

Optimizing MAC Layer Performance based on a Distributed Queuing Protocol for Wireless Sensor Networks

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Abstract—This paper analyzes the performance of a MAC scheme for low-rate wireless sensor networks that makes use of distributed queues to improve radio channel utilization. Analytical values first for the throughput performance, and later for the energy consumption are derived as a function of the system parameters. The obtained results show that the proposed scheme outperforms IEEE 802.15.4 MAC in terms of maximum stable throughput and overall performance, including energy consumption. These benefits are obtained from eliminating back-off periods and collisions in data packet transmissions while minimizing the control overhead. Our proposal takes advantage of being independent of the number of transmitting sensors in the system providing stability for all traffic scenarios and showing that a reduction of energy consumption compared to IEEE 802.15.4 MAC is still possible.

Index Terms— Distributed queuing, MAC, WSN, Energy-saving, IEEE 802.15.4

I. INTRODUCTION

THE release of IEEE 802.15.4 for Low Rate Wireless Personal Area Networks (LR-WPANs) [1] represents a milestone in wireless sensor networks. It targets low data rate, low power consumption, low cost wireless networking and offers device level wireless connectivity. It is expected to be used in a wide variety of embedded applications, including home automation, industrial sensing, environmental control and medical monitoring. In these applications, numerous embedded devices running on batteries are distributed in an area communicating via wireless radios.

The key concern in these applications is that of extremely low power consumption, since it is often infeasible to replace or recharge batteries for the devices on a regular basis. Medium Access Control (MAC) protocols play a significant role in determining the efficiency of wireless channel bandwidth sharing an energy cost of communication. Therefore, we can say there is a correlation between MAC throughput efficiency and energy consumption. Both are thus major metrics for IEEE 802.15.4 overall performance. The performance evaluation study in [2] reveals some of the essential throughput-energy-delay tradeoffs in the IEEE 802.15.4 MAC. They provide an analysis comparing the

energy costs of beacon and non-beacon modes for synchronization, showing that the optimum choice depends upon the combination of duty cycles and data rates. In [3], a Markov chain model of the 802.15.4 is proposed, where each state is based on the counter values as the 802.11 model in [4]. Both models describe the behaviour of the protocols using the probability that the device is in the channel accessing states. However, in 802.15.4 this probability is not suitable for describing the behaviour because the channel sensing should be performed twice before entering accessing states. In [5], Park et al. propose a new Markov chain model of 802.15.4 and analyse the throughput and energy consumption in saturation conditions. The proposed model utilises the probability of a device in the channel sensing states instead of in the channel accessing states. A similar approach for evaluating the performance of slotted IEEE 802.15.4 was followed by Pollin et al. in [6]. The model and analysis are similar in form to Bianchi's [4], but here the key approximation in their model is the independence of the carrier sensing probability, which determines when nodes become active to listen to the channel.

Both analytical models in [5] and [6] show how the saturation throughput, expressed as the number of slots occupied for a successful packet transmission of size L (ignoring protocol overhead), drastically decreases as the number of sensors in the network increases. Energy consumption per useful bit is also obtained through both of their models, presenting their worst results for a high number of nodes (e.g. 20-40 nodes). It is therefore shown that the IEEE 802.15.4 MAC may jeopardize the deployment of dense wireless sensor networks, not only in terms of throughput, but especially in energy consumption. Thus, the IEEE 802.15.4 MAC performance should be improved, targeting at low power consumption MAC protocols that scale up within dense wireless sensor networks.

Having said that, we present hereby in this paper a MAC protocol based on distributed queues, similar to [7] and family variants [8]-[9], to improve radio channel utilization for particularly dense wireless sensor networks (high number of nodes). The proposed scheme is a distributed always-stable high performance protocol, which behaves as a random access mechanism for low traffic load and switches smoothly and automatically to a reservation scheme when traffic load grows. The key feature of the proposed scheme is that it eliminates collisions and back-off periods in data packet transmissions.

The remaining of the paper is organised as follows. We first present a brief overview of IEEE 802.15.4 in section II and section III is reserved to the related work on Distributed

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Queuing (DQ) MAC protocols. Section IV contains our proposed new frame structure for wireless sensor networks. In section V, we present the throughput analytical evaluation derived from [9], but considering IEEE 802.15.4 standard release [1]. Additionally, to give a complete overview of DQ MAC performance evaluation, some primarily energy results are presented. Finally, section VI concludes the paper.

II. IEEE 802.15.4 OVERVIEW

Similar to all IEEE 802 wireless standards, the IEEE 802.15.4 release standardizes only the physical (PHY) and medium access control (MAC) layers [1].

