Quality of Service for IEEE 802.15.4-based Wireless Body Sensor Networks

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Abstract—**We present a novel mechanism intended to provide Quality of Service (QoS) for IEEE 802.15.4-based Wireless Body Sensor Networks (WBSN) used for pervasive healthcare applications. The mechanism was implemented and validated on the AquisGrain WBSN platform. Our results show that the QoS performance of the IEEE 802.15.4 standard can be considerably improved in terms of reliability and timeliness for intra-node as well as inter-node scenarios while keeping backward compatibility to ensure interoperability.**

Keywords-QoS, IEEE 802.15.4, Wireless Body Sensor Networks, Reliability, Timeliness

I. Introduction

Wireless body sensor networks especially those based on the IEEE 802.15.4 wireless PAN standard [1] appear as a very useful technology for a huge amount of pervasive healthcare applications [8] where traditional wireless networks do not provide a suitable solution. Despite the great potential of IEEE 802.15.4 for meeting the requirements of various WBSN applications, the current specification lacks QoS mechanisms that are required for time-sensitive applications.

In many WBSN applications different data packets may have different importance depending on the information they contain. For example an alarm message should have priority over a packet with non-critical sensor readings. Unfortunately, IEEE 802.15.4 treats all packets in the same way. Therefore, it is essential -in particular for medical applications- to introduce a mechanism for traffic prioritization to privilege important over less important packets.

The IEEE 802.15.4 standard allows the use of the Guaranteed Time Slot (GTS) mechanism [1] as a solution for applications with strict timing requirements. However, the GTS mechanism presents several limitations due to the fact that it can only be used in beacon-enabled network, and only for the data transmission between a device and its network coordinator. Besides these drawbacks, it faces severe coexistence problems since other wireless networks (regardless of based on IEEE 802.15.4 or other technologies such as Bluetooth or WLAN) operating in the same channel are agnostic of the time slot allocations made by an IEEE 802.15.4 coordinator and as a consequence ignore them. This turns the GTS approach into being worthless in the presence of interference.

In this paper we introduce some QoS concepts that could be integrated to the IEEE 802.15.4 MAC layer with relatively minor changes, so that backward compatibility could be preserved. We define as the core of the proposed QoS enhancements a packet differentiation mechanism as well as the metrics used to provide a differentiated treatment for packets according to their priorities. We evaluate the performance of the QoS improvements on the Philips AquisGrain platform [6] featuring the IEEE 802.15.4 compliant radio transceiver CC2420 [7] from Texas Instruments (TI). The results show that it is possible to provide a certain degree of QoS over the IEEE 802.15.4 standard with regard to both timeliness and reliability, although further research in this area is still necessary.

The paper is organized as follows: Section II presents the state of the art in providing QoS for WSN with particular focus on those based on the IEEE 802.15.4 standard. Section III presents the concepts we propose to enhance the IEEE 802.15.4 MAC layer in order to achieve QoS. Section IV describes briefly the main aspects related to the implementation of our concepts. Section V presents the results of the performance evaluation. Finally, section VI concludes the paper.

II. Related Work

Some recent research efforts have been conducted in order to improve the performance of the CSMA/CA MAC mechanisms of the IEEE 802.15.4 standard. Particular emphasis has been placed on improving the slotted CSMA/CA mechanism to provide a better performance with regard to latency and reliability.

In [2] the authors modified the CSMA/CA algorithm to enable fast delivery of high priority frames using a priority toning strategy. In this approach tone signals are used to alert other nodes to defer their transmission for a certain amount of time, in order to privilege the transmission of high priority frames at the beginning of the contention access period. Although the responsiveness of high priority frames is being improved, this approach requires significant changes to the IEEE 802.15.4 MAC protocol, making this approach incompatible with the standard.

In [3] a new mechanism is proposed to dynamically adjust the size of the contention window. The results show that the performance of the standard IEEE 802.15.4 could be improved; however no special considerations have been taken in terms of reliability, making it a partial solution only for QoS provisioning.

