Wireless Sensor Networks: QoS Provisioning at MAC and Physical Layers

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Abstract— **Research on wireless sensor networks (WSN) has mostly focused on providing energy-efficient operation of each node that provides as long lifetime of WSN as possible. We argue that it is important to include consideration of quality-of-service (QoS) provisioning in addition to considering energy-efficiency. An overview of QoS metrics and parameters in WSN is presented. Having in mind that throughput, average delay and jitter (delay variance) are the most important QoS parameters at medium access control (MAC) layer, fundamental energy-efficiency vs. delay trade-off, and throughput vs. capacity in wireless communications (WC) are reviewed. Existing energy-efficient MAC protocols for WSN, with some of the QoS-aware features are described. Finally, a review of MAC schedulers based on fundamental results on delay-constrained communications over wireless medium is given.**

***Keywords* - energy-efficiency, MAC, QoS, wireless sensor networks.**

I. Introduction

Wireless sensor networks (WSN) were proposed for monitoring of physical phenomena with little or no human attendance. Inherent to such concept is one of the basic assumptions that every node in a WSN is equipped with a battery, and it has usually been assumed that the battery is irreplaceable. Research in WSN has focused on providing energy-efficient operation of each node that provides as long lifetime of WSN as possible.

However, latter advances in research on sensing technologies, e.g. sensor cameras [1], and various mission-critical applications, e.g. in networked control systems [2] have introduced delay- or packet-loss-sensitive traffic in WSN. This has raised the question of guaranteeing maximum packet delay or packet delay jitter in WSNs, which are some of the QoS metrics.

Recent WSN deployments [3, 4] have shown that WSNs operating close to maximal energy efficiency often do not provide minimal communications QoS guaranties, so QoS support becomes particularly challenging and important as network traffic increases and approaches channel capacity.

In “traditional“ computer networks, QoS provisioning is the ability of communication system to guarantee some specific performance parameters, such as throughput, end-to-end packet delay, and packet loss rate. QoS guaranties depend on application because of various data and traffic characteristics. For instance, data may include event-triggered observations, e.g. snapshots or images, in short periods; it can also contain streaming multimedia contents that require smooth transport over longer time intervals [1]. QoS parameters relevant to streaming communications are guarantied bandwidth, average packet delay, and delay jitter. Typical QoS parameter for real-time (RT) snapshot delivery is maximal delay. QoS requirements of control system applications are accuracy, reliability, and maximal packet delay [5].

In early papers on QoS in WSNs, application QoS requirements, as they are percived by application comunities, are distinguished from communication QoS requirements, as they are interpreted by networking community [6].

Commonly specified communication QoS parameters that have to be provided in WSNs are collective: latency, packet loss, bandwidth, and information throughput. Note that WSNs introduce the event-to-observer paradigm, as opposed to the end-to-end paradigm encountered in traditional networks [6]. Some of these QoS parameters can be supported at MAC layer that is responsible for data queuing, access control, and scheduling of data transmissions. The principal QoS parameters provisioned at MAC layer are throughput, average packet delay, and transmission reliability.

Two different approaches to QoS and RT support in WSNs could be identified. First approach is related to the application layer perspective and solutions emerging from this approach can be applied both to layers above the MAC, and MAC layer itself [7]. Second approach exploits time-variability of wireless channel, at the physical layer, to achieve better QoS and RT performance [8]. Most of the previous work in this area uses the first approach. The exploitation of wireless channel time-variability, although widely used in wireless networks, has not found appropriate usage in WSN QoS support.

Hard QoS guaranties are difficult to achieve in communications over wireless channels, because of their time variations that introduce nondeterministic behavior of communication system and resource constraints. Therefore, alternatives like soft QoS guaranties should be considered.

Our work is focused on QoS support at MAC layer in WSN. The rest of the paper is structured as follows. Section II reviews QoS-related resources, metrics and parameters in WSN. Section III reviews existing energy-efficient MAC protocols for WSN while section IV

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reviews channel-aware MAC schedulers and potential research topics. Section V concludes the paper.

II. WSN-QoS Resources, Metrics and Parameters

Resources used in WSN for signal transmission and QoS provisioning are transmit power, available energy, channel bandwidth, and time, in the sense of maximum acceptable delay in signal transmission, queuing, and processing.

