Energy Optimization at the MAC Layer for a Forest Fire Monitoring Wireless Sensor Network

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Al-Khateeb Anwar, Jun Kyoung Kim,
Luciano Lavagno
Dipartimento di Elettronica, Politecnico di Torino
Torino, Italy
{anwar.al-khateeb, jun.kim, lavagno}@polito.it

Mihai T. Lazarescu
Minteos srl
Torino, Italy
lazarescu@minteos.com

Abstract

This paper describes several optimizations of MAC protocols that can be applied in order to satisfy the constraints that come from a real-life application. Forest fire monitoring requires very different latencies and data sizes, depending on whether it is reporting normal conditions, sending an alarm, or performing network management functions.

We use MAC algorithms that extensively shut down the radio in order to save power. We show that by exploiting knowledge about the Link Quality Index and by effectively using the free time of the channel only when there is more data than usual to transmit, we manage to decrease latency and contention and increase bandwidth usage, while keeping power consumption very low.

1. Introduction

Wireless sensors are easier and much cheaper to deploy than wired sensors for both new designs and retrofits, since they use wireless links to transmit the data and no wires are needed. With no rewiring, the design of new systems and the expansion or upgrade of existing systems is also simplified.

Without wires the sensors rely only on their internal supply reserves for operation. Thus the maximum maintenance period of the devices is often limited by the supply reserve duration. On one hand it should ideally extend beyond the obsolescence time of the device technology itself. On the other hand a smaller power supply reduces the sensor dimensions and cost or it makes energy scavenging possible.

With the above considerations, reducing energy consumption on wireless sensors is of utmost importance. Sensing data acquisition and processing typically requires low energy, both as peak and average. At the other end, the RF subsystem is one of the highest peak and average drains on the sensor power supply reserves.

The RF device usage is given by in-field networking protocol requirements and by the data exchanges required by the application. Application requirements may also define some parameters for the in-field networking protocol, such as the maximum data propagation latency allowed.

Idle listening is often the largest source of energy waste and duty cycling (i.e., periodically putting the radio in a sleep state) is considered as one of the best techniques to reduce energy consumption in WSN MAC protocols.

However, excessive sleeping causes an increase of transmission power, due to lost packets and long preambles.

In this paper, we start from a real application, namely wildfire monitoring, and we use its constraints to illustrate how a power-efficient MAC algorithm can be customized and extended in order to provide significant power savings in a realistic usage scenario.

This application uses a large network of cheap and independent sensors. These are placed on the trees in the monitored area in a suitable spatial pattern aimed to optimize the early detection of most wildfires.

It has two conflicting characteristics that motivated our research:

1. The distribution of packet sizes is very bimodal, with small frequent packets and large rare packets.
2. The latency constraints of packets are very different, since alarm packets must be delivered very quickly, while network status and management data can be delivered more slowly *without impacting the latency of urgent packets.*

The paper is organized as follows. Section 2 summarizes its main contributions. Section 3 describes the background work. Section 4 describes the burst-mode support that is needed to manage overload conditions. Section 5 describes the target application. Section 6 describes the experimental results.

2. Contributions

The Asynchronous Scheduled MAC (AS-MAC) [2][3] is a simple but very energy efficient protocol, in which nodes store the wake-up schedules of their neighbors; therefore they do not need to add long preambles at the beginning of transmission. AS-MAC also asynchronously coordinates the wake-up times of neighboring nodes to reduce overhearing, contention and delays that are typical of synchronous scheduled MAC protocols.

In [5] we described a few improvements of AS-MAC with respect to both power and performance, that we collectively call the Power Efficient MAC protocol (PE-MAC). We dynamically adapt the backoff delay and the minimum backoff exponent (minBE) of the nodes to their bandwidth requirements and channel conditions. This is an example of cross layer interaction between PHY and MAC. In this paper we apply PE-MAC to a concrete industrial case study, and we quantitatively show how it improves with respect to AS-MAC.

