Optically powered fiber networks

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Abstract: Optically powered networks are demonstrated. Heterogeneous subscribers having widely varying needs with respect to power and bandwidth can be effectively controlled and optically supplied by a central office. The success of the scheme relies both on power-efficient innovative hardware and on a novel low-energy medium access control protocol. We demonstrate a sensor network with subscribers consuming less than 1 μW average power, and an optically powered high-speed video link transmitting data at a bitrate of 100 Mbit/s.

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OCIS codes: (060.0060) Fiber optics and optical communications; (999.9999) Power over fiber; (120.0280) Remote sensing and sensors; (040.5350) Photovoltaic; (060.4250) Networks; (060.4256) Networks, network optimization

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#101669 - $15.00 USD Received 16 Sep 2008; revised 12 Nov 2008; accepted 13 Nov 2008; published 17 Dec 2008
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22. Our wavelength-optimized photovoltaic converter has a high conversion efficiency of up to 50 % depending on illumination power and load [13]. For low optical input powers, a pin-photodiode with very small saturation current is optimum.
23. Mixed signal microcontroller, Texas Instruments MSP430-family. At 3.6 V and in *l*ow-*p*ower *m*ode LPM3-VLO ("sleep mode", internal inaccurate clock active) we measured a supply current of 0.5 µA, in LPM3-LFXT1 ("snooze mode", external accurate quartz clock active) it was 1 µA. Further modes are memory retention mode LPM4 (0.1 µA) and active mode (390 µA). An interrupt event can wake up the device from any of the low-power modes, service the request, and restore back to the low-power mode on return from the interrupt program.
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1. Introduction

In optically powered networks, both, communication signals and power for remotely located subscribers, are transmitted over an optical fiber. Optical powering is a key enabler for a new generation of autonomous multifunctional intelligent subscriber and sensor networks with a broad range of monitoring and communication functions related to security of homes and public spaces, of roads, bridges and personal health as well as to general-purpose communications, to name just a few. One can also envisage optical powering of short-range passive optical networks (PON) comprising distributed link-supervision [1].

Key features of optically powered networks are subscriber operation without local power supplies or batteries, operation with negligible susceptibility to electromagnetic noise and lightning due to galvanic isolation between subscribers and central offices, operation in discharge-sensitive environments, and operation without electromagnetic radiation from wires even at high and highest data rates. Last but not least it should be mentioned that optical fibers have very small attenuation, e. g., 0.15 dB / km for standard singlemode fibers. This opens the application field even for large network area coverage.

Despite the advantages of such networks, it is only in most recent years that advance towards inexpensive high-power lasers, highly efficient opto-electric converters and, most importantly, the advent of low-power high-performance electronics have alleviated the problem of limited local electric energy.

Historically, the basic idea of providing photonic energy to an optical network was realized as early as 1978 when an optically powered sound alerter was demonstrated at Bell Labs by DeLoach, Miller and Kaufman [2] for a fiber-based telephone network. A year later, the same laboratory reported satisfactory two-way speech transmission and vigorous sound alerting at the remote station with 14 mW of DC averaged laser power incident onto the fiber, Miller and Lawry [3], and this work was continued over the next three years [4]. A decade of de-

#101669 - $15.00 USD Received 16 Sep 2008; revised 12 Nov 2008; accepted 13 Nov 2008; published 17 Dec 2008
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velopment had passed when Kirkham and Johnston [5] from Jet Propulsion Laboratory provided in 1989 a brief historical review on fiber-optically powered devices along with the description of an optically powered data link with 1 kHz bandwidth for power system applications. It was ventured by Banwell et al. [6] from Bellcore in 1993 that it may be possible to operate conventional telephone station sets using electricity derived photovoltaically from light in a fiber. These authors concluded that with a power delivery to end-loop equipment below 30 mW for a 3.6 km loop (larger link attenuation) and 200 mW for a 1 km loop (smaller link attenuation) the cost of optical powering would be comparable to powering over copper. Further, an optically interrogated network of optically powered sensors was discussed by Pember, France and Jones [7] in 1995. They stored the photogenerated energy locally in a capacitor and emphasized the advantage of GaAs photogenerators (30 % efficiency) over silicon photodiodes (15 % efficiency). Another very specialized network consisting of optically powered electrical accelerometers was successfully built and field-tested by Feng [8] in 1998, while Pena et al. [9] described in 1999 an efficient power-delivery system for an all-fiber point-to-point connection with an optoelectronic sensor unit. With a viewpoint to overall energy saving, Miyakawa, Tanaka, and Kurokawa [10] published in 2004 design approaches to integrate solar energy harvesting in a power-over-optical local-area-network. The authors proposed a fiber optic power and signal transmission system for DC powering to such information tools as personal computers. Only recently, in 2007, the first optically powered video-link with bitrates above 100 Mbit/s was demonstrated [11].

Key to the success of optical powered networks is an energy efficient conversion of optical power into electrical energy. First serious studies on power budgets of optically powered links were performed by Liu [12] from DIAS (UK) in 1991 concluding that GaAlAs photovoltaic cells had to be chosen for a highly efficient power conversion. Record conversion efficiencies of 50.2 % were achieved in 2001 by van Riesen, Schubert, and Bett [13] from Fraunhofer Institute for Solar Energy Systems (Freiburg, Germany) when illuminating GaAs photovoltaic cells with an intensity of 6.5 W/cm^2 at a wavelength of 810 nm. The important influence of cell temperature on the conversion efficiency was emphasized by Miyakawa, Tanaka, and Kurokawa [14] in 2005. A most recent publication in 2008 by Werthen [15] discusses photovoltaic power converters (PPC) with electrical output powers over 1 W. The optimum light for a GaAs PPC lies in the wavelength range of 790 nm to 850 nm where various pump lasers with power levels as high as 5 W are available. For higher light levels above 10 W, InGaAs pump lasers in the range of 915 nm to 980 nm are most practical. To function with such lasers, the PPC also has to be made from a similar material, the bandgap of which and, hence, the voltage output from the PPC is less than that of GaAs devices. A PPC has been demonstrated with over 1 W of electrical output using a 5 W laser emitting at 960 nm. The authors remark correctly that at such output power levels even the remote powering of distributed antenna systems becomes possible.

