Micropower IR Tag - A New Technology for Ad-Hoc Interconnections between Hand-Held Terminals and Smart Objects

Esko Strömmer, Marko Suojanen

VTT Electronics
Oulu, Finland
Esko.Strommer@vtt.fi, Marko.Suojanen@vtt.fi

Abstract

We have developed a communication system for ad-hoc interconnections between smart objects and user terminals. The communication system is based on infrared (IR) technology and enables an ultra-low power operation, a very low price and a small size of smart objects; the power consumption needed for the communication being only a few microwatts in typical applications. The target requirements, the technical implementation principles and evaluation results by a macroprototype of the communication system are described in this paper. According to the evaluation, the communication system is feasible and the target requirements are attainable.

1. Introduction

The amount of intelligent electronic devices residing in our everyday environment is increasing all the time. Electronics are utilized more than ever in smaller appliances inside our homes and in other environments. Wireless communication between these smart objects and hand-held user terminals facilitates easier interaction between humans and the environment. The wireless communication can be based on existing technologies like Bluetooth or IrDA. However, a problem with these is their remarkably high power consumption. For many smart objects, power supply through the mains is expensive or not at all possible. On the other hand, recharging or replacing the batteries weekly or even monthly is often difficult or impossible, which especially concerns fixed installations. Instead, the power supply must be based on energy scavenging [1] or a small battery lasting several months or even years. This often calls for a mean power consumption far below one milliwatt per device.

Our goal was to develop a system for interconnections between smart objects and humans that responds to the challenge of ultra-low power consumption. The architecture of the communication system is presented in Figure 1. The micropower IR communication tag (TAG) and the compatible terminal interface unit (TIU) enables point-to-point bidirectional ad-hoc communication between user terminals and application objects. Line of sight between the terminal and the application object is required. Client-server architecture is applied so that the terminal acts as a client and the TAG acts as a server that provides the terminal with an application-specific service. Generic browser technologies (e.g. http, html, Java) can be applied on higher communication protocol layers.

The TIU can be integrated into personal digital assistants and mobile phones, for example. The TAG can be integrated into various electronic devices via its application interface, which makes these devices application objects capable of communicating with humans. The TAG could also operate as an independent memory or sensor unit, from which the terminal could read data related to the local environment. Examples of possible applications are: providing small appliances with a user interface, repair and maintenance of appliances, delivery of the user instructions of appliances, guidance in museums, galleries and other public buildings, electrical catalogs, electrical business cards, electrical barcodes etc.

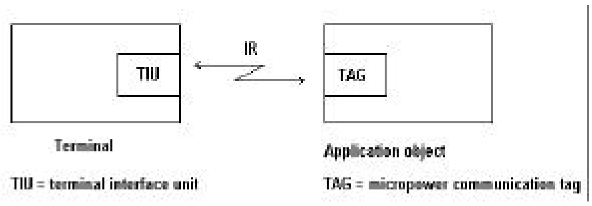

Figure 1: IR tag-based communication system.

The basis for the development of the communication system can be summarized by the following target requirements that were considered to be essential in most of the applications described above:

- The terminal user should be able to activate the communication by directing the terminal towards the TAG and pushing one button on the terminal.
- The data rate and the communication range should be at least close to the IrDA lower speed versions (below 1 Mbit/s). More precisely, this means a data rate up to at least several hundreds of kilobits per second with a communication range up to at least 1 m (single pulse mode like in IrDA Data) [2], and a data rate up to several tens of kilobits per second with a communication range up to several meters (burst mode like in IrDA Control).
- The mean power consumption of the TAG should be ultra-low, more precisely only a few microwatts in typical applications, where the TAG is most of the time in ready-for-communication state.
- The physical size of the TAG and the TIU should be very small, comparable to a coin.
- The price of the TAG and the TIU should be remarkably lower than the target price of Bluetooth modules, which is 5 USD.

