A Preamble-Based Approach for Providing Quality of Service Support in Wireless Sensor Networks

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Abstract. Medium Access Control (MAC) protocols for Wireless Sensor Networks (WSN) are usually designed as random access protocols that apply different kinds of backoff strategies since Time Division Multiple Access (TDMA) based protocols with admission control are very complex and require mechanisms for synchronization. Without such mechanisms, fair or priority based medium access with Quality of Service (QoS) guarantees can hardly be achieved by existing protocols. Therefore, we developed a random access protocol which uses a new preamble based medium access strategy that enables high reliable priority based access. In this paper we introduce different QoS strategies and their use cases. All strategies can be easily integrated in our protocol to meet the requirements of different target applications. Furthermore, we compare the performance of the strategies with a typical carrier-sense based protocol.

Keywords: random access, wireless, quality of service.

1 Introduction

A trend towards heterogeneous sensor networks can be recognized which is driven by the large number of applications with different QoS requirements [1], e.g. light and temperature sensing for autonomous home networks, structural health monitoring of stressed components or multimedia applications. Thus, nodes in such wireless networks typically consist of heterogeneous hardware which suits the requirements of the target application in terms of computational power, memory, and energy constraints.

Dense wireless networks with high utilization or correlated traffic represent a challenging environment for random access MAC protocols due to the shared characteristic of the medium. The fact that nodes cannot send and receive at the same time limits the number of strategies which can be applied to achieve a reliable priority based access. For this reason, carrier sense multiple access with collision resolution, as used by the Controller Area Network (CAN), is not an option. TDMA protocols can solve the problem of priority based access. However, they require time synchronization which represents another complex

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task. As a consequence of the heterogeneous hardware TDMA protocols have to deal with communication issues such as different transmission ranges, clock drift, and unreliable links and sleep schedule of energy constraint nodes.

It has been shown that carrier-sense based MAC protocols require additional mechanisms in order to solve the problem of contention resolution [8] and QoS support [1]. Therefore, we decided to follow a new approach [9] which is based on the transmission of preambles which cover the function of reservation signals and contention resolution. Existing MAC protocols, like the Low Power Listening (LPL) [12] and XMAC [13], only use the preamble transmission to make sure that the destination is listening to the channel. An exception is represented by the PR-MAC protocol [6] which uses preamble transmissions for channel reservation, but still requires carrier-sense based backoff mechanisms for contention resolution. However, no one has yet used the transmission of preambles in the wireless domain to schedule the medium access. In this work, we extend our previous approach and show that the transmission of consecutive preambles can be used to solve contention on the radio channel while providing priority based medium access.

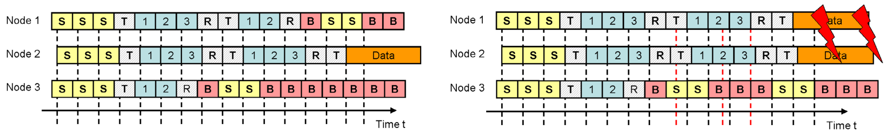
This paper is organized as follows. A brief description of the BPS-MAC protocol, which represents the basis framework for our approach, is given in Section 2. Furthermore, we outline how static and dynamic QoS strategies can be integrated in the protocol to suit the requirements of different target applications in terms of fairness and delay. In Section 3, we propose different QoS strategies and describe how to integrate them into our approach. The performance of the different strategies in the context of challenging scenarios is discussed in Section 4. Finally, we draw our conclusion in Section 5.

2 BPS-Mac

The introduced approach is based on the BPS-MAC protocol [3] which was originally designed to overcome the hardware limitations of low-power transceivers, namely the Clear Channel Assessment (CCA) delay and the rx-tx switching time. In dense WSNs with event-driven data traffic, typical Carrier Sense Multiple Access (CSMA) based protocols cannot achieve high performance since nodes are not able to reliably detect the transmission of other nodes if the transmission has started within duration that is shorter than the CCA delay [7][11]. Thus, the CCA delay represents a critical time-period which has to be taken into account when applying CSMA based protocols. Recall, that state-of-the-art low-power transceivers, like the CC2400 and the CC2520 from Texas Instruments or ATMEL´s AT86RF231, require 128μs to sense the medium. Therefore, high fractions of lost packets in dense WSNs result from the limited sensing capabilities. However, it is obvious that this fraction strongly depends on the node density, the traffic load and the traffic pattern. First, a brief description of the BPS-MAC protocol is given before we introduce our QoS-aware medium access extension.