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[4] Introduces the concept of service differentiation for the slotted CSMA/CA. The service differentiation is particularly based on the use of different CSMA/CA parameters for the newly defined service classes. Although the results presented in this approach sounds promising, there are still some drawbacks that must be overcome. In the first place only a differentiation between MAC command frames (high priority) and data frames (low priority) is established, and in consequence all data packets are treated in the same way, no matter of their priority. Also this mechanism present a poor performance for the high priority frames when a FIFO (First-In First-Out) scheduling mechanism is used, especially in loaded channel conditions.

In summary, most of the QoS approaches found in literature focus on improving the QoS characteristics of the slotted CSMA/CA mechanism, so there remains still the need for providing QoS for non-beacon-enabled networks. Also some of these approaches require considerable and incompliant changes to the standard, and in general all the results are solely based on simulations, which mean that the reported performance improvements have to be validated in real life.

III. QoS CONCEPTS

In this section we present some concepts we propose in order to provide QoS for the IEEE 802.15.4 standard. First we introduce the QoS domains where we focus on, and then we present a detailed description of the suggested improvements to the IEEE 802.15.4 MAC layer.

A. *QoS Domains*

The concept of a QoS domain is introduced as a global term that defines the main focus of our work. In order to provide QoS over the IEEE 802.15.4 we turn our attention to the reliability and timeliness domains.

1) *Reliability Domain*

Different sensor data may have different reliability requirements. For pivotal data it is essential that it is delivered to its destination, no matter what effort that requires for the involved nodes of the network. Supporting this is the main objective of the changes we propose within this domain, but always having in mind that the degree of reliability granted to a packet should be in accordance with its priority.

2) *Timeliness Domain*

Sensor data are typically a snap shot of dynamically changing conditions, so that their readings are valid only for a limited period of time. The timeliness domain covers all the changes we propose to the IEEE 802.15.4 MAC layer to ensure an on-time delivery of packets within a network depending on their priority.

B. *Packet Prioritization Concept*

The first step in the provisioning of QoS for IEEE 802.15.4-based WBSN is the definition of a packet prioritization mechanism according to the importance of those packets. Packet prioritization could be performed at the application layer. However, at the MAC level more powerful means are available for implementing packet prioritization. The idea is to provide a differentiated treatment of packets according to their priority indicated to the MAC layer by an upper layer of the stack. In this sense we introduce a PacketPriority parameter that can take eight different values as shown in Table I: PP1 to PP7 to define the different grades of packet priority, and PP0 to allow devices the use of the standard IEEE 802.15.4 MAC mechanism.

TABLE I. PACKET PRIORITY PARAMETERS

Packet Priority parameter	Data priority description
PP7	Highest
PP6	High-3
PP5	High-2
PP4	High-1
PP3	Low-2
PP2	Low-1
PP1	Lowest
PP0	No QoS mechanism

In order to enable applications to convey the priority of a packet to the MAC layer, we propose to introduce a new argument PacketPriority to the IEEE 802.15.4 packet transmission primitive, as illustrated in Fig. 1.

```
MCPS-QoS-Data.request(SrcAddrMode, SrcPANId,
                      SrcAddr, DstAddrMode, DstPANId,
                      DstAddr, msduLength, msduHandle,
                      TxOptions, PacketPriority)
```

Figure 1. QoS-aware packet transmission primitive

This mechanism allows the differentiated treatment of packets depending on their priority within a node (intra-node QoS provisioning). To make also the other nodes in the network aware of the priority of a packet, we propose the use of some reserved bits of the MAC header frame control field to indicate the packet priority, as depicted in Fig. 2.