The minimization of the power consumption is more essential for the TAG than for the TIU, because in most applications, the TAG should operate continuously and be ready for the communication without any manual activation, but the TIU can be activated by the terminal user. Secondly, application objects with an integrated TAG are often fixed installations and thus more difficult to be recharged than terminals with an integrated TIU. Traditional power supplies would increase both the size and the price of the application object. If power would be taken from electrical network via wired connection, the benefits of easy assembly or mobility of the application object would be thrown away. Ultra-low mean power consumption means the TAG can operate uninterrupted for several years using a small button cell battery or some parasitic power supply scavenging energy, e.g. from ambient light. However, it must be noticed that the maximum data rate and communication range cannot be attained with these limited power supplies, so some adaptivity of these performance parameters to the available peak supply current is needed.

When minimizing the power consumption, the basic advantage of IR compared to RF technologies is the possibility of operation without a precise frequency source such as a crystal or an SAW resonator, and still use an active transmitter. Instead, an imprecise RC-oscillator with fast start-up and integrability on chip can be used. However, ultimate minimization of the power consumption calls for different modulation and medium access control (MAC) solutions from those used in IrDA.

2. Related systems

There are also other proposed communication systems destined for ultra-low power devices. Some of them are described and compared to our communication system below. The comparison is restricted to communication between user terminals and application objects.

Communication between user terminals and application objects can be based on some radio frequency (RF)-based wireless personal area network (WPAN) technology. There are also development activities of very low-power RF-based WPANs occurring [3]. One of the most prominent of these is ZigBee [4]. Compared to ZigBee, our IR-based system can offer the following benefits in applications described above:

- The mean power consumption of the application object can be remarkably lower. This is due to the possibility of communication without high frequency parts and a precise frequency source; the general benefits of which are explained in chapter 1. Based on the estimations of our system in chapter 3, the power consumption needed for maintaining the ready-for-communication state can be minimized down to a few microwatts, which is about 1 % of the minimum mean power consumption announced for ZigBee (two years operation by two AA batteries).
- IR-based implementation can be better optimized with respect to cost and physical size, because no high frequency parts, an antenna or a precise frequency source are needed.
- Due to more restricted penetration of the IR beam, IR-based implementation is less sensitive to the disturbances from adjacent communication links.
- IR-based implementation offers easy selection of the application object. The terminal user can select the object by pointing it and pushing one button on the terminal, after which the object can send its user interface to the terminal. The operation resembles the use of IR remote controllers that people are accustomed to use.

Another possible communication solution is some long-range RFID (Radio Frequency Identification) technology operating on UHF RF band. An example of development activities in this area is project Palomar [5]. Palomar is a passive communication tag, which means that it does not require any battery at all but takes all the power for the operation from the RF energy sent by the terminal. Communication is based on backscattering of the RF energy from the tag back to the terminal. Compared to this, our IR-based system can offer the following benefits:

- Due to the active operation, the communication rate can be higher and the communication range can be longer.
- Due to the IR technology, the disturbances between adjacent communication links are lower, and easy selection of the object by pointing with the terminal is possible.
- The physical size of the TAG can be smaller, because optical transceivers are smaller than antennas.
- The reader device (the TIU in Fig. 1) can be simpler.

MIT Media Laboratory has presented an optical tagging system, which enables a very low 0.5 µA current consumption in standby and a communication range of three meters [6]. Differing from this, our system incorporates an active receiver (amplifier and filter stage) with higher center frequency. This gives better operation on a weak optical beam than the passive filter used in the MIT solution, and makes our system less sensible to external light sources. In addition, our system is capable of bidirectional data transfer.

3. Technical implementation

The functional block diagram of the TAG is presented in Figure 2. The block diagram of the TIU is similar except that the wake-up oscillator and the wake-up logic are not necessary, because the TIU can be activated by the user terminal, and the application interface is replaced by a terminal interface.