Conversely, power consumption can be minimized at the subscriber station. Lowest power device operation with microwatt-power InGaAs photogenerators for lightwave networks were pioneered in 1997 by Giles at al. [16] for powering a remotely-located optical shutter. For this application a 10 V optical-to-electrical InGaAs photogenerator was reported in 1999 by Dentai at al. [17] from Bell Labs.

In this paper we discuss an optically powered fiber network that connects and provides power to a multitude of subscribers, which are attached to a central office (CO) in a combined star and tree-like topology. The focus of this paper is on energy optimized subscriber hardware in combination with a new and flexible *l*ow-*e*nergy *m*edium-*a*ccess *c*ontrol (LE-MAC) protocol, which enables efficient use of the optically provided energy that is transmitted to each subscriber. Both, energy-hungry subscribers with high network priority (as is the need for video conferencing) and energy-preserving subscribers having a low network priority and a very small duty cycle (e. g., temperature or humidity sensors), can be handled by the CO simultaneously.

#101669 - $15.00 USD Received 16 Sep 2008; revised 12 Nov 2008; accepted 13 Nov 2008; published 17 Dec 2008
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For an illustration, we refer first to a network of, e. g., temperature sensors. Temperature sensors need little power and typically are sampled only once in a while. Our LE-MAC protocol allows the sensors to accumulate and store energy within their idle time, then to perform a measurement for a short time, and to send the acquired information back. Multiple sensor modules are connected to one fiber. To avoid collisions of the sending sensors and to poll the multiple sensors on demand, the LE-MAC protocol organizes their idle and communication time slots.

The second example for an optically powered device is a video camera with an uncompressed live video stream in VGA resolution. Fifteen frames per second are sent over 200 m of multimode fiber. This results to a data rate of 100 Mbit/s. This subscriber is never idle, and the acquisition and processing of data is power demanding because of the high processing speed and the large amount of data.

In the following Section 2 we describe the scenario of an optically powered heterogeneous network. A suitable low-energy medium access control (LE-MAC) protocol is developed in Section 3. Next, Section 4 is devoted to optically powered subscribers, and Section 5 presents results for two examples of optically powered networks. We end up with conclusions.

2. Scenario of an optically powered heterogeneous network

For definiteness, we discuss exemplarily an optically powered subscriber network with representatives of the most important device types, see Fig. 1. Photonic power is distributed to a multitude of subscribers S*n* (*n* = 1,2,…*N*) with different power supply and bandwidth requirements.

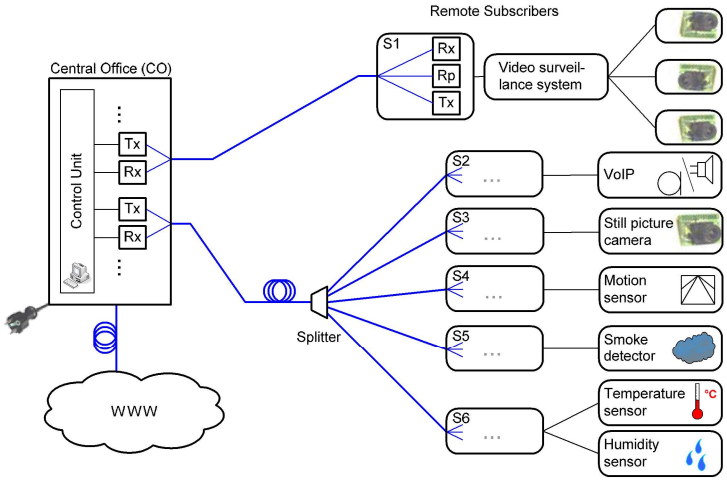


Fig. 1. Photonic network with optically powered subscribers. Optical transmitters (Tx) in the line-powered central office (CO, base station) transmit a downstream data signal with an appropriate average power for remotely supplying data and optical energy to subscribers. Optical receivers (Rx) in the CO sense the upstream data. Remote subscribers (S1…S6) comprise — besides the data acquisition and communication units — a section with optical data receiver Rx, photonic-power receiver Rp (photogenerator supplying electrical energy) and optical data transmitter Tx. A single Tx/Rx section in the CO can supply electrical energy to a multitude of subscriber sub-units. In the case of a video surveillance system (S1), sub-units would house various cameras at different locations or looking into different directions. Subscribers with high electrical power demand like S1 can be point-to-point connected to dedicated Tx/Rx units of the CO. Subscribers with lower energy demand are connected to the CO in a tree-like fashion and share one Tx/Rx of the CO. Such subscribers are for example voice over IP clients (S2), still picture cameras (S3), motion sensors (S4), smoke detectors (S5), temperature and humidity sensors (S6).

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The network consists of a line-powered intelligent central office CO (base station) with optical data transmitters (Tx) and data receivers (Rx) that are spatially or wavelength (de-)multiplexed to (from) a single fiber. The CO transmitters supply data at a mean power level such that sufficient energy is transferred to the remotely connected devices. The subscribers feature an energy head comprising data transmitters and data receivers as well as a photonic-power receiver (Rp), all of which are spatially (de-)multiplexed to (from) the transmitting optical fiber.

In this context, the designation "central office" comprises more or less complex base stations (e. g., "optical line terminations" (OLT)) that provide optical power along with data services, and "subscriber" stands for any remote device like sensors or general-purpose transceivers (e. g., "optical network units" (ONU), "optical network terminations" (ONT)), which are able to communicate with CO via the optical network.

Typical subscribers are compared in Table 1 with respect to their mean power consumption and their operating duty cycle. Here, duty cycle means the ratio of energy-costly active time periods, where measurement and communication tasks are performed, and idle time intervals spent in an energy saving (snooze) or even minimum-power (sleep) mode.