2.1 Protocol Description

The BPS-MAC protocol has been introduced in [3]. It applies a preamble based medium access procedure which is not directly affected by the channel sensing capabilities of the transceiver. The protocol uses the transmission of preambles with variable length to schedule medium access. The preamble covers the function of a reservation signal in order to notify other nodes that there is a competition for the medium access. The node which sends the longest preamble gains access to the medium. Competing nodes switch there transceiver to receive mode after they have transmitted their preamble. If they detect an occupied channel, they assume that other nodes are still competing for the access which means that they have lost the competition and thus have to postpone their medium access. However, the problem of CCA delay is not yet solved since two nodes can still start their transmission at the same time. For this reason, the duration of the preamble has to be a multiple of the CCA delay in order to distinguish preambles of different length. BPS-MAC defines the term slot for duration which corresponds to the CCA delay since it is more related to the context of contention resolution. A collision can still occur if two or more nodes start their preamble transmission at the same time and choose the same preamble length. As a consequence, the nodes would start their data transmission synchronously due to the fact that they would sense an idle channel after their preamble transmission. A longer maximum preamble length in terms of slots results in a lower packet loss since the probability decreases that two nodes choose the same number of slots. The collision probability can even be further decreased if multiple short preambles are transmitted since a collision only occurs in the unlikely event that competing nodes start their preamble transmission within duration shorter than the CCA delay and choose the same number of slots in every sequence, as shown in Figure 1(a). A detailed description of the sequential contention resolution of the protocol can be found in [3].



(a) Synchronous Access (b) Collision Example

Fig. 1. Sequential Contention Resolution

2.2 QoS Extension of the BPS-MAC Protocol

QoS strategies can be applied in many ways to meet the requirements of the target application [2]. However, even the best QoS-support mechanism is affected by the unpredictable nature of the wireless links. No strategy can provide a "'one-size-for-all"' solution since the mechanisms either focus on delay-bounded and reliable data delivery or on fairness. The QoS strategies that are introduced in

Section 3 were selected with respect to this trade-off in terms of fairness and priority based medium access.

The BPS-MAC protocol uses two or more preamble sequences to resolve the contention on the channel. A node assumes to have control of the radio channel if it senses an idle medium after the transmission of its own preamble. Thus, the node with the longest preamble in every sequence gets access to the medium. Instead of using all preamble sequences for contention resolution, we encode the priority of the medium access on the duration of the first preamble. The first preamble covers the function of a priority indicator while the consecutive preambles are used to resolve contention among nodes with the same priority. The modification of the length of the first preamble is the simplest way to provide priority based medium access and can be used to integrate various strategies.

The number of preamble sequences and their length can be freely configured to achieve the desired reliability and medium access delay. Simulations and first testbed results have shown that three to four preamble sequences, each having duration of four slots, represents the best trade-off for most scenarios. In this work, we focus on protocol configurations with three preamble sequences where the first sequence reflects the priority while the two following sequences are used for contention resolution.

Static Medium Access Priority

Priority based medium access strategies can be divided into two groups. The first group is represented by static priorities, e.g. priority for a certain traffic type or network. The advantage of static priorities is that the behavior of the network is more predictable since the node with the highest priority is able to access the medium immediately in case of a free radio channel or after the current transmission if the channel is busy. Thus, it is even possible to calculate medium access delay boundaries for the node with the highest priority if the longest preamble duration and maximum packet length are known. However, we recommend to assign static priorities to groups rather than individual nodes due to the fact that the number of preamble slots should be as small as possible in order to minimize the protocol overhead and medium access delay. Moreover, group based priority assignment can improve the collective QoS [2] in terms of collective latency, collective packet loss, and information throughput.