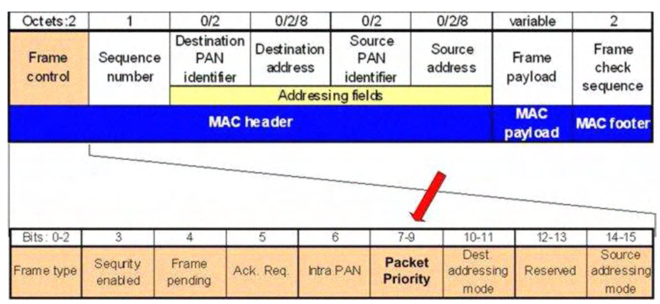

Figure 2. QoS-aware frame control bits in IEEE 802.15.4 MAC header

Due to resource constrains, it is not feasible to maintain a transmission queue for any of the seven possible PacketPriority values presented above. Therefore, we propose to map these values (received from an upper layer) to four different AccessCategory parameters used within the MAC layer to treat packets accordingly to their priority. The mapping scheme is summarized in Table II.

TABLE II. MAPPING BETWEEN PACKETPRIORITY AND ACCESSCATEGORY

Packet Priority (PP)	*Access Category* (AC)
PP7	AC3
PP6 / PP5 / PP4	AC2
PP3 / PP2	AC1
PP1	AC0

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Please note that within each access category the PacketPriority parameter can still be used for differentiation of packets belonging to the same queue.

Enabling applications to make the MAC layer aware of the priority of packets and providing a means for nodes to signal the priority of a packet to the other nodes of the network form the foundation for the reliability and timeliness improvements proposed and presented in the following sections.

C. *Reliability Domain Improvements*

The reliability domain improvements we propose are based on the acknowledgment mechanism already established in the IEEE 802.15.4 standard. However, we enhance this mechanism by applying acknowledgement settings on a per packet basis depending on its AccessCategory parameter. This means that instead of treating all packets in a uniform way, a higher degree of reliability is provided for high priority packets while lower priority packets receive a lower reliability assurance.

This approach implies that different CSMA/CA parameters like the "maximum number of retransmissions" are different for every packet according to its priority. The set of four different values used at MAC layer to provide a differentiated degree of reliability to packets of different priorities is shown in Table III, where the parameter macMaxFrameRetries represent the maximum number of retries allowed after a transmission failure.

TABLE III. RELIABILITY PARAMETERS BY ACCESSCATEGORY

Access Category	**macMaxFrameRetries**
AC3	5
AC2	4
AC1	3
AC0	1
802.15.4 (default)	3

It is clear from the table above, that the probability of a successful delivery is higher for high priority packets (those in high access categories), than for low priority packets. In consequence, the degree of reliability is higher for high priority packets, and gradually decreased to the extent to which the priority of the packet is lower.

D. *Timeliness Domain Imrpovements*

For taking the timing requirements of different data packets into account, the way how they are scheduled for transmission is of crucial importance. Since in the current version of the IEEE 802.15.4 standard a FIFO mechanism is used, a different scheduling mechanism is required in order to incorporate the packet prioritization mechanism presented before. In order to provide QoS, we propose a new QoS-aware MAC scheduler inspired by the IEEE 802.11e enhancements [5], which is illustrated in Fig. 3.

It is important to highlight the three main components of the new scheduler. In the first place we have introduced a mapping function between the PacketPriority parameter received from an upper layer and the AccessCategory parameter used at the MAC layer. This parameter determines in which transmission queue a packet is put, which is the second main module of the priority-aware scheduler.

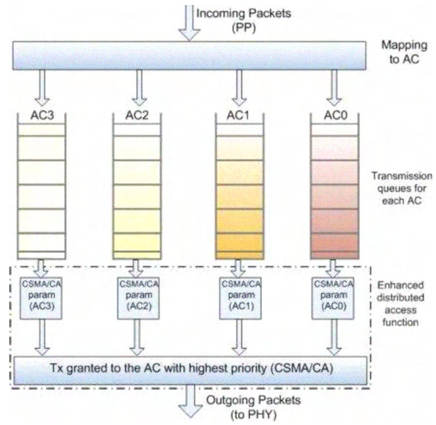

Figure 3. QoS-aware MAC scheduler

Finally we introduce an Enhanced Distributed Access Function which is in control of the channel contention process of the packets in each of the four transmission queues. The fact that we are using a new scheduler implies that we had to modify the CSMA/CA algorithm, as indicated by the red (dark) blocks in Fig. 4 for the unslotted CSMA/CA case.