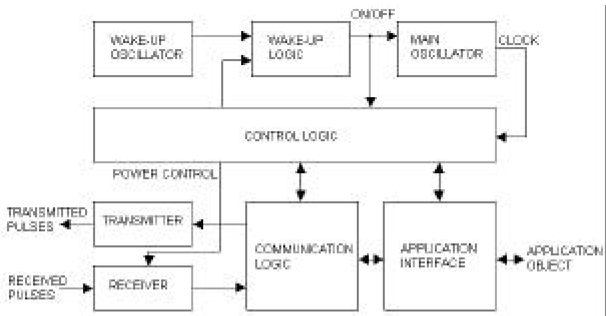

Figure 2: Functional block diagram of the TAG.

The wake-up oscillator is a very low-current (below 1 µA) and low frequency oscillator that runs continuously. Tolerance of the output frequency is not critical, and preferred implementation is an RC-based circuit below 1 kHz. Another possibility is a crystal oscillator of 32 kHz, which is commonly used in low-power clock circuits.

The wake-up logic switches the main oscillator on at regular intervals and off when the control logic asks it. The switch-on is based on counting the clock pulses from the wake-up oscillator. The main oscillator of the TAG is an RC-based circuit that generates the master clock signal for logic parts and has a very short (about 1 µs or shorter) ramp-up time after switch-on. The wide frequency tolerance inherent to RC-oscillators must be considered in the implementation of communication logic, which is explained later. In the TIU, a more precise oscillator (e.g. crystal-based) is preferred.

The control logic controls the operation of other blocks and connects the clock signal and the supply voltage to other blocks for their operation periods, which is essential for minimizing the mean power consumption. The control logic also calls for the wake-up logic to switch the main oscillator off at the end of the operating state of the TAG, after which the TAG is in standby state until the wake-up logic activates the main oscillator again.

The transmitter incorporates an IR LED (or some other IR emitter) and a switching transistor so that the communication logic can generate short IR pulses. For optimizing the usability of the system, the beam of the LED should be quite wide (several tens of degrees) on the TAG side but quite narrow (in the class of ten degrees) on the TIU side. This concerns also the IR detectors in the receiver.

The receiver incorporates an IR detector (e.g. a PIN diode), an amplifier, a bandpass filter, a comparator for detecting the incoming pulses and a switching transistor that controls the supply voltage of the receiver. Like the main oscillator, the receiver should have a short ramp-up time (a few microseconds or less) after switch-on.

The communication logic incorporates digital electronics for modulating the bit stream to be transmitted, demodulating the received bit stream correspondingly, medium access control and higher level communication protocols. The preferred modulation technology is multilevel differential pulse position modulation (L-DPPM), where the bit stream is divided into symbols, each of which can transfer $\log_2 L$ bits [7]. The DPPM modulation enables simple implementation, because no linearity nor automatic gain control are required in the receiver and transmitter, and the demodulation can be done simply by measuring the time between two successive pulses and comparing it to predefined threshold values. However, when defining the symbol lengths and the threshold values, tolerance of the main oscillator frequency must be taken into account.

The communication logic state diagram of the TAG is presented in Figure 3. Most of the time the communication logic is in standby state. When the wake-up logic switches on the main oscillator, the communication logic goes to preamble detection state, in which it listens if the TIU is sending a fixed pulse sequence called preamble. If the TAG does not detect a valid preamble sequence, it goes back to standby state. If a valid preamble sequence is detected, the TAG sends a preamble acknowledge code to the TIU and starts a message exchange procedure with it. During the message exchange procedure, the TAG and the TIU send messages to each other in turn. After the TAG has received or sent the last message, it goes back to the standby state. The preamble consists of sequences of a few pulses with fixed intervals repeated continuously for at least the wake-up interval of the TAG.

The application interface is for interfacing the TAG to the application object. It can be some general purpose serial or parallel interface, a set of discrete lines or a combination of these.