Table 1. Typical mean power consumption and duty cycle of different subscribers.

		Mean power consumption		
		low (few µW)	medium (few mW)	high (few 100 mW)
Duty cycle	Low (10^{-5})	Temperature	Motion	
	medium (10^{-2})	Smoke	Still picture	
	High (10^{0})		Speech	Video

In the scenario of Fig. 1, low and medium power subscribers like speech communication (S2) using the voice-over-internet protocol (VoIP), still picture cameras (S3), motion detectors (S4), smoke detectors (S5), temperature and humidity sensors (S6) share a common fiber using remotely located active or passive power splitters. If need arises, subscribers with large mean power consumption like video conferencing or special surveillance systems (S1) can be supplied by the CO individually. The CO integrates all the heterogeneous subscribers in one network structure, and in addition provides an interface to the world-wide communication network (WWW).

The subscribers' heterogeneity and the specific network architecture — a combined star and tree-like topology — have important consequences for the communication between subscribers and CO: Subscriber signals can only be received by CO, and signals originating from CO must be broadcast to all subscribers. Therefore, a standard carrier sense protocol (for example, an energy-efficient version [18] of a carrier sense multiple access (CSMA) protocol) is not able to organize the communication. This is also true for the *s*ensor-MAC (S-MAC) protocol [19] or for the low-duty cycle *s*cheduled *c*hannel *p*olling MAC (SCP-MAC) [20], both of which were designed for battery-operated wireless nodes. As a consequence, the CO's control unit alone has to organize the communication and all subscribers' needs regarding priority, bandwidth, and expected inactive times. In the following we describe a MAC protocol extension that meets the requirements of heterogeneous subscribers as envisaged in Fig. 1 and Table 1. With respect to low duty cycle subscribers, our protocol compares favorably with SCP-MAC insofar, as SCP-MAC has, for a given configuration, a minimum duty cycle for effectively reducing the power consumption (3×10^{-3} was demonstrated [20]), while our MAC protocol has not. We show experimentally that duty cycles as low as 10^{-5} are feasible, and that

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the lower limit for energy savings by lowering the duty cycle is given only by the devices' minimum energy consumption in sleep mode (for a duty cycle approaching zero).

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

In this section we present a *l*ow-*e*nergy *m*edium *a*ccess *c*ontrol (LE-MAC) protocol that serves the needs for optically powered heterogeneous subscribers in a simple and effective manner. To operate all subscribers with the least possible power consumption we extend specifications of common *m*edium *a*ccess *c*ontrol (MAC) protocols with the following features:

- Communication of subscribers only with CO
- Random and scheduled medium access of subscribers
- Quality of service with flexible assignment of priority and bandwidth
- Polling subscribers by CO broadcast, multicast and unicast replaces carrier sense [21]
- Subscribers with high and low mean energy demand in one network
- Support of energy saving *snooze mode*: Subscribers maintain synchronism with CO.
- Support of minimum-energy *sleep mode*: Subscribers lose synchronism with CO. The sleep mode requires the following built-in features:
    - All communication circuitry switched off
    - Autonomous wake-up needed, no external control possible
    - Quick restoration of synchronism by listening to CO's polling at wake-up
    - Reception of CO-scheduled rendezvous time
    - Returning to snooze mode until wake-up at precise rendezvous time
    - No energy-costly data transmission to CO before rendezvous time
    - Communication with CO at rendezvous time
    - Returning to sleep mode until next autonomous wake-up

The LE-MAC protocol's timing chart schematic is given in Fig. 2. The CO organizes the communication with subscribers by broadcasting the polling signals ① or ②, details of which are shown in the top row of Fig. 2.

The CO's communication protocol consists of alternating polling and Com sequences. A polling sequence comprises Fin, a Lstn and a Addr sequence, see ①. Optionally the polling signal might comprise a RV sequence, see ②. Details of the polling sequences are explained when discussing sequence ①.

In our example, the Fin sequence stops communication between any of the subscribers and CO. Then, subscribers S1 and S2 require CO's attention and send — after a random waiting time to minimize collisions — a request Rq to CO (broken arrows upwards). The CO then listens for a fixed time interval (Lstn) and acknowledges reception. At the end of the Lstn period the CO schedules the subscribers that have requested bandwidth. During the addressing interval (Addr, broken arrows downwards) the CO broadcasts addresses and timestamps for future unicast communication. Subsequently, the scheduled subscribers may communicate with the CO during the assigned communication time slot (Com, solid double arrow). Deferred subscribers learn by the broadcast when the next Fin or Lstn interval is to be expected, and can spend this idle time in an energy saving *snooze mode* before repeating their communication request Rq or listening to the next Addr information.

So far all subscribers maintain time synchronism with the CO, even in snooze mode. For lowest-power subscribers a precise quartz clock could be too energy-costly, so that subscribers with small duty cycle (S3 and S4 in Fig. 2) may reside in a minimum-energy *sleep mode*. Yet, while sleeping, only an inaccurate but ultra-low power clock is running for waking up the device, and so time synchronism with CO is lost. These devices cannot be scheduled accurately over a longer period.

A possible — but inefficient — communication with these subscribers could be as follows: A sleeping subscriber wakes up and either requests communication with the CO during the Lstn sequence, or checks the Addr sequence for scheduled communication. Since the

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wake-up time of the sleep mode subscriber is not accurate, the Addr request has to be repeated many times, and because sending data to the CO is energy-costly, this procedure increases the average power requirement of the subscriber. In addition, a considerable amount of bandwidth is wasted — particularly if there are many subscribers with sleep mode features.