In addition, the application that we consider has two modes of transmission: short and frequent sensor data versus long and rare maintenance data, and also exhibits higher data rates near the sinks due to a data funneling effects. We support this bimodal distribution by adding support for *burst transfers*, with an extended AS-MAC algorithm called Variable Length Mac (VL-MAC). The reason to consider bursts is that in AS-MAC data transmission is available only once per wakeup interval, which results in large potential wasted time, and a very high number of unnecessary contentions, when considering comparatively large amounts of data or a many senders/one receiver scenario. By fully utilizing the time to the earliest wakeup time of another node, we reduce waste and improve network congestion.

3. Background

The Asynchronous Scheduled MAC protocol (AS-MAC) [6,14] has two very desirable properties, which are retained by our improvements, namely (1) energy consumption continuously decreases as the wakeup interval increases and (2) energy consumption for a given wake-up interval is lower than with previously proposed protocols.

In PE-MAC [5] we introduce several cross-layer optimizations with respect to AS-MAC, which improve overall network efficiency in terms of energy and time. We adapt transmission power, backoff delay and minimum backoff exponent to the channel status (as estimated by the current Link Quality Indicator, LQI). All these parameters decrease with high LQI (good channel) and increase with low LQI (poor channel; we use a "dead zone" in which they do not change in order to avoid instability). In the following sections we consider the two phases (initialization and periodic) more in detail.

A. Initialization Phase

When a new node joins a WSN, it first performs the initialization phase, in which it constructs the neighbor table that includes scheduling information from its neighbors, and then chooses and announces its own unique offset for periodic wake-up. Existing nodes may be in the initialization phase or the periodic listening and sleep phase. Nodes in the periodic listening and sleep phase perform Low Power Listening (LPL) at every wake-up interval, I_{wakeup} , and send a Hello packet at every Hello interval (which is an integer multiple of the wakeup interval), $I_{hello.}$ In the PE-MAC protocol, Hello packets are used to publish scheduling information, namely: I_{wakeup}, I_{hello} , offset of the periodic wake-up, O_w and link quality indicator, LQI [4][5]. Note that in the application that we are considering, initialization is performed only seldom, since nodes stay active for months or years.

B. Periodic Listening and Sleeping Phase

After the node has completed the initialization phase and built its local lookup table, it starts the periodic listening and sleeping phase, by setting the wake-up interval timer, I_{wakeup}.

A node performs LPL every I_{wakeup} timeout to receive an incoming packet. If the current time is not Hello time, then the node just senses the channel to receive any incoming packet with a preamble. Otherwise, it first sends the Hello packet, then senses the channel to receive. When a node has a packet to send, it checks its lookup table and remains in the sleep state until the destination wakes up. If the wake-up time of the receiver is Hello time, the node receives the Hello packet and then sends the packet. Otherwise, it directly sends the packet. The mandatory packet preamble also compensates for the clock drift.

4. VL-MAC

AS-MAC and PE-MAC are efficient in terms of power consumption because nodes wake up to listen periodically, or only when they have data to send. However, they both suffer from a major drawback: one packet transmission is done for each wakeup time.

This is problematic both when data sizes do not fit within one packet (in our target application this occurs during network maintenance), or when several senders try to target the same receiver (in our application this occurs very often, when data production rates are close to wakeup rates, because all the data converge towards one sink).

If the sender and the receiver know that there is a free time interval until the next wakeup of their neighbours, they can use it to send other packets. This can be useful either for relatively large amounts of data (e.g., network configuration information), or near the network sinks, where traffic is higher.

Figure 1 depicts the protocol to support Variable Length (hence VL-MAC) burst-mode data transmission, in this case from node 1 to node 2. Node 1 knows its neighbors' earliest wakeups, and hence until when it can transmit to node 2 without interfering with other transmissions in its neighborhood. But it may not know the wakeup times of some neighbors of node 2 ("hidden nodes" from its perspective). Therefore node 2 needs to send back a small packet to announce the earliest wakeup of its neighbors. Then node 1 knows for how long it can send data without interfering.

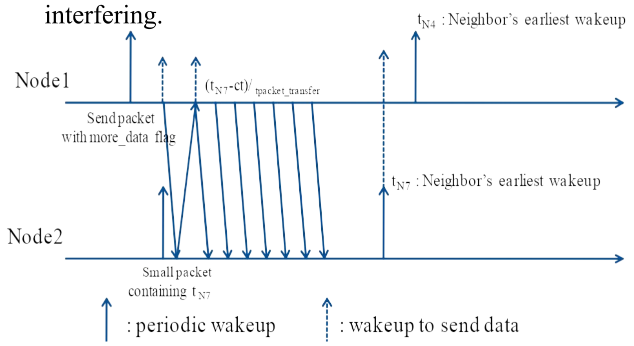

Figure 1 Time diagram for VL-MAC

We follow the contention resolution scheme of AS-MAC here. For brevity, we only consider the data transfer phase.

