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Implementation of low power algorithm for near distance wireless communication and RFID/USN systems

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ABSTRACT

A new power control algorithm for wireless communication which can be applied to various near distance communications and USN/RFID systems is proposed. This technique has been applied and tested to lithium coin battery operated UHF/microwave transceiver systems to show extremely long communication life time without battery exchange. The power control algorithm is based on the dynamic prediction method of arrival time for incoming packet at the receiver. We obtain 16mA current consumption in the TX module and 20mA current consumption in the RX module. The advantage provided by this method compared to others is that both master transceiver and slave transceiver can be low power consumption system.

Keywords*: low power algorithm , synchronization, dynamic prediction method.*

1. INTRODUCTION

Some application requires that communication link between the master and slave transceiver should be kept for life time and should be recovered whenever the link has been broken as soon as possible. In these cases especially for mobile applications, it is most important to reduce the power consumption for both the communication identities. While the master and slave are in linked status, either of the receivers should not wait for incoming packets without the information of the arrival time since the time elapsed before the packet reception creates waste of power in the receiver. One of the best strategies to save power is to let the master and the slave communicate periodically with a given fixed period. Generally this communication link may be broken frequently because of the mobile conditions, in which case it is important to recover the link as fast as possible to save the reception power. When the link is broken, the receiver automatically tries to recover it and in this case the receiver opens up receiving window all the time until the packet is received. This is the period when excessive receiving power is consumed. Moreover, even though a packet has been received successfully, it takes time to return back to the minimal power condition and during this time duration the receiver consumes power. The main problem of periodic setup of communication link is the difficulty of synchronization between the timer of master and that of slave. Once the synchronization is established, it is not possible to maintain long due to the frequency drift of the transmitter clock caused by the temperature or power supply variation, which leads to timer period variation. This will shift the time of arrival at the receiver and the motive for searching a prediction algorithm for predicting the packet arrival time.

2. RELATED WORKS

There is a great deal of research and development into wireless sensor nodes suitable for wireless communication by research groups, as described in [1]. The Mica family of motes [2] is very well-known in wireless sensor network research. The MicaZ updated the RF transceiver to a Chipcon CC2420, which allows the development of networks compliant with the IEEE802.15.4 and ZigBee standards. The Telos [3] mote follows on from the mica motes. It uses the CC2420 radio but replaces the ATmega128 with a Texas Instruments (TI) MSP430. The eco-mote [4] is a miniaturized sensor node. It uses a single chip Nordic nRF24E1, which has a RF transceiver and an embedded 8051 microcontroller unit (MCU). The size of the node including a 30mAh Li-ion battery is 13mm by 10mm by 8mm. Other nodes include the Tyndall 25mm node [5], the 14mm by 14mm stackable node developed at IMEC [6], and the 14mm diameter SAND platform from Philips research [7]. In this paper, we designed and prototyped a near distance communication system with great emphasis on low energy usage small size, and low cost similarly with nodes described above.

Commercial receiver chips typically require 5-25mA at 1.8-5V for proper operation. This level of current consumption, while certainly not high, is much too high for battery operated devices. Many receivers are required to operate from much smaller batteries for much longer periods. To overcome this intrinsic difficulty, a lot of methods have been devised, all of which revolve around the idea of switching the receiver off for certain periods of time while still being available to receive

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data when needed. Thus many commercial receivers have some form of shutdown function available to the designer [8].

Several power reduction schemes have been proposed so far. According to [9], the first typical scheme is Media Access Control (MAC) layer duty cycle scheduling in IEEE802.15.4 Low-Rate WPANs standard. In a master-slave star topology network, every time the master periodically broadcasts a beacon frame, Slaves wake up and listen to the beacon. By doing so, a slave makes MAC processing unit and RF transceiver awake for the length of a beacon in each period. This mechanism has many disadvantages. For instance, only the star topology with one master can support this scheme and the beacon length is quite long as well as both the MAC processing unit and the RF transceiver must be woken up to receive and response for the beacon.

The second scheme is the design of a wake-up-by signal RF transceiver. If a master wants to communicate with a slave in sleeping mode, the first thing it needs to do is to send a wake-up-signal which can wake up the slave. In this way, a slave is woken up on demand instead of periodical wake-up so that power consumption can be dramatically reduced. However, such a passive RF transceiver has still a difficult design challenge and there are no off-the-shelf products so far [9].