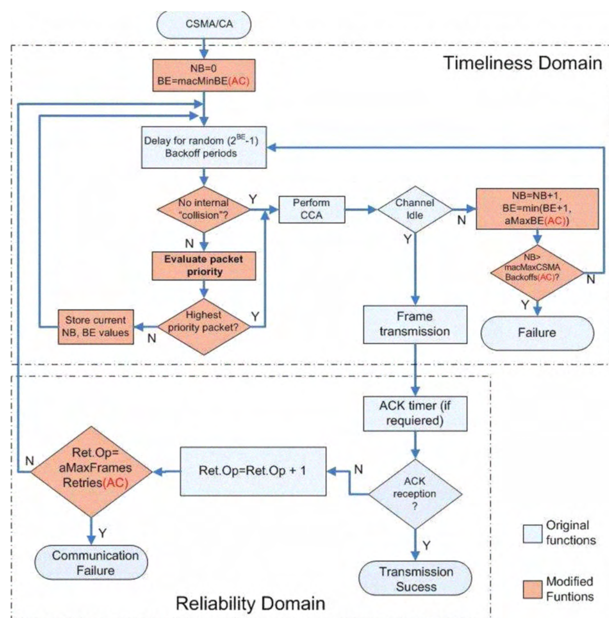

Figure 4. QoS-aware CSMA/CA algorithm

Most of the changes performed allow the algorithm to take the AccessCategory parameter of a packet into account. However, the main change in the algorithm can be observed in the centre of the timeliness domain section. It is in this part of the algorithm where we detect when two or more packets belonging to different transmission queues are trying to access the channel at the same time. The QoS-aware algorithm grants channel access to the highest priority packet while the lowest priority packets will restart the contention process but keeping their current CSMA/CA parameters, in other words, this case is not treated as an external collision. The same changes apply for the slotted version of a QoS-aware CSMA/CA algorithm. The final enhancement we propose in order to provide a differentiated treatment of packets based on priorities is the use of transmission queue specific CSMA/CA parameters. In this way we will guarantee a better timeliness performance for high

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priority packets while it is gradually decreased for lower priority packets. Table IV shows the proposed parameters for the different AccessCategory queues, where macMinBE represents the minimum value of the backoff exponent, macMaxBE means the maximum value of the backoff exponent, and macMaxCSMABackoffs depicts the maximum number of backoffs the CSMA/CA algorithm attempts before declaring a channel access failure.

TABLE IV. TIMELINESS PARAMETERS BY ACCESSCATEGORY

Access Category	macMinBE	macMaxBE	macMaxCSMABackoffs
AC3	1	2	5
AC2	2	3	4
AC1	3	4	3
AC0	5	6	2
802.15.4 (defaults)	3	5	4

IV. IMPLEMENTATION

All concepts described in the previous sections were implemented and validated on the IEEE 802.15.4 compliant Philips AquisGrain platform designed for low power applications and mesh networking [6].

The AquisGrain platform is based on the IEEE 802.15.4 compliant radio chip CC2420 [7] from TI controlled by the Atmel Atmega 128 MCU with 120 KB ROM and 4 KB RAM. In order to implement the proposed QoS concepts, we modified and enhanced the IEEE 802.15.4 MAC layer software licensed from TI.

Some software modules were modified and some others were added, not only to implement the proposed QoS concepts, but also to implement all the required applications (in the nodes and at the PC side) necessary to collect all data related with measuring the performance of the QoS mechanisms.

The implementation was performed in such a way that only a minimum amount of additional physical resources was necessary. Despite we introduced conceptually four different transmission queues our implementation actually maps them onto a single physical queue. As a result solely the scheduler demands some extra processing from the MCU to control the concurrent channel access contention process for packets with different priorities. Fig. 5 shows that following this approach only a modest increase of RAM and ROM is required by our QoS-aware MAC implementation.

