-end delay increases non-linearly which is the consequence of the multi-hop communication. Moreover, the figure points out that the delay of the BPS-MAC protocol is much higher compared to Zigbee if the number of rows is larger than 8. Nonetheless, the average end-to-end delay of the BPS-MAC protocol remains lower than 0.35 seconds even for the 40 row scenario which is quite acceptable for this kind of application. The BPS-MAC protocol achieves a lower packet loss than Zigbee in scenario A as shown in Figure 4 due to the fact that the medium access procedure is optimized for synchronous medium access. The probability increases that two or more nodes start their data transmission within an interval that is shorter than the CCA delay of the low power transceiver in- creases with the number of nodes in the networks. As a result, the packet loss increases almost linearly for both protocols but still remains below 2 percent. Therefore, both protocols represent an acceptable solution for application A.

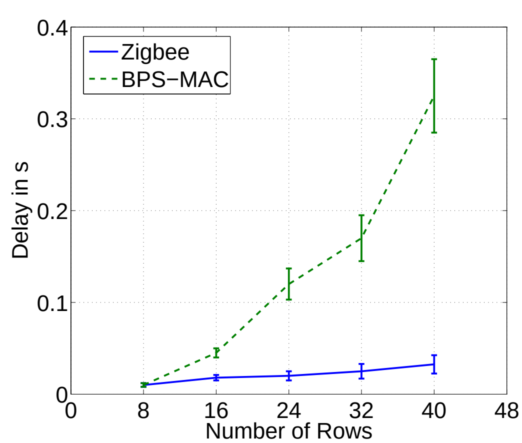


Fig. 3. Application A - Delay depending on the Number of Rows

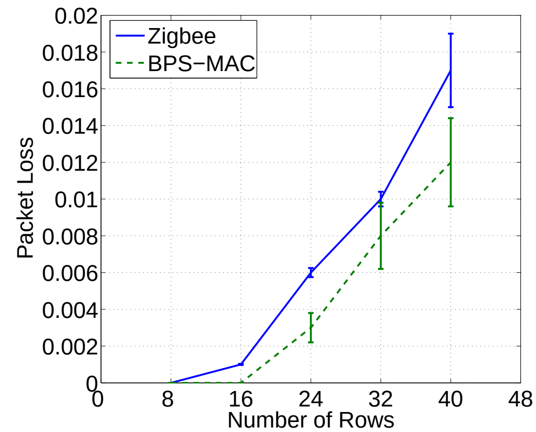


Fig. 4. Application A - Packet Loss depending on the Number of Rows

B. Scenario B

Scenario B uses almost the same traffic pattern as scenario A. The only difference lies in the fact that the offset of the traffic pattern only varies uniformly distributed by 1 seconds. Thus, the traffic load and the medium access of the nodes is highly correlated. Therefore, the probability that two nodes access the medium within an interval that is shorter than the CCA delay and the turnaround time is very high. The average end-to-end delay of the different protocols depending on the number of rows is shown in Figure 5.

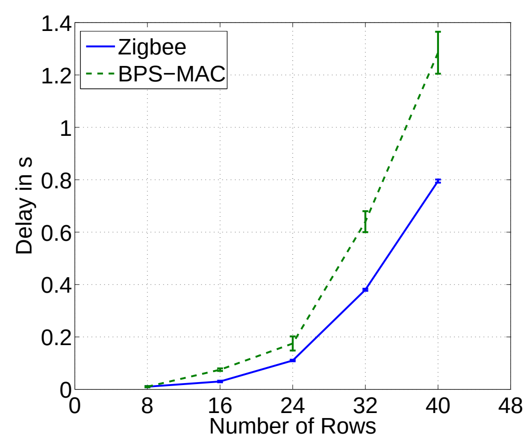


Fig. 5. Application B - Delay depending on the Number of Rows

Both protocols achieve a low delay for scenarios in which the number of rows remains below 24. The delay sharply increases if the number of rows exceeds 24 as a consequence of the multi-hop communication and the highly correlated traffic.