Metrics which quantify QoS requirements include: average throughput, average packet delay, delay jitter, and packet loss rate. The event-to-observer paradigm of WSN calls for collective QoS parameters that are defined over the minimal set of valuable messages that carry reports on an event. The parameters are: collective data rate, which is equal to the sum of individual data rates, needed to transport the data belonging to the minimal set, from sensor nodes to the sink; collective delay, which is equal to the difference between the time instants when the last message were received at the sink and the first valuable message were sent by the transmitter; and collective packet loss rate, which is the packet loss rate of data belonging to the minimal set for a group of sensor nodes that send data to the same sink.

We provide more insight into delay and throughput as QoS metrics, by reviewing fundamental energy-efficiency vs. delay trade-off and distinctions between capacity and throughput.

Schurgers et al. [9] showed that energy used to transmit one bit, E_{bit}, and time to transmit one bit, T_{bit}, both decrease as the symbol rate R_s increases. Therefore, in communication systems with multi-rate support it is preferable to chose signaling at the maximum symbol-rate. Energy-per-bit, E_{bit}, is a monotonically increasing function of the constellation size, expressed in the number of bits per symbol. T_{bit} is monotonically decreasing function of the constellation size. It follows that the constellation size can be reduced if T_{bit} can be larger, which means that a particular application can tolerate larger delay. By reducing the constellation size, E_{bit} is decreased. How small constellation size can be depends on the delay constraint. The proposed method of minimizing E_{bit} subject to the delay constraint (maximum acceptable T_{bit}) is named modulation scaling [9].

In WSNs traffic load is usually much lower than channel capacity and this observation is exploited to duty-cycle transceiver activity, by putting it into power-save mode in inactive periods. The same observation can be used to extend time for packet transmission up to the acceptable packet transmission delay, thereby enabling adoption of modulation scaling to reduce energy-consumption of wireless sensor nodes.

Berry and Gallager [10] provide an information theoretic treatment of delay constrained communication over fading channels. They consider a user communicating over a fading channel with perfect channel state information. Data is assumed to arrive from a higher layer application and is stored in a buffer until it is transmitted. The authors study adaptation of the user's transmission rate and power based on the channel state information as well as buffer occupancy. The objectives are to regulate both the long-term average transmission power and the average buffer delay incurred by the traffic. The second objective can be viewed as arising from the QoS desired by the user. There is a trade-off between these objectives – transmitting at a higher rate requires more power, but reduces the average delay.

This becomes obvious from the concept of outage probability *e*, or *e*-capacity, which is defined to be the solution to the optimization problem:

$$\max R$$
$$s.t.\Pr\left(\log\left(1+\frac{|H|^2\ P(H)}{\sigma^2}\right)\le R\right)\le e$$
$$EP(H)\le \overline{P}$$

where R denotes information rate, H is the channel matrix (random variable), P(H) is transmission power for the given realization of H, σ² is Gaussian noise variance, $0 < e < 1$, and E denotes expectation operator. Analogous formulation of delay-limited capacity, in which transmission power is minimized subject to the given rate of mutual information, is:

$$\min EP(H)$$
$$s.t.\log\left(1+\frac{|h|^2\ P(h)}{\sigma^2}\right)> R$$

where *h* is any one of the channel states.

Two models for this situation are discussed. One corresponds to fixed-length/variable-rate codewords while he other model corresponds to variable-length codewords.

The trade-off between the average delay and the average transmission power required for reliable communication is analyzed. It yields the description of the optimum power/delay curve: P(D) is a decreasing and strictly convex function of D, where D is acceptable delay and P(D) is transmit power, which depends on delay. We note the similarity between this result and the results on modulation scaling.

III. Existing MAC Protocols

A framework for QoS, a complete system that has to provide required QoS is a basic point of system approach. The components that cooperatively support QoS are: QoS model, QoS routing, QoS signaling for resource reservation, QoS MAC, call admission control and packet scheduling scheme [7]. IntServ and DiffServ QoS models are developed as addition to wired IP networks. They provide QoS on a per-flow basis and differentiate traffic into service classes, respectively. Both are of interest in WSN, because of QoS requirements of emerging WSN multimedia and control applications. However, they cannot be directly applied to WSN, but are starting points in defining WSN-specific QoS models.