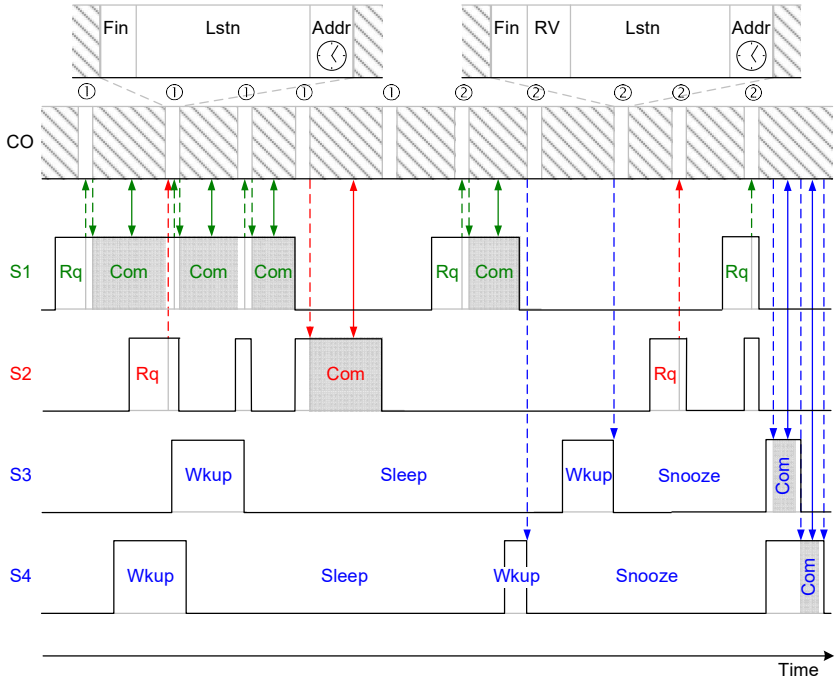


Fig. 2. Timing chart schematic for low-energy medium access control (LE-MAC) protocol; for details, see main text. Due to the treelike network architecture, the central office (CO) broadcasts its messages to each subscriber, which can communicate only with CO, but not peer-to-peer. — *Subscribers with high bandwidth demand* (S1, S2) along with low duty cycle subscribers (S3, S4) are handled by CO via broadcast polling (control) signals ① or ②, top row. Broken arrows stand for unidirectional, solid double-arrows for bidirectional communication (Com) of subscriber and CO. Access requests (Rq) of subscribers are queued by CO during the polling signal's listen interval Lstn in ①. Then CO decides which subscriber will be scheduled next and for what time interval. This is sent during the addressing interval Addr, after which communication can start (Com). — *Low duty cycle subscribers* spend most of the time in a minimum-energy Sleep mode that is interrupted by nearly periodically appearing wake-up intervals Wkup, which are initiated autonomously by the subscribers. Communication with CO is managed by broadcasting special polling (control) signals ②, top row right. During Wkup a rendezvous time stamp RV is sensed, a precise clock is set, and the subscribers return to a power-saving Snooze mode. At rendezvous time the subscribers awake, listen to be addressed, communicate with CO, and go again to Sleep mode.

Therefore, a more efficient protocol is needed. In order to save both energy and communication bandwidth, we introduce an additional rendezvous sequence (RV), the purpose of which is to efficiently inform sleep mode subscribers if and when a communication "rendezvous" will be arranged in not too far a future. The RV sequence typically would be a multicast call to a whole group of subscribers. Yet, it could be unicast as well as being a broadcast call. The protocol then would work as follows:

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When waking up (WkUp in Fig. 2), subscribers S3 and S4 activate their basic receiver circuitry and listen for the CO's polling. If the rendezvous signal RV is *not* received during WkUp (polling signal ① in Fig. 2 as opposed to polling signal ②), the subscribers go back to sleep, as is the case for S3 and S4 during their first WkUp period in Fig. 2. However, if after the Fin sequence a device receives the rendezvous signal RV (polling signal ② in Fig. 2), it extracts the time stamp for the next rendezvous with CO, sets a high precision clock to the rendezvous time, and then goes to an energy-saving snooze mode.

Snoozing subscribers (S3 and S4) maintain a precise quartz clock, awake exactly at rendezvous time and wait for being addressed by the CO. On reception of their individual address (broken arrows downwards), the first chosen subscriber S3 communicates with CO and exchanges data (solid double arrow). Having finished, S3 listens again to CO. On reception of a valid address other than its own (or being triggered by an internal time-out signal), S3 goes back to sleep mode. At this time (broken arrow downwards), S4 senses its own address, starts communicating with CO (solid double arrow), and ends the same way as formerly S3. This can be repeated for as many subscribers as needed. If a subscriber is not addressed or if the addressing signal is corrupted, an internal time-out mechanism sends the device back to sleep mode.

Beginning with the rendezvous time, communication requests Rq from higher-priority subscribers are deferred until the CO decides to end the interrogation of low duty cycle subscribers. It is also possible that — on command of CO — low duty cycle subscribers change their mode of operation and become attentive of polling signals ① in a manner described for the operation of S1 and S2, or that high priority devices fall back to low duty cycles and react to the rendezvous information RV in polling signals ②.

The allocation of bandwidth effected with polling signals ① and ② is very flexible. Subscribers with high priority (e. g., subscriber S1 in Fig. 2) can be preferred to subscribers with low priority (e. g., subscriber S2). Communication with low duty cycle devices (subscribers S3 and S4) can be also arranged at the discretion of CO. Thus a low-latency priority-driven quality of service feature is integral part of the LE-MAC protocol.

Our low-energy medium access control protocol is designed specifically for optically powered devices. The next section discusses the basic hardware of such a subscriber.

4. Optically powered subscribers

An optically powered subscriber must have an optical data transmitter and an optical data receiver as well as a photonic-power receiver. Data exchange and optical energy transmission could basically use either different fibers or different wavelengths or both, but these details are left open for the following consideration. The bandwidth of the optoelectronic converter is assumed to be sufficient for also receiving data. If this was not true, then optical power conversion and optical data reception must be done with separate optoelectronic converters. However, for the scenario Fig. 1, the downstream traffic from CO to subscriber will certainly not be larger than the upstream traffic, and if the subscribers are sensors, the bitrate in upstream will be significantly larger than in downstream, so that the same optoelectronic converter can provide both, electrical power and data. This situation will be assumed here.