Dynamic Medium Access Priority

Dynamic priority strategies are based on changing conditions, e.g. remaining energy, waiting queue length, data rate, buffer level, and distance to the root or number of neighbors. They typically result in a more complex network behavior which requires a detailed understanding of the encoded priority metric. Basically, dynamic access strategies are used to balance or shift the load in the network or to guarantee fair medium access. Metrics which consider the traffic load and buffer level of nodes are of particular interest in WSNs since nodes are very limited in terms of energy and memory.

3 QoS Strategies

QoS in WSNs represents a challenging issue due to unreliable links and time varying channel conditions [10]. Moreover, many established QoS-support mechanisms, like IntServ [4] and DiffServ [5], can hardly be applied in the context of WSNs since nodes have severe resource constraints in terms of computational power, memory and bandwidth. For these reasons, the proposed QoS strategy should be as simple as possible while meeting the requirements of the target applications. In the following, we introduce different scenarios where priority-based medium access can significantly improve the network performance.

3.1 Topology-Aware

Typical WSNs consist of two types of nodes: few powerful nodes with little energy constraints form a backbone for many smaller and more constraint devices. However, the backbone nodes and their smaller and less powerful counterparts access the shared medium and therefore compete for medium access. Thus, mechanisms should be employed to prioritize the medium access for backbone nodes in order to improve the overall network performance. By assigning a high priority to the backbone nodes, the medium access delay of these nodes is reduced and the delivery ratio is increased since the number of nodes with high access priority is very small. Furthermore, this strategy gives the backbone nodes control of the medium access which improves the support for data aggregation mechanisms.

3.2 Network-Aware

The self-organizing capability of WSNs have made the technology an attractive solution for monitoring tasks since nodes can be randomly placed in a field or in areas which are or become hardly accessible, e.g. due to radioactive contamination. In some scenarios, nodes cannot be replaced or removed which represents a problem due to the shared characteristic of the medium. In addition, asymmetric links or partitioning of the network can make reprogramming or remote shut down of the nodes impossible. This can limit the performance of later deployed networks which operate on the same radio channel, especially if nodes frequently transmit data until their batteries are drained. A priority based medium access strategy which employs network IDs can mitigate the problem of co-existing networks. Network IDs can be used to represent the medium access priority of the WSNs: a higher ID corresponds to a higher access priority and vice versa. One the one hand, this strategy allows the deployment of a new high priority WSNs on top of an already deployed sensor network, which could not be removed or shut down. On the other hand, a new low priority WSN can be placed within the area of another sensor network without having a large impact on the performance of the already deployed network.

3.3 Traffic-Aware

More and more sensor networks perform different tasks at the same time. Traffic-awareness within the MAC protocol is required if the tasks have different priorities. Assume a WSN in which nodes generate traffic with different priorities, e.g. the stress and strain measurements of a structural health monitoring application, which has high QoS requirements, and temperature measurements which can be transmitted as best effort traffic. Thus, the traffic of the structural health monitoring application should have a higher medium access priority than that of the temperature application.

3.4 Service-Aware

Virtualization of networks and services has become very popular in recent years. The first implementations for sensor networks are already available [14]. They allow several users to access the nodes and their sensors in a shared manner. Resource allocation for each user, e.g. computational power, memory, sensors, is not a challenging issue in general, since it represents a well investigated field of research. However, as soon as the medium access has to be taken into account, the consideration of user priorities becomes a challenging task. The scheduling of packets at a single node can be easily done by applying pre-defined user priorities. Nevertheless, the best scheduling is useless if a node does not get access to the medium in order to transmit the queued packets. Therefore, the MAC protocol should be able to consider the user priority for the medium access.