Finally we deployed the QoS-enhanced MAC layer version on several AquisGrain nodes to validate the performance and benchmarked it against AquisGrain nodes operating with the standard IEEE 802.15.4 MAC software.

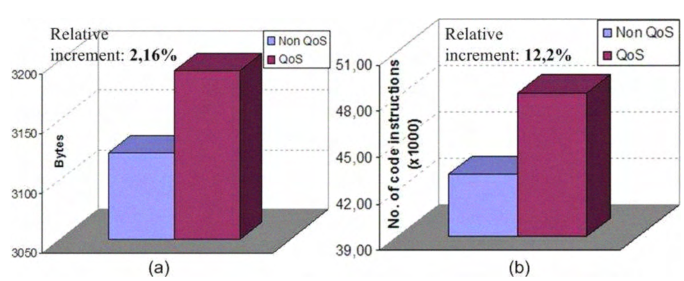

Figure 5. (a) RAM size increment (b) ROM size increment

V. PERFORMANCE ANALYSIS

A. Timeliness Performance

In this section we present the results obtained from a set of experiments we conducted with IEEE 802.15.4 networks composed of devices with and without our QoS extensions. We assessed the real life characteristics and performance of the proposed QoS improvements and compared these results against devices with an implementation of the standard IEEE 802.15.4 MAC layer without QoS as baseline.

1) Intra-node Performance

The tests were performed using five AquisGrain nodes, one node acting as the network coordinator and at the same time as gateway to a PC, three nodes were used to introduce a constant network load of 7 kbits/s each, and one node was used as the control node, from which we gathered detailed statistical performance data, i.e. we measured the maximum packet transmission time as a function of its packet transmission rate. The network scenario used for the tests performed in this section is illustrated in Fig. 6.

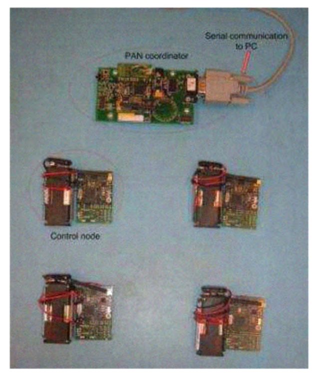

Figure 6. Setup for the perfomance analysis tests

All nodes used the unslotted version of the CSMA/CA algorithm. During the tests, the network load was gradually increased by incrementing the packet transmission rate of our control node. We conducted two different sets of tests, one for a fixed payload size of 40 bytes per packet, and the second one using 80 bytes of payload. Table V shows the load profiles used by the control node for the QoS tests as well as for the non-QoS (i.e. unmodified IEEE 802.15.4) reference test.

TABLE V. LOAD PROFILES OF THE CONTROL NODE

IEEE 802.15.4 with QoS extensions		
Packet Priority (PP)	**Transmission rate (packets/s)**	**Payload size (bytes)**
PP7 (High)	From 2 to 25	40 / 80
PP6 (Medium)	From 2 to 25	40 / 80
PP3 (Low)	From 2 to 25	40 / 80
IEEE 802.15.4 without QoS extensions		
n.a.	From 2 to 25	40 / 80

The maximum observed transmission time of packets belonging to different access categories is shown in Fig. 7 (using 40 bytes as payload) as function of the packet transmission rate of the control node.

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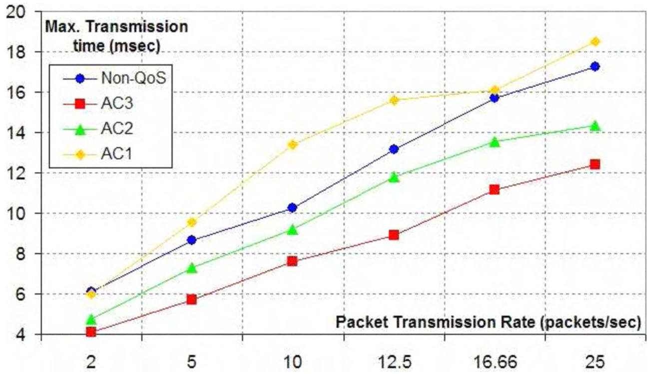

Figure 7. Maximum transmission time vs. packet transmission rate (40 bytes payload)

The measured results clearly show that the packet prioritization mechanism as well as the new QoS-aware scheduler has a significant impact on the timeliness performance of packets depending on their priorities.