4.1 Schematic of an optically powered subscriber

In Fig. 3, the block diagram of such an optically powered subscriber is shown. The incoming light is converted by a photovoltaic cell PV to an electric current [22]. An LC circuit separates the photocurrent's alternating current (AC) from the direct current (DC) which charges a storage capacitor. The AC part enters a receiver amplifier Rx, and the data (Receive Data) are processed by a low-power microcontroller µC.

We start describing the circuit functionality assuming that all electrical circuits are powered down. If optical power becomes available at PV, the direct photocurrent charges a capacitor C_S. When V_C exceeds a minimum voltage typical for the DC/DC converter (DC/DC

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boost), it starts delivering a fixed and stabilized bias supply voltage V_b, which can be chosen to be smaller or (usually) larger than V_C. The voltage V_b then supplies power to μC, to keep it at least in its ultra-low power sleep mode where an inaccurate internal clock takes care of a periodic wake-up [23]. Further, the low-power Charge Monitor circuit is activated, which consumes about as little energy as μC in sleep mode. All other electronics like Rx and subsystems Unit 1…*n* are powered down by μC.

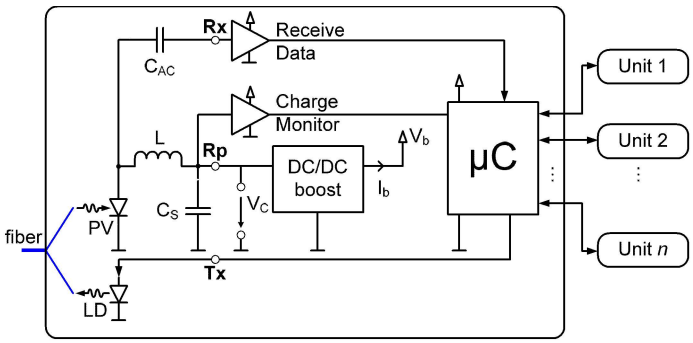


Fig. 3. Block diagram of the photonic-power receiver (Rp), the data receiver (Rx) and transmitter (Tx). The incoming light guided by an optical fiber is converted into an electric current by a photovoltaic cell (PV). An LC network separates the alternating current (AC) data from the direct current (DC) path. The DC charges a storage capacitor C_S. The following DC/DC boost converter delivers a stable output voltage V_b to supply a microcontroller (μC) and two amplifier stages, which either demodulate the incoming data signal (Receive Data), or monitor the voltage V_C at C_S (Charge Monitor), respectively. When V_C exceeds a given value, μC activates any of a multitude of sub-units. The data collected by each Unit are processed by μC, and the result is sent back by a transmitter (Tx) comprising a laser diode (LD), both of which will be powered up for this purpose.

When the Charge Monitor senses that V_C exceeds its preset "charged" voltage level, the μC is informed that it can switch to active mode, activate subsystems Unit 1…*n* and the data receiver Rx, perform their tasks, and send the appropriate information back to CO via transmitter Tx and laser diode LD. Then μC may shut down all dispensable circuitry and return to snooze or sleep mode, so that C_S can recharge. If V_C falls below the preset "discharged" voltage, Charge Monitor senses the event and sends μC a warning to take action.

The average optical power that must be supplied to the subscriber has to be large enough to keep at least the power supply circuitry operational, i. e., DC/DC boost, μC and Charge Monitor. A surplus in optical power is needed if the subsystems are activated, or if receiving and transmitting data is required from the subscriber. Obviously, the average optical power must balance the average need of electrical power. However, it is the subscriber's duty cycle which determines the surplus of average optical power to be supplied.

The dynamic properties of the photonic-power receiver and the electrical power supply were experimentally investigated and are presented in the next subsection.

4.2 Photonic-power receiver and electrical power delivery

The photonic-power receiver which delivers electrical power to the subscriber electronics is the central component of an optically powered subscriber. We therefore investigated experimentally the power supply section from the subscriber schematic Fig. 3 consisting of photovoltaic cell PV (responsivity 0.45 mA/mW [13]), storage capacitor C_S (0.5 F), DC/DC boost converter, and Charge Monitor, which for this experiment connects a resistive load (330 Ω) periodically to the power supply output V_b. Laser light at a wavelength of 808 nm illuminates

#101669 - $15.00 USD Received 16 Sep 2008; revised 12 Nov 2008; accepted 13 Nov 2008; published 17 Dec 2008
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PV with an optical power of 22 mW leading to a short-circuit current of 9.9 mA. In Fig. 4, supply current I_b (lower curve, red), supply voltage V_b (middle curve, green) and storage capacitor voltage V_C (upper curve, black) are displayed as a function of time.

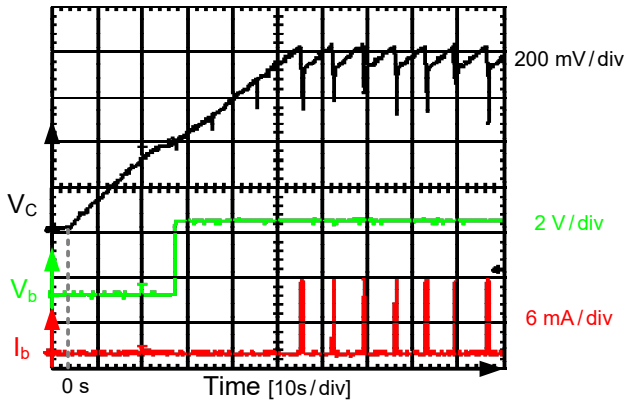


Fig. 4. Measured dynamical behavior of optical power supply for a switched resistive load connected to V_b in Fig. 3. *Upper curve (black):* Charging and partially de-charging the storage capacitor C_S = 0.5 F. *Middle curve (green):* Supply voltage with stable value V_b = 3.3 V (green). *Lower curve (red):* Current I_b through switched resistive load at V_b. — The storage capacitor C_S is charged by the current of a photovoltaic cell illuminated with an optical power of 22 mW. If the capacitor's voltage exceeds V_C = 0.4 V, the DC/DC boost converter starts delivering a fixed supply voltage V_b. For testing this supply, a resistive load of 330 Ω was switched on (for V_C > 0.83 V) and off (if V_C < 0.7 V). If switched on, the resistor consumes 33 mW (10 mA) electrical power for an active period of 540 ms. Then the storage capacitor's voltage falls below 0.7 V, and the load is switched off. This cycle repeats every 6.63 s. (The "**T**" symbols on the second left vertical grid line mark the trigger time and are of no consequence here.)