A. Physical Layer

The IEEE 802.15.4 PHY standard incorporates two physical layers; i) the lower band, 868.0-868.6 MHz (for Europe), plus the 902-928 MHz (for much of the Americas and the Pacific Rim), and ii) the upper band, 2.400-2.485 GHz (substantially worldwide). Both lower and upper bands employ a form of direct sequence spread spectrum (DSSS). In the lower band, binary phase shift keying (BPSK) with raised-cosine pulse shaping is employed. In the 868-MHz band, a data rate of 20 kb/s and a chip rate of 300 kc/s are used, while in the 902-928-MHz band, a data rate of 40 kb/s and a chip rate of 600 kc/s are used. In the upper band, offset quadrature phase shift keying (O-QPSK) with half-sine pulse shaping is employed at a chip rate of 2 Mc/s, along with a 16-ary orthogonal symbol scheme sent at 62.5 ksymbols/s, resulting in a data rate of 250 kb/s.

B. Medium Access Control Layer

In IEEE 802.15.4 networks a central controller, called the Personal Area Network (PAN) coordinator, builds the network in its personal operating space. The standard supports three topologies: star, peer-to-peer and cluster-tree. The star topology communication is established between devices and the PAN coordinator; in the peer-to-peer topology any device can communicate with each other device within its range; and in the cluster-tree topology, most devices can communicate with each other within the cluster, but only some of them may connect to the infrastructure. The standard identifies two channel access mechanisms. Beacon-enabled networks use a slotted Carrier Sense Multiple Access mechanism with Collision Avoidance (CSMA-CA), and the slot boundaries of each device are aligned with the slot boundaries of the PAN coordinator. The communication is then controlled by the PAN coordinator, which transmits regular beacons for device synchronization and network association control. The PAN coordinator defines the start and the end of the superframe by transmitting a periodic beacon. The length of the beacon period and hence the duty cycle of the system can be defined by the user between certain limits as specified in the standard [1]. The advantage of this mode is that the coordinator can communicate at will with all nodes. The disadvantage is that nodes must wake up to receive the beacon. In non-beacon mode a network node can send data to the coordinator at will

using a simpler unslotted CSMA-CA, if required. However, to receive data from the coordinator the node must power up and poll the coordinator. To achieve the required node lifetime the polling frequency must be pre-determined by power reserves and expected data quantity. The advantage of non-beacon mode is that the node's receiver does not have to regularly power-up to receive the beacon. The disadvantage is that the coordinator cannot communicate at will with the node but must wait to be invited by the node to communicate.

III. RELATED WORK ON DISTRIBUTED QUEUING MAC PROTOCOLS

Crucial success of sensor networks is the availability of small, lightweight, low-cost, and above all, energy-saving nodes. The preceding IEEE 802.15.4 medium access protocol may present weaknesses for a high number of nodes in wireless sensor networks, or for some types of sensing applications, where latency and throughput turns out to be important. For that reason, we introduce hereby another family of MAC protocols that could outperform 802.15.4 in the same wireless sensor scenarios.

The Distributed Queuing Random Access Protocol (DQRAP) is a random access protocol based on a queuing system shared among nodes. It was proposed for the first time in 1992 by Xu and Campbell [7]. Starting from a previous protocol called DQDB (Distributed Queuing Dual Bus), they developed the DQRAP protocol for a TDMA environment proposing an analytical model and showing also by means of computer simulations, how the protocol approaches the performance of the theoretical optimum system M/M/1. DQRAP divides the TDMA slot into a "reservation subslot", which is further divided into minislots, and a "data subslot". The basic idea is to concentrate user accesses in the control subslot, while the data subslot is devoted to collision-free data transmission. It provides a collision resolution tree algorithm that results stable for every traffic load even over the system transmission capacity. One of the most interesting features of DQRAP is its capacity to behave like an ALOHA-type protocol for light traffic load and to smoothly switch to a reservation system as the traffic load increases, reducing automatically collisions. An essential property of the DQRAP comes from the distributed queue adoption. Nodes can estimate the system load simply considering the number of busy positions in each queue. The load estimation is important information in a network environment.

