Bluetooth Low Energy (BLE) based wireless sensors

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***Abstract*—The following paper presents the results of a feasibility study about Bluetooth Low Energy (BLE) based wireless sensors. The development of industrial wireless sensors leads to important demands for the wireless technologies like a low energy consumption and a resource saving simple protocol stack. Bluetooth Low Energy (BLE) is a rather new wireless standard which will completely fulfill these fundamental requirements. A self-designed BLE sensor system has been used to explore the common applicability of BLE for wireless sensor systems. The evaluation results of various analyses with the BLE sensor system are now presented in this paper.**

I. INTRODUCTION

The availability of wireless technologies like Bluetooth, ZigBee and WirelessHART enabled the science and industry to explore and develop miniaturized wireless sensors [2-4]. But the development of wireless sensors has many challenges [7-9]. Important challenges are

- the power consumption of the wireless sensor itself because there is the aim is to supply the wireless sensor only with an energy harvester [10];
- the resource limitations of memory and the calculation power of the included microcontroller;
- the possible wireless network structures.

The choice of an adequate wireless technology will significantly affect these challenges and is crucial for the success of the wireless sensor [7-9]. The new Bluetooth Low Energy (BLE) standard which has been published in 2010 by the Bluetooth SIG [1] is supposed to be able to handle these challenges. BLE has been designed to resolve many disadvantages for wireless sensor systems of the traditional Bluetooth technology (today denoted as Bluetooth BR/EDR [1]). In order to give more precise predictions about the applicability of BLE for wireless sensors performance explorations are now necessary.

Due to these facts a BLE based demonstration sensor system has been developed. The system consists of a BLE chip from Texas Instruments. The design and architecture of the BLE sensor system will be described in section II. In the following sections the results of a performance analysis and further investigations of the implemented BLE sensor system will be depicted. Section III views the results of the timing analysis of the BLE sensor system: In Section IV the storage requirements for the BLE stack will be considered. In Section V the power consumption of the BLE data communication and energy examinations will be discussed. The paper ends with a short conclusion in section VI.

II. DESIGN OF THE BLE SENSOR SYSTEM

As described in section I a BLE based demonstration sensor system has been developed to evaluate the BLE wireless technology and to demonstrate the wireless functionality of BLE.

A. *Architecture of the BLE Sensors System*

Fig. 1 shows a picture of the implemented BLE demonstration sensor system. The main part of the system is based on a Carrera racing course with self-developed Carrera cars. The chassis consist of several sensors and a BLE transceiver chip which includes a microcontroller. The Carrera car is transmitting sensor data like acceleration while driving through the racing course. The data will be send to a PC based system for further computation. The PC uses an off the shelf BLE dongle for sensor data acquisition. The dongle and the Carrera car allowing a bidirectional data link if required.

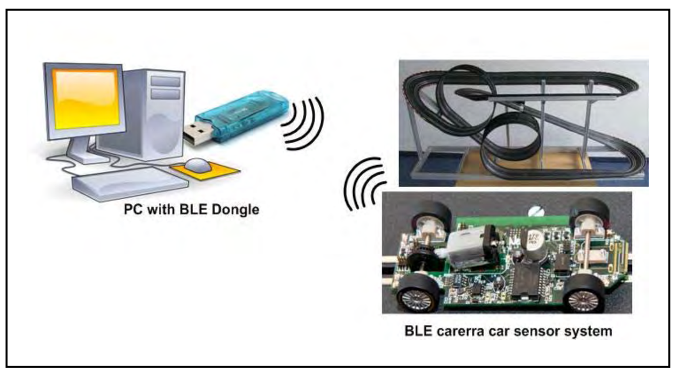

Figure 1. BLE sensor system for BLE evaluation and demonstration

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Fig. 2 shows the detailed architecture of the BLE carerra car sensor system. The central unit of the sensor system is a BLE One-Chip-Solution CC2540F256 from Texas Instrument (TI). The CC2540F256 [5] consist of a BLE transceiver and an integrated 8051 microcontroller. Additionally the BLE CC2540F256 consists of a BLE software stack which is provided for free from Texas Instruments [6].