When there are more data to send, the sender side state machine sets the *more* flag to true. When it receives the response packet back from the other node, it calculates how much data can be transmitted.

$$\#packet = (\min(t_{earliest\_wakeup\_sender}, t_{earliest\_wakeup\_receiver}) - t_c)/t_{send\_one\_packet}$$

where $t_{earliest\_wakeup\_sender/receiver}$, is the earliest wakeup time among the sender's and the receiver's neighbors respectively (t_{N4} / t_{N7} in Figure1), t_c is the current time and $t_{send\_one\_packet}$ is the time to send one packet.

When the receiver side state machine receives a packet, it checks the *more* flag, and if required it sends back a small packet recording the earliest wakeup time of its neighbors, receiving more data if the *more* flag is set.

We can achieve two advantages with this scheme, as will be shown more in detail in the last section:

- Less contention, due to fewer transmissions
- Much shorter latency for large amounts of data.

5. Target Application

As mentioned above, our target application monitors forest fires with spatially distributed sensors. Here we describe the main constraints that apply directly to the MAC layer.

Every second each sensor performs a temperature reading and processing, as well as an auto-test. Under normal conditions it sends out a heartbeat message every hour that also carries temperature statistics. Under alert conditions the messages are sent much more often, every 10 seconds, to make sure that the event is delivered before the sensor is damaged by the intense heat (this means that routing nodes must wake up to listen every 10 seconds). Last, it reports the errors detected during auto-test every minute, as long as the error persists.

To reduce the hardware and energy costs of the sensor nodes, they do not have networking capabilities. Larger nodes are installed, that are able to receive the sensor node communications and establish ad hoc mesh network connections with peers for bidirectional data transfer. Some of the mesh nodes may offer special services, such as an out-of-field data link (e.g., a GPRS link). As there are many sensor nodes in a typical WSN application, even a low message rate per sensor may add up to a significant network load upstream, often translating into a considerable strain on the energy reserves of several field devices, especially when power management is used extensively and nodes spend most of the time sleeping, as with AS-MAC and its variants discussed in this paper.

Thus we adopt several techniques to limit the data traffic both within the network and over the out-of-field links. The computing power of the mesh nodes is used to process most of the sensor data locally. Since the energy required for processing a message is by far lower than the energy to forward it, this technique alone is quite effective for energy saving. The urgency of the sensor messages is first assessed. Alert messages are forwarded with the highest priority, while only changes of sensor state are forwarded. Other sensor data, such as temperature readings, are forwarded only for a few sensors, specifically selected by the operator.

The mesh nodes perform non-critical data aggregation (periodic status messages) to further save energy.

6. Experimental Results

The topology under evaluation is a mesh structure with 16 nodes, acting both as packet sources and routers, and 3 sinks. I_{hello} is 1 minute (which could be increased, since nodes enter and leave this network only very rarely), and $I_{wakeups}$ is 10 seconds (in order to support the application requirement under emergency conditions). We currently do not model detailed aspects of the application scenarios, such as packet aggregation for status information, because we know from application developers that such status information is neither performance- nor energy-critical. However, the conditions of overload are reasonably realistic, since in a real application each router near the sinks may have to manage thousands of nodes, Every simulation has been run for 24 hours of simulated time, requiring under a minute of simulation time, using a custom-built simulator. The channel model uses log-normal shadowing to determine the packet error rate [1]. Errors are simply modeled as dropped packets in these simulations.

Figure 2 demonstrates how VL-MAC improves the performance under higher network load conditions. The delay per hop increases significantly in case 4 with AS-MAC. However, VL-MAC can cope with the overload by exploiting burst transfer mode, and it also has better contention win probability.

