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Review article

Energy efficiency of MAC protocols in low data rate wireless multimedia sensor networks: A comparative study

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ABSTRACT

Some new application scenarios for Wireless Sensor Networks (WSNs) such as urban resilience, smart house/building, smart agriculture and animal farming, among others, can be enhanced by adding multimedia sensors able to capture and transmit small multimedia samples such as still images or audio files. In these applications, Wireless Multimedia Sensor Networks (WMSNs) usually share two conflicting design goals. On the one hand, the goal of maximizing the network lifetime by saving energy, and on the other, the ability to successfully deliver packets to the sink. In this paper, we investigate the suitability of several WSNs MAC protocols from different categories for low data rate WMSNs by analyzing the effect of some network parameters, such as the sampling rate and the density of multimedia sensors on the energy consumption of nodes. First, we develop a general multi-class traffic model that allows us to integrate different types of sensors with different sampling rates. Then, we model, evaluate and compare the energy consumption of MAC protocols numerically. We illustrate how the MAC protocols put some constraints on network parameters like the sampling rates, the number of nodes, the size of the multimedia sample and the density of multimedia nodes in order to make collisions negligible and avoid long queuing delays. Numerical results show that in asynchronous MAC protocols, the receiver-initiated MAC protocols (RI-MAC and PW-MAC) consume less energy than the sender-initiated ones (B-MAC and X-MAC). B-MAC outperforms X-MAC when the sampling rates of multimedia nodes is very low and the polling periods are short. PW-MAC shows the lowest energy consumption between the selected asynchronous MAC protocols and it can be used in the considered WMSNs with a wider range of sampling rates. Regarding synchronous MAC protocols, results also show that they are only suitable for the considered WMSNs when the data rates are very low. In that situation, TreeMAC is the one that offers the lowest energy consumption in comparison to L-MAC and T-MAC. Finally, we compare the energy consumption of MAC protocols in four selected application scenarios related to Smart Cities and environment monitoring.

1. Introduction

Wireless Sensor Networks (WSNs) are considered as the building blocks of new network paradigms and application scenarios in Smart Cities [1]. In this context, applications such as structural health and urban resilience, smart house/building, smart agriculture and animals surveillance, among others, can be enhanced by adding multimedia sensors (MMSs) able to capture and transmit small multimedia samples such as still images or audio files.

In these networks, namely Wireless Multimedia Sensor Networks (WMSNs) [2], maximizing the network lifetime is of a paramount importance. To achieve this goal, using an energy efficient Medium Access Control (MAC) protocol is key since the radio is a major source of energy consumption in the sensing nodes [3]. The MAC layer coordinates nodes' access to the shared wireless medium. Doing so in an energy efficient way becomes more complicated when nodes of different sampling rates exist in the network and generate different traffic loads.

Based on applications, WMSNs' traffic can be classified into two main categories, multimedia streams (e.g., video streaming) and multimedia data (e.g., snapshot multimedia content). Each of these categories can be further classified, according to the level of Quality of Service (QoS) required by the overlying application, into real-time and delay-tolerant [2]. Multimedia streaming applications put a lot of effort on achieving high bandwidth for a steady flow of data while real-time applications require a delay-bounded delivery of packets. In these cases, energy efficiency is of a lower priority. However, these applications are out of the scope of this

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paper. Here, we focus on non-streaming and delay-tolerant WMSNs that require relatively lower bandwidth demands than streaming ones [2]. This includes a wide range of environment monitoring and Smart Cities application scenarios, where on the one hand it is essential to keep monitoring the surrounding environment, but on the other hand the phenomenons' observation is delay-tolerant and the generated multimedia traffic is lower -compared to multimedia streams. In this kind of applications MMSs can be deployed to sporadically send still-images or audio files (e.g., images about structural health in a territory, crops status in vineyards, pets and children in a house, sounds and noise in bar zones, among others). This imposes a higher traffic load compared to the typical WSNs where only scalar sensors (SSs) – which sense scalar data and physical attributes (e.g., temperature and humidity readings)- are deployed, and it directly affects the energy efficiency of the MAC layer.

