Energy-efficient MAC Protocol Enabling an Optically Powered Sensor Network

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Abstract: A new MAC protocol allows communication with both awake and asleep network elements. The protocol and its capabilities are demonstrated in an exemplary sensor network.

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1. Introduction

Energy is a precious resource, and telecommunication networks tend to demand more of it due to the fast growing traffic volume, so energy efficiency becomes an important issue [1]. Much energy is wasted by devices which are fully powered up without having traffic to deal with. The easiest and most efficient way to save energy is to switch off network devices or components which are currently not in use [2]. Because switched-off, "sleeping" devices are not listening to requests and cannot be addressed, appropriate protocols need to re-establish the communication channel first.

Here, we describe a protocol which handles the communication with continuously active and with temporarily sleeping network elements [3]. For low duty-cycle sensors, sleep modes can be exploited efficiently, so that the average power consumption can be decreased to a level where even optically powering of network elements becomes feasible. As an example, we demonstrate a long-range optical network of sensors, where only 16 µW optical power per sensor node is sufficient for its operation. Such networks are of interest if galvanic connections must be avoided, or if a local electrical power supply does not seem appropriate.

2. Low-energy medium-access control (LE-MAC) protocol

The LE-MAC protocol relies on one (or more) base stations (BS) that control the communication within the network. Control signals from the BS (Fig. 1(upper left)) coordinate the traffic from and to the BS. Network elements (sensor nodes in Fig. 1(upper left)) could take over the role of a base station. Traces S1 to S4 indicate activity of S*i* when set to "high", but show possible energy-saving modes for "low" levels. The base station in charge controls the network by repeatedly sending polling signals carrying different information, Fig. 1(right, top trace, ①): The Fin symbol signalizes the end of a communication timeslot. It is followed by a listening (Lstn) period where sensor nodes (S*i*) can request a communication timeslot (Rq, broken arrows upwards). A back-off algorithm avoids collisions between requests of several S*i*. The BS acknowledges each request (broken arrows downwards). At the end of the listen period the BS assigns to one of the S*i* the next communication timeslot. The node's address (Addr) and the length of the following communication timeslot (clock symbol) are broadcast over the network. The S*i* assigned to the actual timeslot exchanges data with the BS (Com, double arrows and shaded region in BS trace). Deferred S*i* wait for the next polling signal in an energy-saving mode (low level of S*i* traces). Sleeping time can be exactly timed

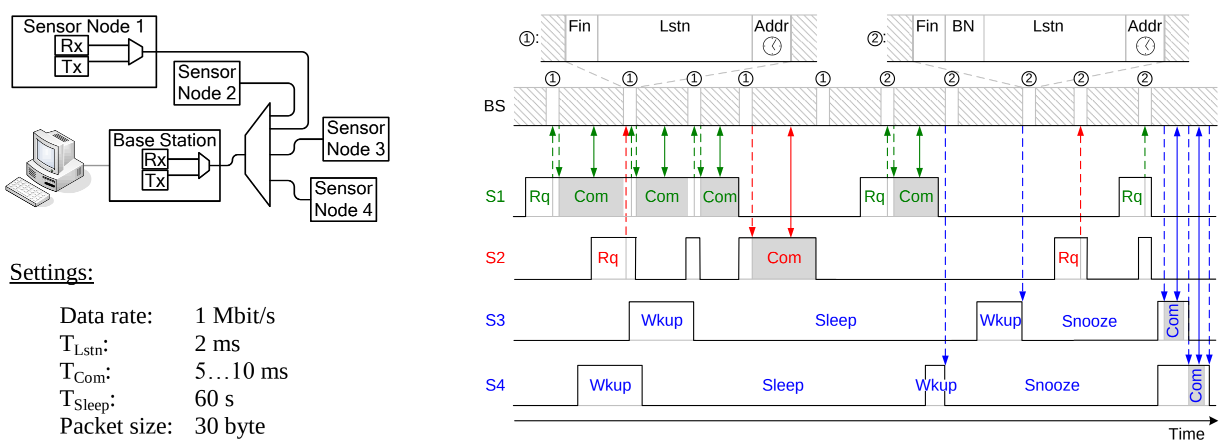

Fig. 1 General network structure and LE-MAC protocol. (upper left) Example network with base station (BS) and sensor nodes S*i*. Nodes communicate only with BS. (lower left) Protocol settings (right) Timing chart. The base station (BS) organizes communication with different sensor nodes S*i* by polling signals 1 or 2 (top trace). A detailed description is given in the text.

as the length of the communication timeslot was broadcast. The BS can give some S*i* (here: S1 and S2) a higher priority in terms of assignment frequency and length of the assigned timeslots. Therefore, quality-of-service and dynamic bandwidth allocation are inherent properties of the protocol, such supporting networks with high traffic load.