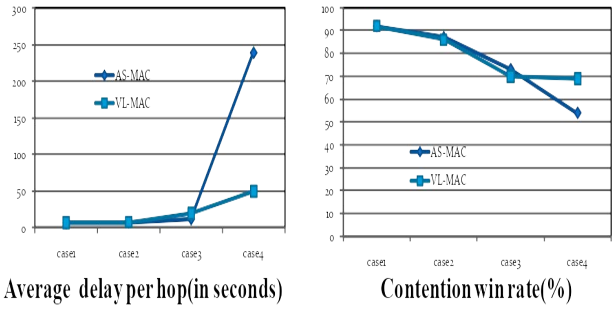

Figure 2 PE-MAC and VL-MAC: Burst Case

Figure 3 shows how a combination of PE-MAC and VL-MAC, called VLPE-MAC, improves over the basic AS-MAC and over PE-MAC and VL-MAC alone. The data generation rate is one packet per minute. PE-MAC can adapt itself to the status of channel to use less power for transmission. The histogram shows the number of packets transmitted at every power level using the TI CC2430 radio, where P0-P10={0, -0.4, -0.9, -2.7, -4, -5.7, -7.9, -10.8, -15.4, -18.6, -25.2}dBm. Figure 4 demonstrates the effect of the protocols on the number of backoffs. The Y-axis represents the total backoff count and the X-axis shows each node. We assume that data is generated every minute, which implies a high network load and thus a long hop delay, because with packet interval of 1 minute and wakeup interval of 10sec 6 nodes can saturate a node.

The AS-MAC protocol suffers from high contention losses, which result in a high number of backoffs. On the other hand, VL-MAC can send a lot of data with only one contention resolution; hence it achieves much better results. The combination of VL and PE shows the best performance results.

AS-MAC	PE-MAC	VL-MAC	VLPE-MAC
0.1512	0.1382	0.1070	0.0968

Table 1 Average power comparison

Power results, shown in Table 1, are similar. Note that the improvements provided by the PE-MAC channel-adaptive strategy and by the VL-MAC burst transmission are somewhat orthogonal, in that their combination VLPE-MAC is better than both.

5. Conclusions

In this paper we showed how, by exploiting asynchronous scheduling, that wakes up a node for transmission only when it has data to send and the destination is known to be awake, we can achieve effective data transmission under different network load conditions, in order to satisfy the diverse requirements of a real forest fire detection application. In particular, channel-aware backoff scheduling and burst-mode transmission significantly improve bandwidth, latency and contention, while keeping power consumption very low.

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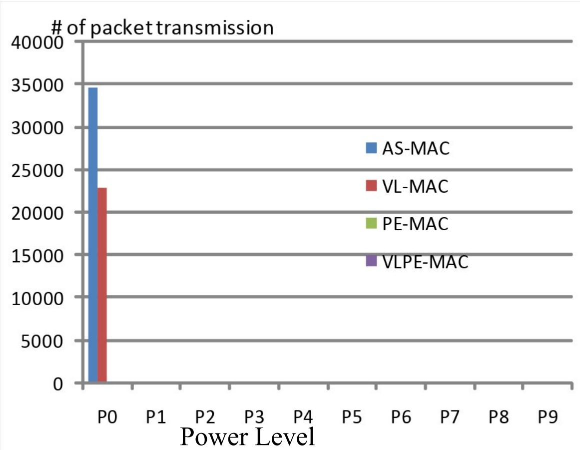

Figure 3 Transmission Power mode histogram

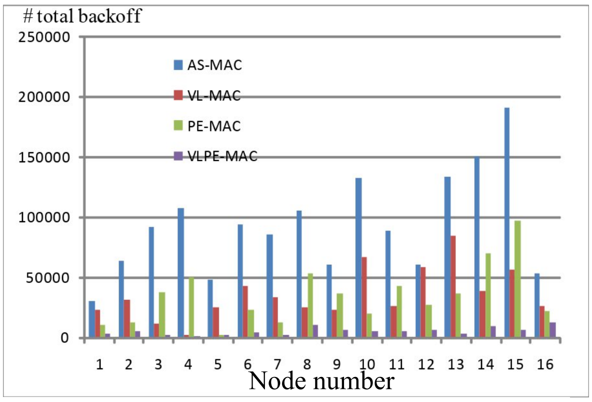

Figure 4 Total Backoff for Congested Case