The maximum transmission time of a packet directly relates to the time the packet needs to gain the channel access. As intuitively expected using a prioritized scheduling mechanism results in a privileged access to the channel and consequently a lower transmission delay for high priority packets than for low priority packets.

Please note that the access categories AC3 and AC2 show a better performance than the non-QoS reference case while AC1 has a similar one, which means that in terms of timeliness our QoS-aware MAC exhibits a better performance than the standard IEEE 802.15.4 implementation.

2) Inter-node Performance

The previous results show that our QoS mechanisms allow differentiated treatment of packets depending on their priority within a single node of a network. To evaluate the performance of the QoS mechanism in a more realistic situation, we studied the BASUMA telemonitoring scenario for chronically ill patients [8] where different types of medical sensors (such as ECG, oxygen saturation, blood pressure, lung sound monitor) represented in this case by different nodes, are transmitting data with different priorities and at different transmission rates in a single hop network setting

For this we used four different nodes, each one transmitting a mixture of data as shown in Table VI. This experiment allowed us the simulation of a real situation where within a personal area network (PAN), some nodes are constantly transmitting data (and once in a while some highly important data, i.e. alarms) while other nodes transmit data with a different transmission rate and a different priority. In the telemonitoring scenario, this could be the case for a patient with four different sensors attached to her body.

TABLE VI. LOAD GENERATED BY NODES PER ACCESSCATEGORY

Access Category	Node 1 Load (bits/s)	Node 2 Load (bits/s)	Node 3 Load (bits/s)	Node 4 Load (bits/s)
AC3	880	-	1,120	1,120
AC2	880	1,769	-	-
AC1	4,400	9,750	-	-

Although the traffic generated by each node is specific to the BASUMA scenario, it shows effects typical for many real WBSN situations. The results obtained using the QoS-aware MAC layer are shown in Table VII, while the results for the non-QoS reference case are shown in VIII.

TABLE VII. IEEE 802.15.4 WITH QOS INTER-NODE RESULTS

Maximum transmission time (ms)				
Access Category	Node 1	Node 2	Node 3	Node 4
AC3	3.452	-	6.053	6.651
AC2	4.513	6.869	-	-
AC1	11.568	13.115	-	-

TABLE VIII. IEEE 802.15.4 WITHOUT QOS INTER-NODE RESULTS

	Node 1	Node 2	Node 3	Node 4
Maximum transmission time (ms)	9.927	10.884	7.376	7.365

There are several interesting conclusions that can be derived from the results shown in the previous tables. The first aspect we could highlight is the fact that looking into one single node, it can be seen that high priority packets are always preferred over low priority packets, no matter of the different transmission rates of packets with different priorities inside a node.

Table IX presents the time difference between the results obtained for the QoS experiment (Table VII) and the reference non-QoS case (Table VIII). Green (dark) colored cells indicate improved performance; red (clear) colored cells declined performance.

TABLE IX. TIME DIFFERENC BETWEEN IEEE 802.15.4 WITH AND WITHOUT QOS RESULTS

Access Category	Time difference (ms)			
	Node 1	Node 2	Node 3	Node 4
AC3	-6.478	-	-1.327	-0.719
AC2	-5.417	-4.011	-	-
AC1	1.638	2.235	-	-

The table above helps us to explain some observations related with the inter-node performance of our QoS mechanisms. In general the performance of AC3 and AC2 is better than the non-QoS case (green/dark blocks). The time differences are negative; meaning that the transmission time for packets in AC3 and AC2 were lower than in the non-QoS case. On the other hand, AC1 presents a performance slightly worse than in the non-QoS case (red/clear blocks). That is the price we have to pay for the improved performance of the higher priority access category queues.