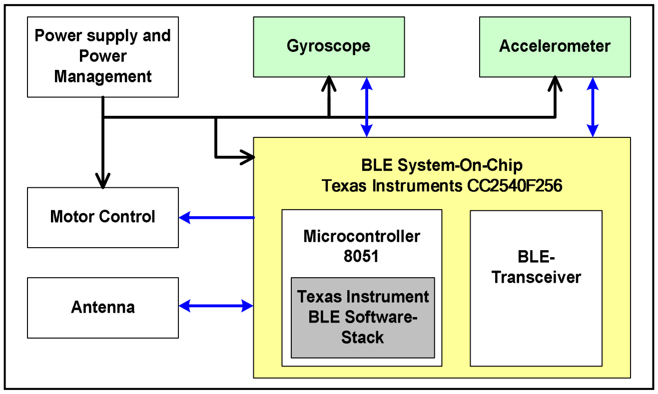

Figure 2. Architecture of the BLE sensor

B. *Features of the deployed wireless BLE transceiver chip*

The wireless BLE transceiver CC2540F256 from Texas Instruments is a small and powerful chip with 256 kByte programmable Flash and 8 kByte SRAM. It has the possibility to switch the chip in three different power-down-modes during operation. This switching is important to save energy.

The BLE transceiver CC2540F256 operates like specified in the 2.4 GHz ISM band at 2402 MHz - 2480 MHz [1]. The transmission power of the BLE transmitter can be varied between 0.01 mW (-20 dBm) and 2.5 mW (+4 dBm). BLE is using the frequency hopping spread spectrum (FHSS) for the data transmission. Furthermore BLE combines two multiple access schemes: Frequency division multiple access (FDMA) and time division multiple access (TDMA) [8, 9]. BLE is using 40 RF channels separated by 2 MHz. Three channels are used for advertising and 37 are used for the data communication itself.

The development of the wireless BLE sensor system was supported by Texas Instruments. They supplied development kits, software and detailed documentation. The BLE dongle is also from TI and is shown in Fig. 1. One more interesting feature of the chip is the possibility to run a small operating system called OSAL on the chip. This OSAL helped to program the CC2540F256 [6].

III. TIMING BEHAVIOUR OF THE BLE SENSOR SYSTEM

The timing behaviour of the BLE sensor system will be determined by the common operation modes of BLE. The common operation modes of BLE are described by the state machine of the Logical-Link-Layer which is depicted in Fig. 3. The state machine of a BLE device has been kept very simple.

BLE is a connection oriented wireless technology, i.e. two devices which want to exchange data must enter a fixed connection before a data transmission is possible. In the state "Advertising" BLE devices (so called advertisers) can transmit connectionless data like a broadcaster to scanning devices. Furthermore advertising BLE devices can signalize scanning and initiating devices that they are ready to go into a fixed connection. Only three of 40 data channels are used for the advertising communication. A device in the state "Scanning" (a scanner) and the state "Initiating" will listen for packets from a specific advertising device. This device will than respond to these packets to initiate a new connection. A device in the state "Connection" is called being in a connection. There are two different roles within a state "Connection". These roles are named as "Master Role" and "Slave Role". When changing from the state "Initiating" to the state "Connection" the device will have the Master Role. When entering the state "Connection" from the state "Advertising" the device will fulfill the Slave Role. Important to know the Master defines all timings of the transmission.

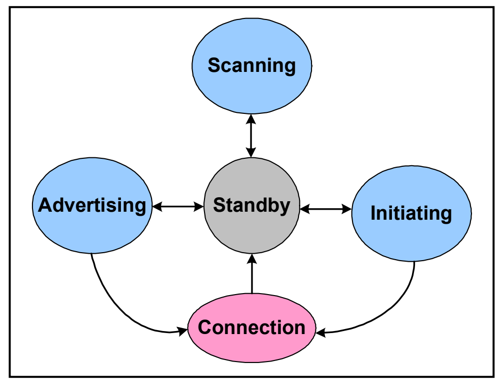

Figure 3. State Diagramm (Operating Modes) of a BLE Device [1]

A. *Connection setup time of BLE*

The power consumption of a Bluetooth based wireless sensor system in the state "Connection" is normally larger than in the state "Standby". To save energy during the operation of a wireless sensor system it's better to build up the connection between two Bluetooth devices only if data must be exchanged. The connection setup time is the duration to build up a connection between two Bluetooth devices.

The connection setup time of the traditional Bluetooth BR/EDR technology ranges between several seconds [7]. This long connection setup time is a great disadvantage for the sensor system, especially if the wireless sensor system shall react quickly to incoming sensor events.