3.5 Distance-Aware

Measured data is typically transmitted to a small number of data sinks in the WSN which evaluate and process the data or simply function as a gateway. The topology of these networks is often arranged in a tree structure [15]. Such a tree topology allows taking advantage from data aggregation and data processing mechanisms. However, medium access plays a critical role in this task due to the fact that the traffic load increases towards data sinks. A priority based medium access procedure which takes the distance to the sink into account can support the data aggregation mechanisms and decrease the energy consumption of the sensing nodes. If nodes that are closer to the sink have a higher priority, the delay in event-based WSNs can be reduced since the node which is triggered by the event and is closest to the sink has the highest priority. Thus, it can immediately access the medium to transmit its data. Furthermore, the priority of the transmitted packets further increases on the path towards the sink, which results in a low delay. If energy consumption is the major constraint, rather than high delay, a medium access strategy should be preferred which gives nodes further away from the sink a higher priority than nodes closer to the sink. This medium access strategy reduces the energy consumption since nodes that are furthest away from the sink can transmit their data immediately and turn off their transceiver at the end of the transmission. Furthermore, it improves the potential of data aggregation due to the fact that all children of a node in the tree have a higher medium access priority than their parent. As a result, the children can transmit their data to the parent before the parent gains access to the media in order to forward the data.

3.6 Energy-Aware

Wireless sensor nodes have very limited power supplies. Therefore, designers of communication protocols try to minimize the energy consumption as much as possible while meeting the requirements of the target application. Routing protocols, which take energy consumption into account, typically try not to forward traffic via nodes that have only a small amount of energy left. Such mechanisms have proven to balance the traffic load and to prolong the lifetime of WSNs. However, the access to the medium can become costly as well in terms of energy if a node requires several attempts. For this reason, nodes which run low on power should have a high medium access priority in order to reduce the average number of access attempts.

3.7 Buffer-Aware

The limited amount of memory of wireless sensor nodes becomes a serious problem if the nodes should be able to support the Internet Protocol (IP). Especially, fragmentation of data packets and forwarding of packets leads to high memory consumption. It has to be kept in mind that most sensor nodes, e.g. TelosB, T-Mote and Mica, only have 8KB or 10KB of ram which makes buffering of multiple large packets almost impossible. Furthermore, the event-driven traffic patterns in WSNs lead to temporary high network load. Routing protocols with load-balancing support can mitigate the impact of this issue in multi-hop networks. However, the MAC protocol can further improve the performance by taking the length of the waiting queue into account. Thus, nodes that have more packets stored in their waiting queue should have a higher medium access priority. As a consequence, the maximum waiting queue length and the percentage of dropped packets due to buffer overflows could be decreased. This strategy also improves the fairness in dense single hop networks provided that the nodes generate traffic at the same data rate.

3.8 Data-Rate Aware

The latest generation of routing protocols for WSNs, e.g. the Collection Tree Protocol (CTP) [15], apply adaptive mechanisms to cope with frequent topology changes. In general, these protocols increase their beacon transmission rate if they detect changes in their neighborhood. Topology changes usually result from interference or mobility of the nodes. The latter may lead to frequent topology changes which significantly increase the routing overhead. In dense networks, the routing overhead can even result in temporary congestion of the network. Temporary congestion can also be caused by applications which generate event-driven traffic, e.g. intruder detection or structural health monitoring applications. For these kinds of applications, it is important to receive information from all nodes which have detected the event to gain more precise information and to minimize false positives. The priority of the medium access should depend on the transmission rate of the nodes. A fair medium access can be achieved if a higher transmission rate results in a lower access priority and vice versa. Thus, nodes which rarely transmit traffic have a high probability of gaining access to the medium immediately. However, nodes that frequently transmit traffic can utilize the whole bandwidth as long as no other nodes need access to the medium.

3.9 Combined Strategy

Depending on the target scenario and application, a combined strategy could further improve the performance, e.g. a combination of a traffic-aware and buffer-aware strategy. Such a strategy would represent a trade-off between delay of high priority packets and packet loss of packets due to buffer overflows.

4 Performance Evaluation

In this section, we take a closer look on the performance of a static and a dynamic priority QoS strategy in terms of delay. Furthermore, we compare their performance with the standard BPS-MAC protocol as defined in [3]. The majority of sensor networks uses the IEEE 802.15.4 standard since it is supported by almost every state-of-the-art transceiver. Therefore, we decided to compare its performance with our approach even though the protocol does not support QoS.