Another interesting conclusion can be derived when analyzing the performance of one AC but in different nodes of the network. It can be observed how some nodes present a better performance than other nodes of the network for the same AC, i.e. compare the performance of AC3 for Node 1, Node 3 and Node 4. This result shows that the network load as well as the characteristics of the load a node is transmitting have an effect on the performance of the QoS mechanism.

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However, when comparing the results obtained for all nodes in the network for the different ACs, we can observe that there is a node-local prioritization of the data transmitted, since in general terms all data transmitted in AC3 is granted a better performance than the data transmitted in AC2, and these two ACs show a better performance than AC1, no matter of the transmitting node. This result implies that allowing different nodes of a network to transmit data in one specific AC, different from other nodes, could establish a node-based prioritization mechanism inside the network.

The previous results also let us conclude that a packet would receive a similar treatment based on its priority while flowing through a multi-hop network. This means that the reserved bits of the MAC header we used to indicate the priority of a packet to the other nodes of a network are an effective means. In general the behavior of our QoS-aware nodes is the same for all packets with the same priority within a network, which is the ultimate objective of the QoS provisioning in an inter-node scenario.

B. Reliability Performance

In this section we explore the performance of our QoS mechanisms from a reliability point of view in front of different network load conditions. In this case the scenario used to perform the experiments was different than the scenario presented in Fig. 6.

For these experiments we used two different networks operating in the same channel. One network was used to study the reliability performance of the control node, while the other network was used to control the amount of background traffic on the channel. For this test setup, the load generated by our control node remained constant, while the channel background traffic was varied for each set of experiments.

Fig. 8 (left) shows the results measured for our control node while sending packets with different access categories at 28 kbits/s, and facing a channel load of 19 kbits/s, which sums up to a total network load of 47 kbits/s. The results are compared against the non-QoS reference case performed under the same conditions. For a higher aggregated network load (88 kbits/s), the results we obtained are shown in Fig. 8 (right).

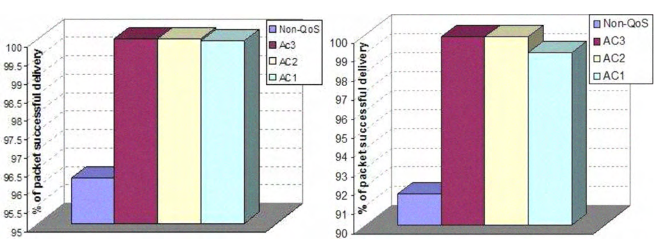

Figure 8. Packet delivery rate @19% (left) and 35% (right) network load utilization respectively

We observe that although in a higher loaded network more packets get lost, the proposed QoS mechanisms show a better performance than the standard IEEE 802.15.4 MAC implementation. We assume that the modifications of the CSMA/CA algorithm result in a higher channel utilization.

The QoS mechanisms we have proposed increase the reliability performance of the IEEE 802.15.4 standard, which means that in conjunction with the timelines improvements we can guarantee an on time and secure delivery of packets according to their priority.

VI. CONCLUSIONS

The unreliable nature of wireless communication imposes the need of QoS mechanisms to accomplish the QoS requirements of many applications. In this paper we have described several mechanisms for enhancing the IEEE 802.15.4 standard while keeping backward compatibility. We have also demonstrated that the proposed QoS extensions can be implemented on existing sensor platforms requiring only a small amount of additional memory resources.

It has been shown that using a packet prioritization scheme and a QoS-aware packet scheduler significantly improve the performance of the standard IEEE 802.15.4 MAC in terms of timeliness and reliability, allowing its use for time-critical applications.

We have also validated that our QoS improvements can be used to establish a differentiation among nodes within a network, making possible its use in applications where certain nodes of a network should experience a prioritized access to the channel, without considerably affecting the performance of the remaining nodes of the network.

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