The laser is switched on at zero time, and the photocurrent starts charging C_S. When the voltage at C_S has reached V_C = 400 mV (Fig. 4, upper curve, black), DC/DC boost starts and eventually delivers a stable supply voltage of V_b = 3.3 V (middle curve, green). The storage capacitor continues charging (upper curve, black), and when reaching the preset "charged" voltage region V_C > 0.83 V, the Charge Monitor circuit switches the resistive load on. This causes a supply current of I_b = 10 mA to flow (lower curve, red), and the capacitor discharges. On reaching the "discharged" voltage range V_C < 0.7 V, the Charge Monitor circuit switches the resistive load off. This process repeats every 6.63 s, and during an interval of 540 ms an electrical power of 33 mW is supplied. The duty cycle amounts to 540 ms / 6.63 s = 8.1 %. The overall efficiency for converting an average optical power of 22 mW to an average electrical power of 33 mW × 8.1 % = 2.7 mW is as high as 12 % including the DC/DC boost circuit with an average efficiency of about 30 % for these operating conditions. If the optical power was larger, the efficiencies of PV and DC/DC boost would increase, and so would the overall conversion efficiency.

5. Optically powered networks

The scenario of heterogeneous subscribers in Fig. 1 combines two device groups, namely high duty cycle subscribers with large (S1) and medium average power demand (S2), and low duty cycle subscribers (S3 … S6) with low average power requirement. Timing chart schematics of the network were provided and discussed in Fig. 2. In the following, we show important aspects of both subscriber groups in an experimental network environment. First we

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prove the efficiency of our low-energy medium access control (LE-MAC) protocol, and second we demonstrate the feasibility of a high-bitrate optically powered video camera link.

5.1. Ultralow duty cycle subscriber network

The most challenging part of the LE-MAC protocol is communication with low duty cycle subscribers that spend most of their time in sleep mode. During this time, the devices cannot be addressed by CO and lose time synchronism as described earlier. To validate the design of this part of our protocol we set up a network of four ultralow duty cycle subscribers S3 … S6 and a CO. For avoiding unnecessary complications we connected CO and subscribers by a wired network, the topology of which is shown in Fig. 5.

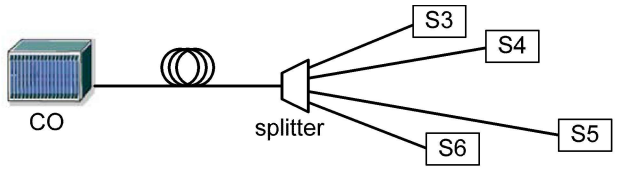


Fig. 5. Network of ultralow duty cycle subscribers S3 … S6 connected to a central office CO.

The experimental CO and the subscribers were realized each with a mixed signal microcontroller μC from the Texas Instruments MSP430-family and powered with a supply voltage V_b = 3.6 V [23]. These μC are designed for sensor systems that capture analogue signals, convert them to digital values, and then process the data for transmission to a host system. One microcontroller serves as CO, is therefore always kept active and maintains an accurate clock. The other μC act as subscribers. The devices communicate by exchanging serial data via their inbuilt universal asynchronous receiver / transmitter (UART) units [24].

Four subscriber operating modes were experimentally tried, and the total supply currents I_b are listed in Table 2. In *sleep mode* the μC maintains an internal low-quality (low-Q) very low power clock (I_{Sleep} = 0.5 μA), while in *snooze mode* an external high-quality (high-Q) 32 768 Hz quartz crystal clock (I_{Snooze} = 1 μA) is active. In *active mode* the μC operates with a digitally-controlled oscillator (DCO) frequency of 8 MHz ($I_{\mu C}$ = 3.5 mA). The internal DCO provides a fast turn-on clock source and stabilizes in 1 μs, however, the external quartz clock needs about 60 ms settling time.

Table 2. Subscriber operating modes and total DC supply currents I_b for a supply voltage V_b = 3.6 V.

Subscriber modes		Attributes	μC current $I_{\mu C}$	Supply current I_b	Total I_b
Sleep	μC low-power modes	Low-Q clock	0.5 μA	I_{Sleep}	0.5 μA
Snooze		High-Q clock	1 μA	I_{Snooze}	1 μA
Receive	μC active mode	Receiver on	3.5 mA	I_{Rx}	6 mA
Transceive		Transceiver on		I_{RxTx}	11 mA

In addition, the *receiving mode* and/or *transmitting mode* require external (optical) receiver (Rx in Fig. 3) and/or (optical) transmitter circuitry (Tx in Fig. 3) to be switched on, and this increases the supply current — depending on the actual Rx and Tx design — to practical values of I_{Rx} = 6 mA (receiving) and I_{RxTx} = 11 mA (transceiving), respectively. The *transceiving mode* comprises both an activated receiver and transmitter.