MAC layer defines scheduling, access policies for transmitting nodes, and arranges queues of data ready for transmission. Some functions for QoS provisioning, reservation of channel resources, ensuring successful transmission control and packet scheduling can be realized at MAC layer. A comprehensive survey of MAC layer protocols for WSN and their energy-efficiency is given in [11]. They classify MAC protocols into four groups: random-access, slotted-access, frame-based access and hybrid protocols. Random-access protocols are simple for realization and have predictable behavior in the case of low loaded networks while in the case of high loaded or even overloaded networks their performances decrease rapidly. Slotted-access protocols introduce duty-cycle, defined as the ratio of wake-up state duration and the sum of sleep and wake-up states durations, with intention to enhance energy-efficiency. During active period, time is organized into slots while access policy can be random, collision-free or both. Frame-based protocols are suitable for providing hard RT QoS guaranties because they use TDMA (Time Division Multiple Access). Weakness of this access scheme in WSN applications is complex realization and high memory demands of source code. Hybrid MAC protocols combine advantages of random-access and collision-free access polices to achieve high performance.

A survey of RT QoS support for WSN, [12], analyzes I-EDF [13] and dual-mode RT MAC [14] medium access protocols to support transportation of messages with hard real-time requirements and some other MAC protocols that reduce message latency but do not offer real-time guaranties. Caccamo *et al.* designed implicit prioritized EDF (Earliest Deadline First) based hard RT MAC protocol [13] for WSN with periodic traffic. Based on assumptions that nodes are synchronized and router nodes that stand in the center of each cell are equipped with two independent radio transceivers, they construct FDMA-TDMA collision-free MAC scheme. Dual-mode real-time MAC protocol for linear WSN with identical nodes is presented in [14]. The protocol employs random access in first mode, when load is low, while it switches to collision-free access in second mode, when load is high. The protocol uses FDMA-TDMA scheme, similar to I-EDF protocol. Both protocols suppose that there are no transmission errors caused by wireless link variability.

In what follows we list basic mechanisms used to support QoS and representative examples of random access and collision-free MAC protocols. Finally, we present MAC layer features of IEEE 802.15.4 standard that support QoS and RT communications.

Three mechanisms for QoS provisioning in WC are presented in [15]. The first one uses prioritized contention and back-off parameters to allow faster access to traffic classes with higher priority. In the second mechanism, nodes exchange information about packets stored in their buffers, to assess their relative priorities. The third mechanism allows the highest-priority nodes to be the first to signal to prevent lower-priority ones from gaining access to the channel. The authors suggest two alternatives for hard QoS guaranties. The first alternative is service differentiation. The second is soft QoS, defined as the graceful acceptance of QoS specification violation over transient periods.

Various mechanisms based on prioritized contention and back-off parameters with a goal to provide service differentiation and soft QoS guaranties have already been proposed, see [16] and references therein.

There are many energy-efficient TDMA based, application specific WSN MAC protocols, with features suitable for support of delay sensitive traffic. PEDAMAC [17] is an example of TDMA based MAC protocols designed for WSNs with periodic traffic. LEAD-MAC [18] employs node heterogeneity of Wireless Sensor/Actuator Networks (WSAN) and assumes tree topology. It assigns consecutive time slots to each gathering tree, inverse multicast structure [19], so that packets travel from leaf nodes to the sink within one frame. Powerful actuator nodes capable of transmitting packets to all sensor nodes, directly, are seen to be cluster-heads and form WSAN communication back-bone.

IEEE 802.15.4 physical layer and MAC layer standard for low-rate personal area networks [20] has de facto established as the most suitable, but still not optimal, standard for WSN applications. IEEE 802.15.4 MAC specification employs GTS (Guarantied Time Slot) mechanism to provide RT guaranties. Basic analyzes of GTS allocation in IEEE 802.15.4 for RT WSN applications concerning delay and throughput metrics is given in [21].

Despite the fact that some MAC protocols provide some types of QoS in WSNs, this area is still rather unexplored field. The problem is how to balance between QoS requirement and energy-consumption.