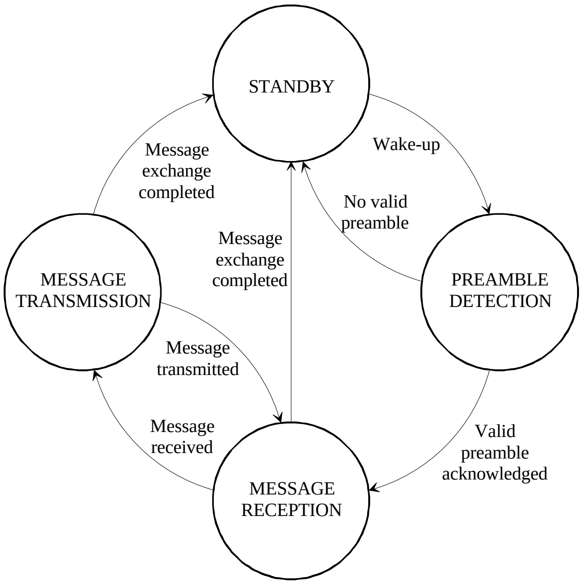

Figure 3: State diagram of the TAG communication logic.

The mean power consumption of the TAG can be roughly estimated by the following example. It is assumed that the TAG draws a 1 µA supply current in standby state, when only the wake-up oscillator and the wake-up logic are operating. In preamble detection state, the main oscillator, the control logic, the receiver and the communication logic are also operating, and the assumed supply current is 4 mA for a 20 µs operation period. During the message exchange, all the blocks of the TAG are active and the current consumption is assumed to be 10 mA for a 1 ms operation period. It is also assumed that the wake-up interval is 200 ms, and the average message exchange interval is 60 s. Based on these assumptions, the average current consumption can be calculated as follows:

$$I_{\text{total}} = I_{\text{standby}} + I_{\text{preamble}} + I_{\text{message}} \quad (1)$$

$$= 1\mu A + 4mA * 20\mu s / 200ms + 10mA * 1ms / 60s$$

$$= 1\mu A + 0.4\mu A + 0.17\mu A = 1.57\mu A$$

Thus, a small button cell battery of 100 mAh would last over seven years, which is close to its self-discharge time.

4. Evaluation by a macroprototype

For evaluating the feasibility and performance of the communication system, a macroprototype was designed, implemented and tested. The macroprototype consists of separate TAG and TIU units, assembled on four-layer, one-sided, printed circuit boards of size 40x60 mm^2. Only the single pulse mode was evaluated at this stage.

The wake-up oscillator, wake-up logic and main oscillator were implemented with discrete 74AHCXXX logic circuits of Philips, and comparators MAX919 and MAX975 of Maxim.

The output frequencies of the wake-up oscillator and the main oscillator are 5 Hz and 12 MHz +/-5%, respectively. A switching transistor IRLML6402, which switches on and off the supply voltage of the main oscillator under the control of the wake-up logic, was included.

The communication logic and the control logic were implemented with a single-chip microcontroller (PIC16F877 of Microchip). 4-DPPM was selected for modulation. Two bits of the data stream are mapped to one symbol of four possible lengths. The bit patterns 00, 01, 10 and 11 are modulated to symbol lengths of 15 µs, 22 µs, 29 µs and 36 µs, respectively, which are based on the analysis of the relation between the minimum symbol lengths and the performance parameters of the electronics. The use of 4-DPPM enables the detection of received pulses by a simple comparator, and demodulation can be done by comparing the time difference of two consecutive pulses to the defined threshold levels.

The transmitters were implemented with IR LEDs SFH486 (TIU) and SFH485P (TAG) of Osram. A switching transistor of type IRLML2402 was used for generating 333 ns pulses under the control of the microcontroller.

The receivers were implemented with PIN diodes SFH213 (TIU) and SFH214FA (TAG) of Osram, operational amplifiers MAX4412 of Maxim in amplifier and filter stages and a comparator MAX941 of Maxim for detecting the received pulses. The filter stages attenuate the disturbances from external light sources and the internal noise of the electronics. To minimize the power consumption, a switching transistor IRLML6402, which switches on and off the supply voltage of the receiver under the control of the microcontroller, was included.