Alonso et al. [8] proposed a version of DQRAP adapted for a CDMA environment in 2000. They presented an analytical model of the protocol and validated its performance by computer simulations. They showed how the protocol approaches the performance of the optimum queuing system M/M/K, where K is the number of spreading codes being used. All the features of stability and soft switching from an ALOHA-type system to a reservation system are still present in this version of the protocol. In 2003, based on their previous research works, Alonso et al. [9] presented the Distributed Queuing Collision Avoidance (DQCA), which is a

distributed high-performance medium access protocol designed for Wireless Local Area Networks (WLAN) environments. DQCA presents some main features compared to the legacy IEEE 802.11; i) it eliminates back-off periods and collisions in data packet transmissions, ii) it performs independently of the number of stations transmitting in the system, and iii) it does not suffer from instability under all traffic conditions. Since DQCA [9] presents the aforementioned advantages in front of 802.11 WLAN systems, we would like to further analyze this DQ MAC family in order to prove its performance under new low-rate wireless sensor network scenarios. We will then measure the potential benefits for these type of networks and applications, not only in terms of throughput performance, but also in energy saving and power management.

IV. A DISTRIBUTED QUEUING MECHANISM FOR WIRELESS SENSOR NETWORKS

Herewith we present the new adapted frame structure for wireless sensor networks. We derive from it DQ MAC throughput evaluation performance and energy consumption analysis. Like other DQ family protocols and unlike IEEE 802.15.4, back-off periods and collisions in data packets are eliminated. DQ protocol performance is independent of the number of sensors transmitting in the system and it is stable under all traffic conditions [7]. That is the main reason why these DQ family protocols are high-performance mechanisms, that scale well to networks with a large number of sensors (dense wireless sensor networks). Fig. 1 shows the frame format structure of our adapted proposal for wireless sensor networks, suitable for an evolved 802.15.4 LR-WPAN.

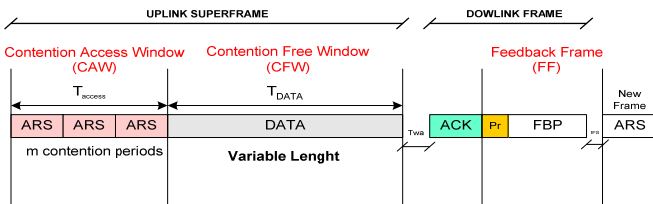


Fig. 1: New power-saving frame format for wireless sensor networks

The whole frame structure comprises an uplink superframe and a downlink frame, seen from the transmitting sensor node perspective. The uplink superframe consists of a Contention Access Window (CAW), with fixed length T_{ACCESS} , divided into m contention periods. Within these contention periods Access Requests Sequences (ARS) are sent to gather a position for transmitting data into the Contention Free Window (CFW) of variable length T_{DATA} . ARS are the minimum signal required for the central sensor to detect channel access. That means, the PHY level only needs to detect three different states (empty, success, collision), but no information bits have to be carried through [11]. The downlink frame starts in the worst case after T_{AW} , which corresponds to the maximum time to wait for an acknowledgment frame to arrive following a transmitted data

frame. T_{AW} is followed by the acknowledgement (ACK) and the feedback packet (FBP), the latter preceded by a preamble (Pr). Pr enables better power management between the CAW and FF (Feedback Frame) for non-transmitting sensors. At the very end of the downlink frame an Inter Frame Space (IFS) is added to allow the MAC layer to process the data received from the PHY.

The main differences of this DQ frame format with respect to the other distributed queuing family protocols (see section III) are firstly that the ACK may contain link quality information, and secondly that a new field is introduced in form of a preamble (Pr) to enable synchronization after turning off the radio chip. Both new aspects turn this DQ MAC scheme into a better power management protocol. That is, the coordinating sensor sends, on the one hand the ACK to a specific transmitting node and broadcasts the FBP to all associated hearing sensors, including the ones that have just awoken and synchronised via the preamble. Additionally, there is now the possibility to transmit data packets of variable length (T_{DATA}), using the same frame structure, at the same time that energy-saving benefits are maintained.

V. PERFORMANCE EVALUATION

We must bear in mind that our performance evaluation is a straightforward application from [9] to a star-base topology scenario in wireless sensor networks, but with an further energy consumption characterization. However, this analysis is also feasible for a peer-to-peer topology, as shown in [10], with a master-slave configuration. In the later, each new master assumes the coordinating role for a period of time and the same evaluation can be performed. The main objective hereby is to analyse the benefits that could be obtained from using this DQ mechanism in a LR-WPAN environment giving an energy saving new approach.