Figure 6 shows a similar picture for scenarios with less than 24 rows. Nonetheless, an extra ordinary high packet loss can be mentioned for the Zigbee protocol which results from the highly correlated traffic. The packet loss of Zigbee reaches unacceptable high values for scenarios with more than 24

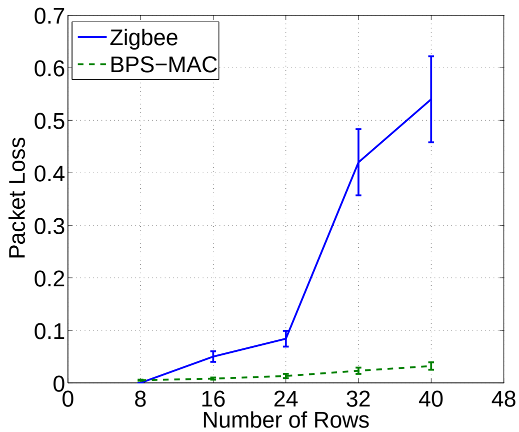


Fig. 6. Application B - Packet Loss depending on the Number of Rows

nodes. Zigbee is not able to resolve the contention in this case due to the fact that the protocol is not addressing the problem caused by the CCA delay and the turnaround time. In contrast to Zigbee, the packet loss of the BPS-MAC remains on a low level such that it only increases to a maximum of 2 percent for the 40 row scenario.

C. Scenario C

In scenario C the performance of the protocols is simulated under a higher traffic load. The nodes in network generate traffic according to the traffic pattern of application C shown in Table 1. The traffic load is ten times higher than the load that is generated by application A or application B. Thus, the overall generated traffic load is 61.4 kB/s for the 40 row scenario. However, this calculation excludes the traffic that is required for forwarding data. It has to be kept in mind that some nodes require up to four hops to reach the sink in the 40 row scenario. Moreover, the packet inter-arrival time varies uniformly distributed by 100 milliseconds which results in less correlated traffic compared to scenario B.

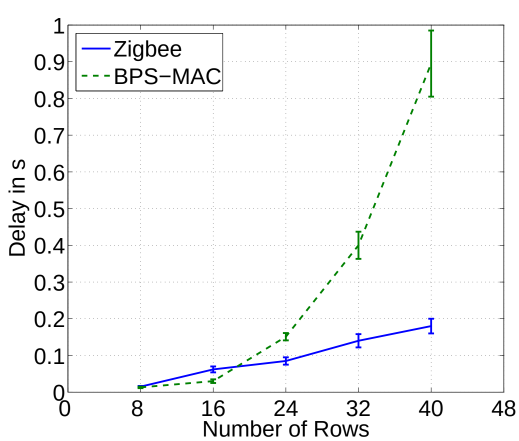


Fig. 7. Application C - Delay depending on the Number of Rows

Figure 7 shows the average end-to-end-delay in scenario C depending on the number of rows. The figure reveals that the BPS-MAC protocol achieves a slightly lower delay than Zigbee as long as the number of rows is smaller or equal than 16. The delay of Zigbee increases almost linearly while the slope of the delay graph of the BPS-MAC protocol shows exponential characteristic. This slope results from the high utilization of the medium and the large number of nodes in the network. For that reason, the bandwidth that is wasted by the BPS-MAC protocol to transmit backoff preambles becomes the performance dominating factor for the delay. Nonetheless, the average delay of the BPS-MAC protocol remains below one second.