For the new BLE technology the connection setup time has now been reduced. The longest connection setup time that has been measured was 4.7 ms. Thus it is possible to switch the wireless sensors system to the energy saving standby mode and also to react quickly to sensor events which must be transmitted.

B. *Data throughput of the BLE sensor system*

The data throughput of the implemented BLE sensor system has been measured. Thus it is possible to estimate whether the achieved data throughput of BLE is sufficient for wireless sensor systems.

If BLE devices are connected they can send and receive data on a specific data channel. This action is called “connection events”. The time between two connection events is the connection interval. The connection interval can range from a minimum of 7.5 ms to a maximum of 4.0 s [6].

There are many options to exchange data for a BLE device which is placed into the state “Connection”. The transmission of notifications [1] has been investigated as an example for the data transmission from the sensor system to the PC. The notifications are messages which allow asynchronously data transmission. Notifications data packets are not acknowledged. Fig. 4 shows the measured data-throughput for the BLE sensor system in dependence of the number of data packets. One data packet consists of 20 payload bytes. The transmission power was 0 dBm and the connection interval has been set to 7.5 ms. The communication is directly linked to the connection interval. This fact leads to a lower data throughput in the case that only a few data packets are transmitted.

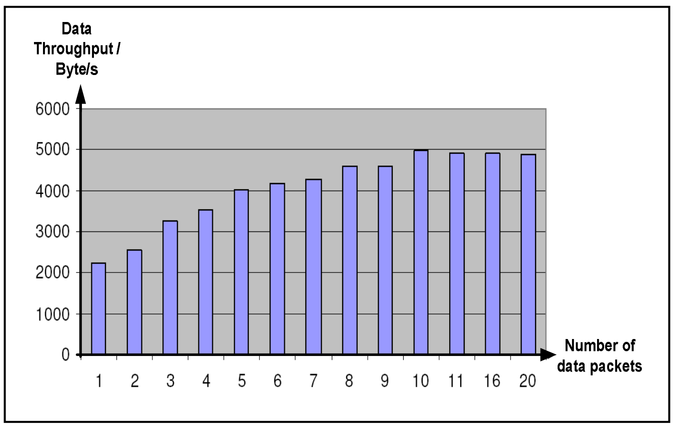

Figure 4. Measured data throughput during transmission of notification

A further possibility to exchange data between BLE devices is the response-request-procedure. This is a procedure the transmitting device can “request” an acknowledgment from the receiving. The successful data transmission will be acknowledged from the receiving device via a “response”. In comparison to the notification transmission the data throughput is lower due the fact that the data transmission is acknowledged. A minimum of two connection intervals is necessary to transmit one data packet with a maximum of 20 bytes data. This fact leads to an maximum data throughput of 1,3 kByte/s if more than 20 bytes of data shall be transmitted.

In summary the result of the measurements shows that the throughput is good enough for many wireless sensor applications.

IV. Storage Requirements for The BLE Stack

The complexity of the BLE stack was reduced to obtain a lightweight stack for sensor node applications. This leads to the fact that many transceiver manufacturers support the developers and researches with software stacks free of charge.

TI supports and supplies the developer of wireless sensors systems with two different BLE stacks [6]: A stack for slave devices and one for master device. TABLE I shows the measured allocated memory space in comparison to the existing Bluetooth and ZigBee. Benchmark figures of existing Bluetooth and ZigBee are derived from previous performance analyses of wireless technologies [7]. The size of the protocol stack of BLE is rather small compared to the traditional Bluetooth BR/EDR. It can be noticed that the memory allocation of the whole BLE stack is less enough to store the complete BLE stack on small microcontrollers. With the implemented wireless sensor system it has been shown that an eight bit controller with only a size of 256 kByte memory is sufficient enough to host the stack and the sensor application.

TABLE I. Allocated Memory Space of the TI BLE Stack in Comparison to Bluetooth BR/EDR and ZigBee

Bluetooth BR/EDR	ZigBee-Stack without the IEEE 802.15.4 layers	BLE Stack for slaves devices	BLE Stack for master devices
~ 100 kByte ROM	~ 32 kByte ROM	~ 82 kByte ROM	~ 70 kByte ROM
~ 8 kByte RAM	~ 1 kByte RAM	~ 1 kByte RAM	~ 1 kByte RAM

V. Power Consumption of the BLE Data Communication and Energy Examinations

An elaborate energy analysis of the BLE sensor system has been done. The current consumption and the electrical discharge characteristics have been precisely measured to obtain detailed information about the influence of different states to the power consumption of BLE sensor systems.