A. Throughput Bounds Calculation

As derived from [7]-[9], the here proposed DQ protocol for wireless sensors networks is able to achieve a maximum stable relative channel usage up to the channel capacity. This is possible whenever the contention periods m are more than 2 (as demonstrated in [7]), only deducting the time intervals devoted to transmit control information. As we are considering a particular case, it results that this condition is still fulfilled. We can evaluate the normalized saturation throughput (i.e. channel net usage) from the average transmission time of a data packet (payload) ($T_{payload}$) and the total duration of a frame (T_{FRAME}) as:

$$\rho = \frac{T_{payload}}{T_{FRAME}} \quad (1)$$

The complete duration of the DQ frame format (Fig. 1), uplink and downlink, can be expressed as,

$$T_{FRAME} = T_{UPLINK} + T_{DOWNLINK} = (T_{ACCESS} + T_{DATA}) + T_{DOWNLINK} \quad (2)$$

where T_{ACCESS} is the duration of the contention access window (CAW), T_{DATA} is the variable time the channel is busy

for a successful transmission during the contention-free period, and $T_{DOWNLINK}$ is the time devoted to control information transmissions in the downlink - including a new preamble for synchronization after sleep modus for power management purposes. The value T_{ACCESS} is calculated as follows,

$$T_{ACCESS} = m \cdot (tPHY_{header} + tARS) \quad (3)$$

where $tPHY_{header}$ represents the synchronization period (PHY level) and $tARS$ is the period of time needed to transmit the access requests represented by the special ARS packets, which could be minimized in duration [11]. The value for T_{DATA} can be calculated as,

$$T_{DATA} = tPHY_{header} + tMAC_{header} + T_{payload} \quad (4)$$

where $tMAC_{header}$ is the time needed to transmit the MAC header bytes. Finally, $T_{DOWNLINK}$ can be evaluated as,

$$T_{DOWNLINK} = Twa + 2tPHY_{header} + tACK + tFF + SIFS \quad (5)$$

where Twa corresponds to $macAckWaitDuration$ as defined in IEEE 802.15.4 [1], which comprises already the turn-around time or round-trip propagation delay. $tACK$ is the time required to receive the downlink acknowledgment frame, and tFF is the duration of the feedback frame ($Pr+FBP$). FBP could also be reduced in order to minimize control information and maximize net throughput. The downlink frame ends with a Short Inter Frame Space (SIFS) for MAC processing purposes. In these conditions, the obtained throughput value ρ results in the following equation, which is derived from equation (1):

$$\rho = \frac{T_{payload}}{m \cdot tARS + (3+m) \cdot tPHY_{header} + tMAC_{header} + T_{payload} + Twa + tACK + tFF + SIFS} \quad (6)$$

B. Throughput Comparison

Both IEEE 802.15.4 analytical models in [5] and [6] consider the saturation throughput, expressed as the number of slots occupied for a successful packet transmission of a determined size (payload length). There, it can be seen that the saturation throughput of IEEE 802.15.4 MAC drastically decreases when the number of sensors in the network starts increasing. Fig. 2 shows the results derived from [5], using default parameters values defined for 2.4 GHz frequency channels (i.e. minimum back-off exponent, $BE_{min}=3$, payload length, $L=68$ bytes) at 250 kb/s. In order to validate our proposed approach and to get a figure of the obtainable gain, reference [5] analytical model has been implemented and compared to our throughput analytical model as a function of payload length (L) and number of sensors (N).

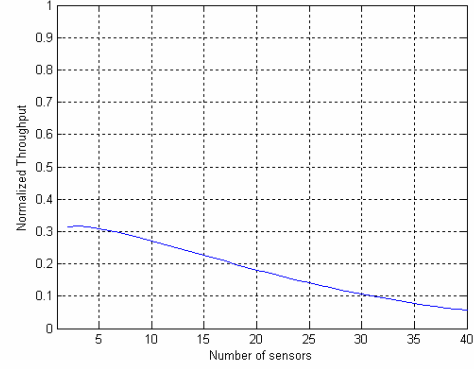


Fig. 2: Saturation throughput of LR-WPAN 802.15.4 MAC

To get example figures, a scenario with N always-active sensors in saturation has been selected. The reference scenario is defined by a set of parameters provided in Table 1, whose fields correspond to IEEE 802.15.4 default values [1].

TABLE 1
IEEE 802.15.4 Scenario Parameter Values

PHY header	6 bytes	ACK	11 bytes
MAC header	9 to 25 bytes	Pr	4 bytes
Payload	8 to 127 bytes	FBP	13 bytes
Taw	864 μ s	SIFS	192 μ s