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In Fig. 6 we show a measured timing diagram for our experimental network Fig. 5 which consists of a CO and four ultralow duty cycle subscribers S3 … S6. The upper curve labeled CO shows the transmitter signal of the central office. For our experiments, the control signal ② of Fig. 2 has been simplified and reduced to its rendezvous (RV) part, which has the duration T_{RV}. Inside a period that must be smaller than the subscribers' smallest sleeping time T_{Sleep}, the CO broadcasts to the subscribers R rendezvous signals repeated at intervals $T_R = T_{Sleep} / R$. The RV signal (details see left inset of Fig. 6) comprises a time stamp which tells each listening subscriber the waiting time T_{Snooze} that can be spent snoozing until the next rendezvous with CO.

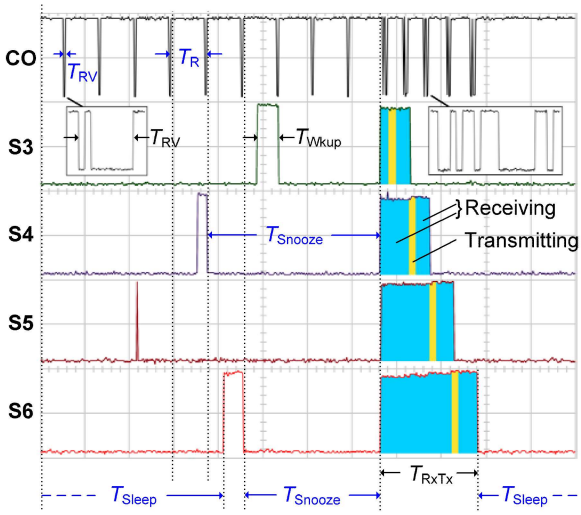


Fig. 6. Measured timing chart for low-energy medium access control (LE-MAC) protocol. Four randomly self-activating subscribers (S3…6) synchronize and communicate with the central office CO. Trace CO displays the data transmitter voltage of the CO. High S3…6 levels indicate energy-costly receive or transceive (RxTx) modes, low levels mark low-power Sleep or Snooze modes. Within a time interval T_{Sleep} the CO polls the subscribers with rendezvous signals RV (width T_{RV}) that repeat with a period $T_R = T_{Sleep} / R$ where R is a fixed number. These RV signals transmit information about the next rendezvous time with CO. If a sleeping subscriber becomes awake during a rendezvous signal is broadcast by CO, the subscriber senses the rendezvous time, starts a precise clock and goes snoozing. At rendezvous time all subscribers awake, wait for being addressed and exchange data with CO. An ending signal issued by CO sends the subscribers back sleeping.

Each subscriber stays sleeping as long as possible for the envisaged application, and its CPU remains disabled for about the sleeping time T_{Sleep}. Then an internal low-Q clock interrupt awakes the CPU, which, having activated the external high-Q quartz clock, waits for 60 ms until the clock has stabilized. Next the receive mode is activated for a time $T_{Wkup} > T_R$, and the subscriber stays listening whether CO broadcasts a rendezvous signal RV, see Fig. 6 trace S3. On reception of RV, the subscriber switches to an energy-saving snooze mode, watches its high-Q clock and activates itself precisely at the scheduled rendezvous time. If no valid RV signal could be decoded, the subscriber goes back sleeping.

At rendezvous time all subscribers switch to receive mode and stay listening for their address to be broadcast by CO (signal details see right inset of Fig. 6). When for instance subscriber S4 recognizes its address (transition from the dark (blue) to the light (yellow) region in Fig. 6), it activates its transmitter, sends to CO whatever information was required, and

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deactivates its transmitter again (transition from the light (yellow) to the dark (blue) region in Fig. 6). If CO fails to receive the subscriber's data, CO repeats addressing S4 a fixed number of times until either reception succeeds, or until the subscriber's time-out mechanism sends S4 back sleeping. When CO received the subscriber's data (or gave up interrogating S4), CO broadcasts the next subscriber's address (S5 in our case), and the previously addressed subscriber S4 returns to sleep mode as soon as it recognizes a valid address not being its own. The data exchange process repeats as described for the time interval T_{RxTx} that depends on the discretion of CO. Having interrogated all desired subscribers, CO broadcasts an End command (not marked in Fig. 6) thus sending the remaining listening subscribers to sleep mode.

For an estimate of the subscriber's energy consumption we determine the average supply currents I_b in the various modes assuming the following parameters, see Fig. 6: CO polls [21] the subscribers periodically in intervals $T_{\mathrm{Poll}} = 30$ min. All subscribers wake up randomly inside a time interval with length $T_{\mathrm{Sleep}} \approx 600$ s. When polling, the CO broadcasts $R = 20\,000$ rendezvous signals with a period of $T_{\mathrm{R}} = T_{\mathrm{Sleep}} / R = 30$ ms. Consequently, the subscribers need staying in receive mode for an average wake-up time of $T_{\mathrm{Wkup\,av}} = T_{\mathrm{R}} /2 = 15$ ms. At rendezvous time, the longest data exchange lasts $T_{\mathrm{RxTx}} = 5$ ms. With these assumptions, the various duty cycles for wake-up, data exchange and polling times are

$$\tau_{\mathrm{Wkup}} = \frac{T_{\mathrm{Wkup\,av}}}{T_{\mathrm{Sleep}}} = 2.5\times10^{-5},\ \tau_{\mathrm{RxTx}} = \frac{T_{\mathrm{RxTx}}}{T_{\mathrm{Sleep}}} = 8.3\times10^{-6},\ \tau_{\mathrm{Poll}} = \frac{T_{\mathrm{Sleep}}}{T_{\mathrm{Poll}}} = 0.33. \quad (1)$$

With the data provided by Table 2, the average supply current I_b may then be estimated,

$$\begin{aligned} I_b &= (1-\tau_{\mathrm{Poll}})(I_{\mathrm{Sleep}} + 2\tau_{\mathrm{Wkup}} I_{\mathrm{Rx}}) \\ &\quad + \tau_{\mathrm{Poll}}(\tfrac{1}{2} I_{\mathrm{Sleep}} + \tfrac{1}{2} I_{\mathrm{Snooze}} + \tau_{\mathrm{Wkup}} I_{\mathrm{Rx}} + \tau_{\mathrm{RxTx}} I_{\mathrm{RxTx}}). \end{aligned} \quad (2)$$