IV. Channel-Aware Schedulers

There have been a lot of research efforts on transmission power control intending to mitigate interference that users cause to each other and to improve channel capacity for a given transmission power as close to Shannon's limit as possible [8, 10, 19, 22-24]. With progress of wireless battery operated devices, transmission power control has been used to minimize transmission power and energy consumption subject to a given amount of data that have to be communicated.

Papers [8, 19, 22-24] propose scheduling algorithms concerning energy-efficient WC, following the observations presented in section II, minimizing transmission power subject to time constraints.

After the communication model has been established and formulas for total energy and time constraints have been evaluated, an optimal solution in the form of an off-line algorithm can be found. Such off-line algorithms are not suitable for optimization of WC for two reasons. First, wireless channel is highly time-variable and channel state is not available in advance. Second, algorithms for calculation of optimal solutions often have high computation complexity and are not computable within allowed time constraints. Therefore, development of run-time approximation of optimal off-line algorithm is the next step.

Lazy, energy-efficient packet schedulers over wireless fading channel are developed for single-user communication in [22] with the goal to minimize total energy needed to transmit a number of data packets, with defined maximum delays, arriving to the user queue. The authors have shown that multiple user problem has optimal numerical off-line solution. Off-line iterative algorithm named MoveRight that converges to the optimal schedule and on-line version MoveRightExpress that is comparable with MoveRight in terms of energy-efficiency and delay are proposed in [23].

Single-hop sensor data fusion problem, like a special case of packet-scheduling problem presented in [23] is discussed in [24]. In [24], optimal and suboptimal centralized schedulers are developed, that are much less complex than MoveRight algorithm. Distributed versions of schedulers to reduce control overhead inevitable in centralized approach with similar performance are developed. In distributed version of schedulers, sensor having data for transmission can make decisions taking into account only information on own channel condition and own queue length. The authors report 80% energy reduction compared to traditional TDMA.

The most suitable energy-efficient WC model for collective QoS parameters provision in WSNs is proposed in [19]. The model assumes multiple sensor nodes sending packets to a single sink through the data gathering tree. They minimize energy subject to latency constraints, in depth of the gathering tree, for all generated packets. Off-line numerical optimization algorithm and simple distributed on-line algorithm that relies only on local information are developed and compared to the baseline. They report 90% energy savings of the algorithms compared to the baseline.

Transmission of B bits with hard deadline T over slotted block fading channel with a goal to minimize energy consumption is discussed in [8]. The authors employ time-dependant scheduler that sums weighted delay-associated term and an opportunistic term, given by formula

$$b_t = \frac{\beta_t}{t} + \frac{t-1}{t}\log\frac{g_t}{\eta_t}$$

where b_t is the number of bits to serve at time slot t, β_t is the number of remaining bits, g_t is the current channel state, and η_t denotes a channel threshold. They solve the problem of optimal schedule numerically, using one-dimensional convex optimization. Two suboptimal schedulers as the solutions of relaxed convex optimization problem are also proposed.

Previous examples show that some work considering energy-efficient communications with time constraints, over fading wireless channel, has already been done, providing many readily applicable scheduling algorithms.

V. Conclusions

In WSN, QoS provisioning vs. energy-efficiency trade-off is still a research challenge. Most research on WSN has focused on energy-efficiency, whereas QoS support has been neglected. Deployments of WSN have shown a drawback of this approach – communication can be very unreliable with long delays.

We have reviewed several aspects of this research challenge: definitions of QoS requirements relevant for WSN; time-varying wireless channels and fundamental results on delay-constrained WC; existing energy-efficient QoS-aware MAC protocols; and methods facilitating energy-efficiency vs. delay trade-off. QoS support approaches, which mimic approaches from wire-line computer networks, such as traffic differentiation, packet prioritization, use of duty-cycle and exploitation of non-energy-constrained nodes, do not yield desired performance in WSN. On the other hand, an approach based on quantitative modeling of energy-efficiency vs. delay trade-off, based on information theoretic and WC principles, is promising. However, only WSN MAC scheduler has been suggested based on this model.

We conjecture that if WSN QoS and RT requirements can be translated into the model of delay-constrained communication, then off-line and approximate on-line optimization algorithms exist. Combination of the approaches based on QoS support in computer networks and delay-constrained WC may yield methods for fine-tuning energy-efficiency vs. QoS trade-off.

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