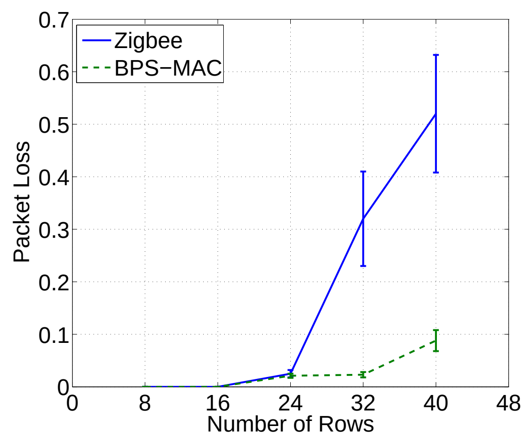


Fig. 8. Application C - Packet Loss depending on the Number of Rows

The packet loss shown in Figure 8 points out that the BPS-MAC protocol in combination with a directed diffusion based routing protocol provides a better solution than Zigbee for scenario C. The figure indicates that Zigbee is not able to handle a network that is larger than 24 rows if the nodes generate traffic according to application C. In this case, the high traffic load in combination with the correlated traffic limit the performance of Zigbee since the MAC does not address the CCA delay and the turnaround time explicitly. The packet loss of the BPS-MAC protocol increases to approximately 2 percent in the 32 row scenario which is sufficient for non-mission critical data. If the number of rows exceeds 32 the packet loss of the BPS-MAC protocol increases to 9 percent as a consequence of the high utilization. Therefore, acknowledgments might be necessary depending on the reliability requirements of the application. Nevertheless, acknowledgments would further increase the traffic and might thus not be applicable for scenarios with more than 32 rows.

IV. Related Work

The idea of using preamble based medium access was already introduced by different authors in 2002. Hill and Culler [15] proposed a low power listening mechanism where nodes periodically probed the medium. The nodes keep listening if the medium is busy until a certain symbol is detected. This mechanism was used to reduce the idle listening overhead by sending out long preambles. In the same year, El-Hoiydi presented an Aloha based protocol with preamble sampling [16]. The main goal of the protocol was to support unsynchronized sleep times. Thus, nodes probed the the medium periodically and kept listening if they have received a busy channel. Therefore, a node that wants to transmit a packet to another node has to send a preamble that is longer than the sleep interval in order to be assure that the destination node is listening to the medium. It is clear that such a protocol wastes a lot of energy and bandwidth by transmitting preambles. El-Hoiydi introduced an improved version of the protocol in 2004. The WiseMAC protocol [17] takes advantage from loose synchronization. A sending node starts its preamble transmission right before the wake up period of the destination node which reduces the required preamble duration in a significant way. A similar approach was presented Mahlknecht and Bock [18]. Their approach is based on CSMA with minimum preamble sampling. However, the proposed protocol requires a transceiver with a high data rate and a low turnaround time to reduce the energy consumption. Another very interesting protocol was presented by Buettner et al. in 2006. They introduced the X-MAC protocol [19] which uses short strobed-preambles instead of a single long preamble. The gap between two consecutive short preambles is long enough to allow the destination node to reply with an early acknowledgment in order to inform the originating node that it is already listening. As a result, the originating node does not need to send all short preambles which reduces the preamble duration in unsynchronized networks.

V. Conclusions

In this work we have simulated the performance of Zigbee and the BPS-MAC protocol with a directed diffusion based routing protocol in a typical intra-aircraft scenario. The intra-aircraft scenario was chosen in order to evaluate whether preamble based protocols represent a suitable solution in the context of multi-hop wireless communication. The performance of the protocols was simulated under three different data centric traffic pattern. The results pointed out that Zigbee achieves a low end-to-end delay if the traffic load is low and uncorrelated. The delay of the BPS-MAC protocol is higher in low traffic scenarios. However, its performance is less affected by correlated traffic since its backoff preamble based medium access procedure directly addresses the large CCA delay and the turnaround time of the transceiver. Additionally, the impact of the traffic load on the network performance was simulated. The results showed that the communication issues of the low power transceivers become more important if the traffic load is increased. Therefore, Zigbee only represents an acceptable solution for intra-aircraft applications if the number of rows is less than 24 and the traffic load is low and uncorrelated. The BPS-MAC protocol achieves a low packet loss for all scenarios due to the preamble based contention resolution. Nonetheless, the transmission of preambles induces additional protocol overhead which results in a higher end-to-end delay of the BPS-MAC protocol.

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