The performance of MAC protocols is mainly affected by the number of competing nodes, traffic pattern, and utilization of the medium and characteristics of the radio channel. Especially, asymmetric links and non-circular transmission and/or interference range have to be taken into account. These issues do not allow reproducibility of measurements in multi-hop wireless sensor testbeds. Thus, we decided to evaluate the performance of the strategies and protocols in a controlled single hop simulation scenario instead of employing them on real sensor nodes to avoid distortion caused by interference or other side effects.

We focus on the default configuration of the BPS-MAC protocol and IEEE 802.15.4 standard since most users deploy the sensor nodes without modifying the configuration of the link layer. The results of IEEE 802.15.4 standard are marked with the 'CSMA' tag. The BPS-MAC protocol uses three backoff preamble sequences. Each sequence has a maximum length of four slots. The graphs marked with the 'NONE' tag represent the performance of the standard protocol without any modification. The only difference between the standard protocol and our approach is represented by the way nodes chose the length of the first preamble sequence. The static priority QoS strategy, which is marked with the 'TRAFFIC' tag, uses fix preamble length of four slots for high priority traffic and a preamble length of two slots for low priority traffic. The length of the consecutive preambles is chosen as specified in the standard protocol. The dynamic QoS strategy, which is marked by the 'WQL' tag, takes the fill level of the buffer into account to determine the length of the first preamble. A preamble length of one slot is used if the buffer fill state is below 25%. A fill state between 25% and 50% results in a two slot preamble while a fill stat between 50% and 75% is represented by preamble duration of three slots. The maximum preamble duration of four slots is used if the buffer fill state exceeds 75%. We set the maximum buffer size to 16 packets. Thus, the buffer thresholds correspond to a fill state of 4, 8 and 12 packets.

The OPNET Modeler network simulator is used to simulate the performance of the protocols. However, we use a self-developed wireless sensor framework 3 which considers hardware limitations of low-power transceivers such as CCA delay. A CCA delay of $128\mu s$ is applied to reflect the limited sensing capabilities of the sensor hardware. The data rate is set to 256 kb/s. The simulated scenario should include all aspects of typical WSNs, e.g. event-driven traffic with high priority and periodic traffic with low priority. For this reason, we simulate two different kinds of traffic pattern which are shown in Table 1. The first pattern is used to simulate event-driven traffic, e.g. stress and strain measurements. This burst-like pattern is triggered approximately every 10 seconds. It generates packets every 20 milliseconds with a packet size of 1024 bit for duration of 2 seconds resulting in 100 packets per burst. Thus, the average data rate of this pattern is 10 kb/s while its peak rate is 50 kb/s. The second traffic pattern is used to reflect periodic tasks, like temperature or humidity measurements. Nodes, applying this traffic pattern, generate one packet with a size of 1024 bit approximately every second. Both traffic patterns start with a uniform distributed offset between 0 and 1 second to avoid exact synchronization. For the same reason, the burst inter-arrival time of the first pattern and the packet inter-arrival time of the second pattern are also chosen according to a uniform distribution. The simulated scenario consists of two nodes which generate traffic according the burst traffic pattern. The number of nodes, which generate traffic according to the single traffic pattern, is increased from 10 to 100 in steps of 10 nodes to simulate the performance of the different protocols and QoS strategies under different traffic load. The simulation results represent the average from 30 simulation runs with duration of 1100 seconds. Statistics are collected after 100 seconds to avoid the transient phase. Due to the low variance of the simulation results, we use the average instead of error bars.

In order to evaluate the performance of our approach, we take a closer look on the delay of the periodic and the burst traffic. The nodes which generate traffic according to the periodic traffic pattern are in the following referred to as low traffic nodes while their counterparts are referred to as high traffic nodes. Figure 2 shows the average delay of the periodic traffic depending on the number of low traffic users. The results point out a slight delay increase of the delay for the non-modified BPS-MAC protocol as well as for the WQL strategy and the IEEE 802.15.4 standard. The increase is the consequence of the higher traffic load due to the higher number of low traffic users. Moreover, the increase of delay is on a comparable level which indicates that the network is not congested. However, the average delay of the periodic traffic in the TRAFFIC scenario shows a significant increase which results from the fact that the periodic traffic is assigned a low priority. As a consequence, transmissions of high traffic nodes use a longer preamble which prevents the medium access of the low traffic nodes. Thus, the periodic traffic is delayed while the delay of the burst traffic is kept