There is no local minimum for the average supply current I_b as opposed to [20], only a lower bound $I_{b\,\mathrm{low}} = I_{\mathrm{Sleep}} = 0.5$ µA if the duty cycles approach zero, τ_{Wkup}, τ_{RxTx}, $\tau_{\mathrm{Poll}} \to 0$ for $(T_{\mathrm{Wkup\,av}}, T_{\mathrm{RxTx}}) \ll T_{\mathrm{Sleep}} \ll T_{\mathrm{Poll}}$. For the realistic operating parameters chosen in Eq. (1), all subscriber modes as listed in Table 2 contribute about equally (some 10^{-7} A) to the total average supply current. It amounts to $I_b = 0.86$ µA, hardly more than its lower bound $I_{b\,\mathrm{low}}$. With a supply voltage of $V_b = 3.6$ V the average electrical power per subscriber is 3 µW. With the overall opto-electric conversion efficiency 12 % as derived from the experimental results in Fig. 4, each subscriber needs receiving an average optical power of only 25 µW (−16 dBm).

5.2. High-speed video link

A larger power budget is needed for the high-speed video camera link that was demonstrated recently [11]. The block diagram of this link is shown in Fig. 7(left). The CO (base station) and the subscriber with camera module are linked with a graded-index multimode fiber (62.5 µm core diameter). Power and data channels are multiplexed into this single fiber with 810 nm / 1310 nm wavelength diplexers. An ordinary electrical power supply (PS) resides in the base station and drives the 810 nm high power laser diode (HPLD) which typically launches 670 mW into the fiber. The optical attenuation for an exemplary 200 m fiber link is 2.3 dB including diplexers, splices and connectors.

At the input of the subscriber's photonic-power receiver, an optical power of about 390 mW illuminates a GaAlAs single element photovoltaic converter (PVC) optimized for a wavelength of 810 nm [13]. The cell produces an open circuit voltage of $V_{\mathrm{OC}} = 1.13$ V with up to 50 % measured optoelectronic conversion efficiency. When the cell supplies a current,

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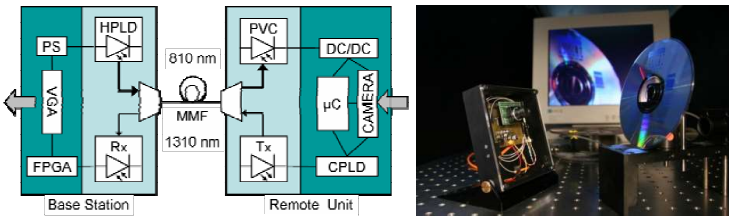


Fig. 7. (*left*) Schematic of high-speed video link with data and power transmission over a multimode fiber. An electrical power supply (PS) in the base station drives the high power laser diode (HPLD) emitting at $\lambda_{HPLD} = 810$ nm. This light is guided through a multimode fiber (MMF) to the remote unit, where a photovoltaic converter (PVC) is illuminated. The electrical power generated by the PVC is used to generate to a stabilized supply voltage of $V_b = 2.5$ V through a DC/DC boost converter. A video camera collects data which are serialized by a complex programmable logic device (CPLD) which is supervised by a microcontroller (µC). The Manchester coded data are transmitted back to the base station by a laser (Tx) at a wavelength $\lambda_{Tx} = 1310$ nm. Both λ_{HPLD} and λ_{Tx} are separated by diplexers at the remote unit and at the base station. The base station's receiver (Rx) delivers the raw data to a field programmable gate array (FPGA), which directs them after processing to a VGA graphics port. The video stream is a color signal with format YCbCr 4:2:2 (*right*) Optically powered video camera link in action. Left-hand figure reprinted from [11] © 2008cIEEE.

this voltage drops as low as 0.8 V. A DC/DC boost converter stabilizes the supply voltage to $V_b = 2.5$ V as is required for the camera electronics. The electrical output power amounts to 130 mW, so that the overall optoelectronic conversion efficiency becomes 130 mW / 390 mW = 33 %. Because the DC/DC boost converter operates more efficiently at larger electrical output powers, the overall conversion efficiency is larger than for the case of the photonic-power receiver discussed in Section 4.2.

When the subscriber has been powered on, the 4 MHz microcontroller µC starts acquiring an 8-bit parallel data stream from a low-power CMOS video camera. A complex programmable logic device (CPLD, 128-cell Xilinx CoolRunner, 100 MHz) serializes the video data and directly modulates them on a 1310 nm laser diode which launches an average power of 0.5 mW (–3 dBm) into the fiber. VGA images (640 × 480 pixel, format YCbCr 4:2:2) at 15 frames per second are sent from the subscriber to the CO (base station) corresponding to a data stream with a bitrate of 100 Mbit/s. The base station receives the video data signal with a standard receiver having a sensitivity range of –3…–38 dBm. A field programmable gate array (FPGA) decodes and processes the video data, and a VGA RAM buffers the frames for viewing on an external monitor, Fig. 7(right).

6. Conclusion

Optically powered networks of heterogeneous subscribers are described. The available optical power is used optimally with a novel low-energy medium access control (LE-MAC) protocol that allows the simultaneous operation of large duty cycle large-bandwidth subscribers together with ultralow duty cycle low-bandwidth devices. The subscriber's hardware is presented and the dynamical behavior of the optical power supply is measured. We prove the feasibility of the LE-MAC protocol with an experimental network of ultralow duty cycle (10^{-5}) devices and demonstrate the potential of an optically powered 100 Mbit/s video link.

Acknowledgments

We acknowledge support from the BMBF joint project "Components for Optical Monitoring of Access Networks (COMAN)", funded by the German Ministry of Education and Research.

#101669 - $15.00 USD Received 16 Sep 2008; revised 12 Nov 2008; accepted 13 Nov 2008; published 17 Dec 2008
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