Note that for our DQ protocol the number of contention minislots m is also 3 (i.e. 3 ARS packets). As previously said, the duration of these ARS packets could be reduced to a very small value (i.e. between 2 μ s and 100 μ s), since no data information is needed to be carried through [11]. For our calculations, we will use 100 μ s as ARS value in order to consider the worst case scenario. Fig. 3 shows the difference between the obtained saturation throughput using IEEE 802.15.4 MAC analytical model in [5] and our DQ protocol analytical model for wireless sensor networks as a function of the payload length (L). While IEEE 802.15.4 throughput analytical models depend on the number of sensors (see Fig. 2), DQ mechanism throughput model is independent of the number of transmitting sensors in the network. That is basically thanks to its distributed queues, which treat collisions from access requests and data transmissions separately (see section III or [7]). DQ curve has been obtained analytically by means of (1) and Table 1. IEEE 802.15.4 curves have been implemented based on [5] throughput analysis, but now expressed as a function of the payload length. All values have been obtained assuming the transmitter buffers always have packets to send, i.e. in saturation. We can observe in Fig. 3 that results obtained with our proposed DQ mechanism for wireless sensor networks improve significantly the system capacity over IEEE 802.15.4 MAC. Above all, it must be considered that our DQ protocol is able to maintain better throughput values for any number of nodes N in the network. It can be seen that IEEE 802.15.4 MAC is not suitable for dense wireless sensor networks, because when the number of sensors increases, its saturation throughput solid decreases.

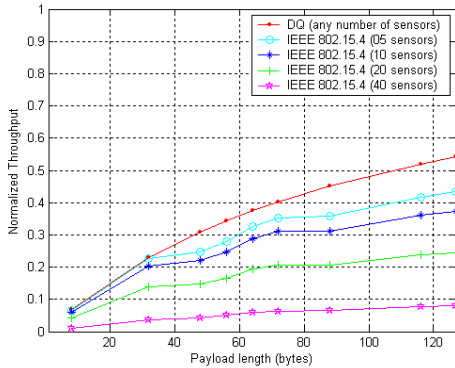


Fig. 3: Achievable estimated throughput improvement

This is one of the main reasons why we suggest that our here presented DQ protocol should be particularly considered for a high number of sensor nodes (i.e. for more than 20 sensors), since it outperforms IEEE 802.15.4 MAC throughput from 15% for small packets to 45% for large packets. Observe that the system efficiency is improved when packets grow in bit size. The reason is that the control part of the frame becomes smaller with respect to the total frame duration. Thus, the relative overhead is reduced.

C. Energy Consumption Evaluation

Sensor nodes are limited in stored energy, computational capacity and memory. New protocols and algorithms must be designed with special attention to these differences and above all to their limited and sometimes non-renewable power storage. Significant power is consumed at a sensor node when it either transmits a packet or when it receives a packet. Fig. 4 portrays the achievable estimated energy consumption improvement per utile bit of DQ mechanism versus IEEE 802.15.4 MAC protocol based on [5] and aforementioned parameter values. In saturation conditions, the IEEE 802.15.4 MAC shall deal with a certain level of data collisions, which steadily increases with a high number of sensors in the network (e.g. 20 or 40 sensors). This results in a progressive reduction of the energy consumption efficiency of IEEE 802.15.4 MAC. In contrast, when applying DQ MAC protocol in saturation, no collisions will be produced in the data part of the frame [7] and therefore no energy is wasted.

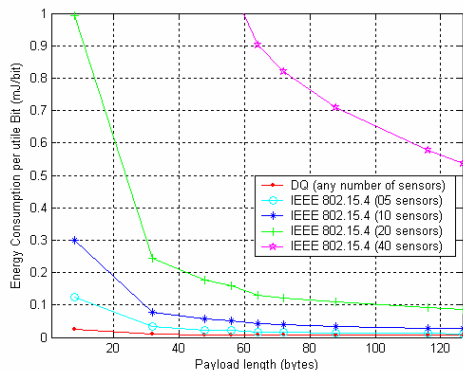


Fig. 4: Achievable estimated energy consumption improvement

Thus, although the collision resolution mechanism requires some energy consumption, the complete elimination of data collisions represents a remarkable enhancement in the overall network energy efficiency. A notable feature is that DQ MAC saves more than 50% of energy consumption with respect to IEEE 802.15.4 for a high number of sensors ($N > 40$).

VI. CONCLUSION

In this paper, we have presented an analytical evaluation of an enhanced distributed queuing medium access protocol (DQ MAC) for wireless sensor network scenarios. We have shown that our here proposed DQ mechanism outperforms IEEE 802.15.4 not only in terms of throughput, but also in the overall energy efficiency of the network. The validity of the DQ throughput analytical model is based on previous published results. Additionally, here we have shown that our proposed DQ protocol represents a remarkable improvement of the overall network energy efficiency for a large number of nodes. Therefore, our DQ MAC proposal may scale far better than IEEE 802.15.4 for wireless sensor networks with a high number of nodes (more than 20 sensors).

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