The estimated communication range in the direction from the TAG to the TIU was 2.51 m and from the TIU to the TAG, 4.68 m at the optical axis of each other. The estimation was based on the data sheets of the IR components, the specified signal to noise ratio of IrDA [2] and the simulations of the electronics. The measured maximum communication range of the macroprototype was 0.91 m in the direction from the TAG to the TIU and 1.63 m from the TIU to the TAG. The measured communication range was shorter than estimated. The main reasons for this are tolerances of the optical components and crosstalk from the digital parts to the receiver, which caused the threshold levels of the comparators to be higher than estimated.

The mean power consumption of the TAG was measured in different situations:

- Standby: 9.6 µA
  (oscillator and processor stopped
  receiver off, transmitter off)
- Preamble detection, no message exchange: 15.4 µA
  (wake-up interval: 200 ms
  logic switch-on period: 44.8 µs
  receiver switch-on period: 43.4 µs)
- Preamble detection with message exchange: 15.6 µA
  (message exchange repetition interval: 60 s
  logic switch-on period: 976 µs
  message exchange period: 932 µs)

From these results, it can be seen that the measured current consumption is about ten times as high as the estimation in chapter 3. This can be explained by the following facts: The macroprototype is implemented with a large number of standard components that cause excess leakage currents and dynamic power consumption. The power consumption could be lowered by implementing these parts with dedicated logic and ASIC technology. Also the power consumption of analog circuits implemented with discrete components is higher than could be obtained with ASIC technology. The detection of preamble takes more time than estimated in chapter 3, which could be amended by speeding up the operation with dedicated logic and ASIC technology.

5. Conclusions and further work

As a conclusion, it can be stated that the presented IR communication system is feasible. Also the target requirements concerning the power consumption of the TAG, communication range and data rate are realistic, although they were not obtained by the macroprototype, which was implemented by a general purpose microcontroller, discrete logic and discrete analog circuits. If dedicated logic circuits and ASIC technology could be used, the power consumption could be much lower and the data rate much higher.

Further actions planned concerning this communication system are the evaluation of the burst mode by simulations and the macroprototype, and investigating the opportunity to implement the TAG as a solely passive module by taking the energy from the light sent by the TIU. The effect of limited power supplies on the performance parameters and automatic adaptivity of the performance parameters to the power supply are also among the further investigations planned.

6. References

[1] Rabaey, J. M., Ammer, M. J., da Silva Jr., J. L., Patel, D. and Roundy, S., "PicoRadio Supports Ad Hoc Ultra-Low Power Wireless Networking", *Computer, July 2000, pp. 42-48.*

[2] "Infrared Data Association Serial Infrared Physical Layer Specification, version 1.4", web page: *http://www.irda. org/standards/specifications.asp2001, 2001.*

[3] Callaway, E., Bahl, V., Gorday, P., Gutierrez, J. A., Hester, L., Naeve, M. and Heile, B., "Home Networking with IEEE 802.15.4, a Developing Standard for Low-Rate Wireless Personal Area Networks", *IEEE Communications Magazine, special issue on Home Networking, v. 40, n. 8, August 2002, pp. 70-77.*

[4] Bahl, V., "ZigBee Q & A", web page: *http://www.zigbee. com/zigbee_new/about/faq.asp.*

[5] Annala, A-L. and Friedrich, U., "Palomar - an European answer for passive UHF RFID applications?", web page: *http://eu.atmel.com/atmel/randd/downloads/palomar_v1. pdf, 2001.*

[6] Ma, H. and Paradiso, J. A., "The FindIT Flashlight: Responsive Tagging Based on Optically Triggered Microprocessor Wakeup", *UbiComp 2002, LNCS 2498, pp. 160-167, 2002.*

[7] Shiu, D. and Kahn, J.M., "Differential Pulse-Position Modulation for Power-efficient Optical Communication", *IEEE Transactions on Communications, August 1999, pp.1201-1210.*