In this paper we study the energy efficiency of the MAC layer in this kind of WMSNs applications by modeling and evaluating the energy consumption of several and different MAC protocols, designed for traditional WSNs, taking into account the existence of MMSs in the network. The paper addresses the spectrum of low data rate applications where the main target is to minimize the energy consumption and increase the lifetime of the sensor network. Therefore, the selected MAC protocols should be those ones which improve the energy efficiency, regardless if they are QoS-aware or if they provide constant bandwidth -as required by streaming applications. To achieve this goal we develop a general sensor network traffic model which allows to integrate different types of sensors with different sampling rates. The model is an extension and a generalization of the model presented in [4] and helps to analyze the effects of various parameters of MMSs -such as the sampling rate, the size of multimedia sample and the density of MMSs- on the traffic each node transmits, receives and overhears. There are previous works on modeling and evaluating the energy consumption of MAC protocols in WSNs like [4,5]. However, none of those papers models and evaluates the energy consumption of MAC protocols in WMSNs. Moreover, there is a lack of comparisons between the energy consumption of recent MAC protocols and the early designed ones. Therefore, the main goal of this paper is to assess and compare the energy performance of those MAC protocols in low data rate WMSNs, under variable sampling rates and densities of MMSs, in order to find out the suitable MAC protocols for this kind of networks and the WMSNs' scenarios and applications in which each MAC protocol works better.

The rest of the paper is organized as follows: Section 2 provides a brief overview of the related work. In Section 3, the design principles are presented and the multi-class traffic model is derived. The energy consumption of MAC protocols is modeled in Section 4 and Section 5. In Section 6, we conduct a numerical evaluation of the energy performance of MAC protocols under different configurations of WMSNs and in various application scenarios. Finally, the paper is concluded in Section 7.

2. Related work

The design and implementation of MAC protocols in WSNs have been strongly related to the requirements of applications enabled by sensing nodes. Classical MAC protocols have been originally designed for applications that handle scalar data only. Other MAC protocols have been later developed for more sophisticated applications that usually require a steady flow and/or a real-time delivery of packets. Such applications typically demand high throughput, bounded delay, and high reliability. In this section we will review the two groups of MAC protocols, though later in the paper we will model and evaluate the ones belongs to the first group only, since the set of applications we are considering does not require any streaming support, and using streaming MAC protocols in those applications will increase nodes' energy consumption for an undesired service.

2.1. The main categories of MAC protocols in WSNs

MAC protocols for scalar WSNs have been classified in various categories based on when and how nodes decide to transmit data. These categories are: asynchronous (or random access), synchronous (locally or globally), and hybrid schemes [3,4,6]. In terms of energy efficiency, idle listening and collisions are major concerns of MAC protocols in WSNs. Research work have focused on how to improve the performance of MAC protocols in a way the energy wasted in idle listening, collisions, and overhearing is minimized. To reduce idle listening, the duty cycling technique has been widely adopted. With duty cycling, nodes switch periodically between active and sleeping states. Using the asynchronous scheme, each node decides when to wake up autonomously, given the rules defined by the particular MAC protocol, and the duty of the MAC protocol is to establish communication between nodes. Asynchronous MAC protocols for WSNs include: B-MAC [7], X-MAC [8], RI-MAC [9], and PW-MAC [10], among others.

Another category of MAC protocols is the synchronous MAC protocols. This category is further divided into two main branches: locally synchronized and globally synchronized (i.e. frame-slotted) [3]. Locally synchronized MAC protocols (e.g., S-MAC [11] and T-MAC [12]) also adopt the duty cycling mechanism. To save energy, they allow nodes to turn off their radio when no communication occurs during a certain time period. They differ from asynchronous MACs in the sense that each cluster of neighboring nodes are scheduled to wake up at the same time. Frame-slotted MACs (e.g., L-MAC [13] and TreeMAC [14]) divide time into frames and assign time slots to nodes in a way that no two nodes within the two-hop distance are allocated the same time slot. The problem of synchronous MAC protocols is that they require to keep the network synchronized which implies a high control overhead.

2.2. QoS-aware MAC protocols in WSNs

The deployment of resource-constrained sensing nodes in critical environments (e.g., real-time applications) impose additional challenges on the MAC layer in order to assure a certain level of QoS required by the application. For instance, a MAC protocol has to be flexible and dynamic to changes in the network, minimize the medium access delay by minimizing collisions, and maximize reliability by minimizing traffic losses. There are several examples of MAC protocols in the literature that support QoS metrics such as Q-MAC [15], RL-MAC [16], PQ-MAC [17], CoSenS [18], among others. The QoS-aware MAC protocols for WSNs and WMSNs have been surveyed and classified in [19].

2.3. MAC Protocols for streaming WMSNs

Designing a MAC protocol for streaming WMSNs is a complicated task since they require a steady flow of data, in addition, to a delay-bounded delivery of packets, which may be very challenging for any category of MAC protocols mentioned in Section 2.1 (e.g., due to the increasing probability of collisions in asynchronous MACs or the limited slots duration in synchronous MACs). There are several considerations when designing a MAC protocol for video streaming WMSNs which are summarized in [20]. For instance, nodes need to implement intra- and inter-node traffic class differentiation in order to separate traffic according to its classes and serve each class based on its priority. Intra-node traffic class differentiation is achieved by adding queuing management and priority control mechanisms. Inter-node traffic class differentiation

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