A. Measurement Method

To measure the current consumption of the BLE sensor system a measurement resistor with 1 Ω and an oscilloscope have been used. Fig. 5 shows an example of the measured current consumption and electrical discharge of the BLE sensor system during a data transmission in the advertising state.

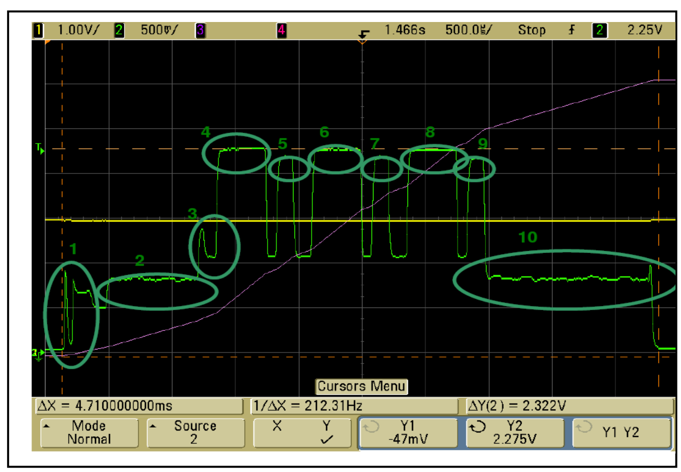

Figure 5. Example of the measured current consumption (green curve) and electrical discharge (lilac curve) during the advertising state

The transmission power of the system during the measurement depicted in Fig. 5 was set to -6 dBm and the power supply has been adjusted to 3.3 V. The number of payload bytes was 31 bytes. In this example the measured peak current was 25 mA. The electrical discharge for the whole transmission time was 0.043 mAs. Therefore it can be calculated as representation of Joule, which comes than to an overall energy consumption of 142 µJ.

B. Energy harvesting based BLE sensor systems

In future wireless sensor systems shall be operating only with energy harvester and without batteries. Due to the power measurements a short estimation has been done whether a BLE sensor system can supplied only by energy harvesters.

The following energy consumption has been measured with the implemented BLE sensor system (notice that the sensory has been neglected, the system has been supplied by a 3.3 V power supply and a sum of 20 bytes payload has been transmitted):

- Energy consumption for a connection setup: 0.3 mJ
- Energy consumption for a data transmission with a notification packet: 0.13 mJ
- Energy consumption for single data transmission if the transceiver is switched on/off between the data transmission: 0.78 mJ

If a preceding DC-DC-converter (efficiency of 60 %) is taking into account for the last case (0.78 mJ), then an energy harvester must provide a minimum of 1.3 mJ energy for those single data transmission. In TABLE II the output power of today's available energy harvester is pointed out [10]. Assuming well energetic conditions the provision of the calculated energy for such a BLE based sensor system is with today's energy harvester possible. The provision of this energy is only critical if short cycle times for the data transmission are required.

TABLE II. OUTPUT POWER OF COMMERCIAL AVAILABLE ENERGY HARVESTER [10]

Energy Harvester	Range of output power
Redio Frequency Energy Harvester	mW … W
Solar Cells	µW … mW
Thermogenerators	µW … mW
Electromagnetic Generators	µW … mW
Piezo Generators	µW … mW
Capacitive/Electrostatic Generators	µW

VI. CONCLUSION

In this paper the results of a feasibility study about Bluetooth Low Energy (BLE) based wireless sensors have been presented. A self-designed BLE sensor system has been used to explore the common applicability of BLE for wireless sensor systems. The results state clearly that BLE is a very interesting wireless technology for wireless sensor systems especially for wireless sensor system powered through energy harvester. The major facts of BLE based wireless sensor system are:

- low power consumption,
- good data throughput,
- small and simple software stack, applicable for 8-bit microcontrollers,
- simple implementation of BLE based wireless sensors due to a good stack support of transceiver manufacturers.

For the future our overall important investigation results shall be used as to calculate in detail lifetime of BLE based sensors and to compute new BLE simulation models.

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