Table 1. Traffic Pattern

Pattern Name	Parameter	Distribution	Range / Values
Burst	Burst IAT	uniform	[9.9; 10.1] s
	Packets per Burst	constant	100
	Packet IAT	constant	0.02 s
	Packet Size	constant	1024 bit
	Number of Sources	-	2
	Offset	uniform	[0; 1] s
Single	Packet IAT	uniform	[0.9; 1.1] s
	Packet Size	constant	1024 bit
	Number of Sources	-	[10;20;30;40;50; 60;70;80;90;100]
	Offset	uniform	[0; 1] s

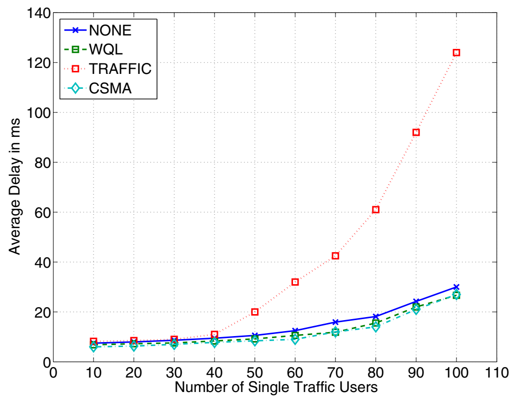


Fig. 2. Delay of periodic traffic depending on the employed QoS strategy

at a minimum, as shown in Figure 3. Only a slight delay increase of the burst traffic can be recognized for the TRAFFIC QoS solution if the number of low traffic nodes increases. The increase results from the fact that it becomes more likely that the medium is already occupied. Thus, the high traffic nodes have to wait until the medium becomes idle in order to transmit their first preamble. The graph of the IEEE 802.15.4 standard points out that the CSMA-based protocols only provide a good performance up to a certain utilization of the radio channel. A high utilization often leads to idle periods since the backoff duration is doubled if a busy medium was sensed. The standard BPS-MAC protocol achieves a better performance than the IEEE 802.15.4 standard, but has a much higher delay compared to the TRAFFIC QoS strategy. In addition, the variance of the delay of the standard BPS-MAC protocol can lead to rare buffer overflows in this scenario which affects the overall delay as a result of the lower traffic load. The WQL QoS strategy shows a high performance up to 70 low traffic users before a significant increase of the delay can be recognized. The

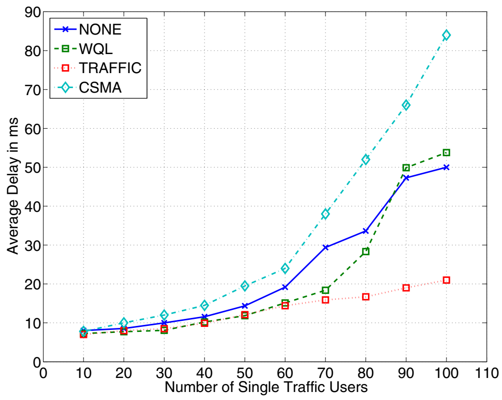


Fig. 3. Delay of burst traffic depending on the employed QoS strategy

dynamic medium access priority of the WQL QoS approach is the only simulated solution which minimizes the delay of the low and high traffic. Therefore, it represents an optimal choice for scenarios which require fair medium access.

5 Conclusion

In this work, we introduced a new comprehensive approach for priority-based medium access with QoS support for WSNs. The approach offers a high level of flexibility to suit the requirements of a wide range of target applications. It uses the transmission of short preambles to indicate the priority of a transmission and to resolve contention on the radio channel.

We implemented a static and a dynamic medium access strategy with our approach and compared their performance with the standard BPS-MAC protocol and the IEEE 802.15.4 standard in a one hop scenario with periodic and event-driven traffic. Our results have shown that our approach can be used to minimize delay and buffer utilization, e.g. by employing a dynamic QoS strategy which takes the buffer fill state into account. Moreover, static medium access priorities can be used to minimize the delay of a certain traffic type or to deploy a high priority network on top of an existing network.

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