When network elements generate only little traffic, other aspects come into play (exemplified by sensor nodes S3 and S4), because transceivers and logic circuits can be switched off most of the time to save energy (Sleep and Snooze in Fig. 1(right)). However, for being addressed the S*i* have to wake up in intervals (Wkup), and have to listen to the BS. This task is assigned to an internal clock that is available in two versions: A very energy-efficient voltage controlled oscillator with poor accuracy (Sleep), and a high precision quartz clock with higher power requirements (Snooze). Sleeping leads to synchronization loss between the BS and the S*i*. A re-synchronization has to be done before communication takes place. To this end, the polling signal ① is supplemented by a beacon (BN) added after the Fin symbol (polling signal ②). The BN signalizes the S*i* if and when a communication “rendezvous” will be arranged. The BN signals have to be sent inside a period larger than the sleep time of the S*i* to ensure that each S*i* receives one BN at least. As soon a BN is received, the S*i* extracts the time stamp for the next rendezvous with the BS, sets a high precision quartz clock, and then goes snoozing (Snooze). Snoozing S*i* awake exactly at rendezvous time and wait for being addressed by the BS. The ratio of energy-costly active and energy-saving sleep and snooze times can be tuned down to an arbitrarily low level, a duty cycle of 10^{-5} is very practical. If necessary, the sensor nodes can switch from low-availability (S3,4) to high-availability status (S1,2) on request of the base station.

In an experimental setup with electrically connected sensor nodes, Fig. 1(lower left), we checked the operation of the LE-MAC protocol. An ARM STR-E912 evaluation board acted as base station, four boards equipped with MSP430-F2234 µC represented sensor nodes. The boards where directly connected over their UART ports. The effective co-existence of sensor nodes with high availability (duty cycle 1) and low availability (duty cycle 3×10^{-5}) within one network was successfully demonstrated.

3. Optically powered sensor network with LE-MAC protocol

When a protocol can handle loss of synchronism, so that network elements can employ lowest-power sleep modes, even optically supplied power can suffice to operate a sensor node. In Fig. 2(left), an optically powered sensor network is sketched. The base station, responsible for data collection and energy supply, comprises a standard DFB laser (λ = 1510 nm, $P_{BS,\max}$ = +6 dBm). The laser operates continuously (CW) and provides the nodes with the necessary optical power. The CW light is slightly modulated (modulation depth 10%) for transmitting the necessary protocol data to the sensor nodes. Three sensor nodes are connected to the base station via an optical 1:8 splitter. One of the nodes is remotely connected via a 10 km standard singlemode fiber (SMF28). The data collected by the BS are read with a standard USB connection and visualized on a PC. The USB connection also supplies electrical power to the base station, so that the whole sensor network is powered and controlled by one USB port.

In Fig. 2(right) a block diagram of an optically powered sensor node is shown. The incoming light with a power of 16 µW (–18 dBm) is distributed by a 1:8 splitter to 6+1 photodiodes [4]. The upper six photodiodes supply electrical energy to the node. Each photodiode provides a voltage of 0.35 V generated out of –29 dBm optical power. As the photodiodes are connected in series, they deliver up to 2 V for the microcontroller (µC). A 470 µF capacitor acts as energy buffer, and is charged by the photodiode array. In sleep and snooze mode the surplus of electrical power coming from the photodiode array charges the storage capacitor, whereas in active periods the capacitor is partially discharged by 0.1 V. For one S*i* in sleep mode, the current consumption was measured to be 550 nA. Recharging the capacitor after an active period of 1.5 ms takes 8 min. The voltage at the capacitor slowly increases with time. However, the µC does not reliably operate at startup, where supply voltages are very low and only slowly increasing, therefore an auxiliary device, a so-called voltage supervisor (VS) is needed. When the voltage at the storage capacitor reaches 2 V, the VS switches the µC power on. Then the µC switches the VS off. The complete power management now remains with the µC. If the sensor node needs to connect to the base station, a DC/DC boost converter is

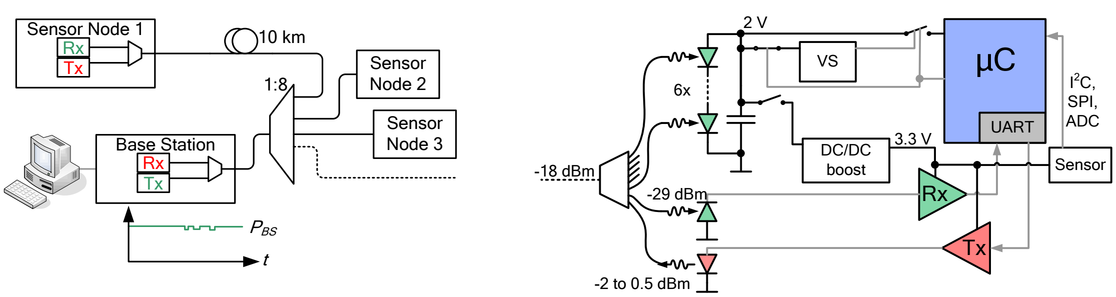

Fig. 2: Optically powered sensor network (left) Drawing of the sensor network consisting of a base station electrically connected to a PC and optically connected to three sensor nodes via a 1:8 splitter. (right) Block diagram of a sensor node with opto-electronic power conversion, multiple communication interfaces and power management functionalities.

started and delivers (for a limited time period) a fixed output voltage of 3.3 V supplying the receiver circuitry (Rx). The Rx photodiode is connected to the seventh port of the 1:8 splitter and receives the BS control signals. Sensor data are transmitted back to the base station with a directly modulated VCSEL diode (Tx, λ = 1310 nm, P_{out} = -2…+0.5 dBm). It is connected to the eighth port of the splitter. Both Rx and Tx use the UART port of the µC.

The open circuit voltage of the photodiode defines the maximum charge voltage for the storage capacitor and increases logarithmically with the optical input power. The sensitivity of the receiver circuitry is therefore influenced twofold by the input power: Directly by the optical control signal power, and indirectly because Rx is supplied by the DC/DC boost converter which is losing stability with a decrease of optical input power, resulting in a decreased input voltage for the DC/DC converter. Fig. 3 displays the measured frame error ratio (FER) in dependence of the optical input power. The strong increase of the FER for P_{opt} < –21.7 dBm results from instable operation of the DC/DC boost converter. As the node is normally supplied with an optical power of –18 dBm, a margin of 3 dB is left. Input powers of more than -13.8 dBm drive the receiver amplifier into saturation, and strong signal distortion occurs. In between, the FER drops below $4 \cdot 10^{-6}$.

The sensor node can be equipped with a number of different sensors. The node provides 3.3 V supply voltage as well as digital (I²C, SPI) and analog sensor interfaces. In our network, the three nodes where equipped with a temperature, an acceleration and a light sensor, respectively. With a minimum input power of –18 dBm per sensor node, 24 dB are available as distribution loss. This corresponds to a maximum splitting of 1:128 including 2 dB excess loss, or up to 120 km of standard SMF.

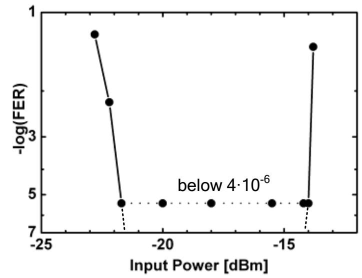

Fig. 3: Measured frame error ratio depending on the optical input power.

4. Applications

Sensor networks are increasingly deployed for home automation, facility management, monitoring the structural integrity of buildings and bridges, and high-voltage applications. As a power supply is needed for nearly all kind of sensors, unwired sensors need an inbuilt energy source like a battery, or have to harvest their energy from their environment. Thus, a limitation of lifetime or application area results. Instead of supplying power by electric wiring, our sensor nodes are supplied by optical power delivered in a fiber, which is required anyway for the data exchange with the base station. This enables operation with negligible susceptibility to electromagnetic interference and lightning due to the galvanic isolation between sensor nodes and base station. Likewise, operation in a discharge-sensitive environment and operation without electromagnetic radiation from wires even at high and highest data rates become feasible. Furthermore, the low loss of optical fibers enables to bridge large distances between sensors and controlling base station. Emphasis is on low power consumption for this kind of sensor nodes to achieve long reach, to meet security aspects, and to lower costs.

A recently emerging and very promising application field for such optically powered sensor networks is the envisaged smart power grid. As generation and consumption of electrical power will strongly vary in time, storage and routing of electrical energy will be mandatory. Therefore, measuring of the available and needed power as well as monitoring of the components of the power grid will strongly gain importance [5]. Small optically powered sensor nodes are promising candidates for simplifying this task by offering sufficient bandwidth, long reach, and perfect galvanic isolation. Future monitoring devices combine low- and high-latency services which can be handled favorably by the LE-MAC protocol. Another application of optically powered devices can be found in telecommunications. At so-called demarcation points, a traffic-transparent energy-autarkic sensor (demarcation device) is placed. It can be interrogated by the central office to monitor the link performance independently of an attached ONT [6].

5. Summary

We demonstrate an energy-efficient MAC protocol which enables the addressing of unsynchronized and sleeping network elements. As an application, we test an optically powered sensor network. A sophisticated choice of optical and electronic components reduces the minimum optical input power for a sensor node to only 16 µW. The LE-MAC protocol enables low-duty cycle bidirectional communication although the nodes' electrical power consumption for sending and receiving is much larger than the optical supply power.

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6. References

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