The third scheme, preamble sampling technique was proposed in [10]. In this scheme, each RF transceiver periodically wakes itself up for a very short time, the moment when RF transceiver detects whether the channel is occupied or not based on the information of a Received Signal Strength Indicator (RSSI). If the channel is occupied, then the RF transceiver will wake other parts of the device up for receiving the signal on that channel. One of the advantages of this scheme is that the time needed for sampling is much shorter than hearing a beacon as specified in the IEEE802.15.4 standard. Whereas, other drawbacks of the WUP scheme are its low efficiency of channel capacity due to the transmission of preambles and the extra power consumption when sending long WUPs [9].

In [11]–[13], the WiseMAC protocol is proposed based on the WUP scheme, in which each device stores its neighbors' sampling schedule which has been piggybacked on the last received packet from the neighbor. Based on the piggybacked schedule information, this scheme uses a very short WUP to wake up its neighbor. To do that, it is required to send a long WUP at the beginning phase. The instabilities of the clocks in the small devices cause time drift, to handle this, the length of the preamble must be prolonged to compensate for the time drift especially when the schedule has been received a long time ago. Also the relative clock drift is different to each point to point link since each device has different quartz crystal. And the duration of the WUP must be computed to compensate for the time drift [13]. Thus the time drift compensation could result in much longer WUP [9].

To achieve even lower power consumption, this paper presents a proposal that prediction-based synchronization scheme is used to compensate the time drift between the clock of the master and that of the slave.

3. BATTERY MODELS AND LITHIUM COIN CELL BATTERY

3.1 Battery Models

In order to estimate the lifetime of the device when using a battery, the power consumption of the circuit has to be characterized. At lower supply voltages, circuits draw less current, resulting in less energy consumption. Capacity models of battery are usually used to estimate life time of battery-operated devices. An accurate battery model can reveal how the battery is discharged by the circuits that consume power. In [14]-[16], there have been recent efforts to generalize complexities of the battery by modeling batteries' inherent characteristics. These models range from simple linear model to a complex model that attempts to incorporate the "relaxation" phenomenon. So far, these models, though novel in conceptual sense, lacked the validation in the real world [17]. In order to overcome these difficulties, [17] propose a technique that can be used in characterizing the battery capacity. This technique is to carefully measure the battery's current and voltage output for the duration of the battery lifetime as the circuit board consumes power from the battery. In this paper, we also used the measuring technique similar to [17] rather than model-based estimation for calculating the power consumption of our transceiver board.

3.2 Lithium coin cell battery

In this paper, for experiments, we used CR2450 lithium coin cell battery. With high energy density and relatively flat discharge characteristics, lithium batteries are equipped with mobile devices. Especially for micro sensor nodes, small form factor is an essential requirement and the size of lithium coin cell batteries should satisfies the stringent requirement of micro sensor nodes [17]. Table 1 shows the manufacturer's specification [18] of CR2450.

Table 1. CR2450 Lithium cell battery specification

Nominal Voltage	Cutoff voltage	Nominal Capacity	Continuous Standard Drain	Dimension Diam. × Ht.	Approx. Weight
3.0 V	2.0 V	620 mAh	0.2 mA	24.5mm × 5.0mm	6.3 g

4. THEORY OF OPERATION

4.1 Prediction based synchronization scheme

The basic operation of arrival time prediction for transmitted packet at the receiver is based on the relatively constant period of packet transmission. The receiver sets the initial value for the target period prediction as the value smaller than the period of transmitted packet. Once the transmitter begins to send packets, the receiver opens up the receiving window and stays at receiving mode until it receives a packet. Just after the first packet reception, the receiver initialize a timer to measure the time between the start and end of the receiving duration. At the end of the packet reception, the receiver automatically returns back into sleep state where power consumption is minimized and generates an interrupt signal which calls the timer interrupt service routine. This routine samples the timer value and calculates the estimation error value which is the difference between previous estimation value and the sampled one. Basically the prediction value is calculated by adding the previous estimation value and the correction value, *delta* which

$$delta = \begin{cases} 1, & timer2 > timer2_{prev} \\ 0, & timer2 = timer2_{prev} \\ -1, & timer2 < timer2_{prev} \end{cases} \quad (1)$$

is determined by the criteria shown in (1). The $timer2_{prev}$ represents the previous value of the timer2.Then the prediction value is loaded into another timer to generate next timer interrupt which will make the receiver state changed into receiving one from idle one. Once the new timer interrupt is generated the process of error estimation follows as described before. However algorithm described so far gives poor convergence time and moreover in some conditions it does not even converge at all. Here we need convergence acceleration criteria that will guarantee fast and robust convergence. The delta value given (1) should be reduced to minimum value, 1 and the $target_{delta}$ value should be modified depending on the different convergence steps more exactly the number of packets received. The criteria providing suboptimal convergence we devised are shown in (2) and (3). Depending on the number of packets received we use different $target_{delta}$ value. Actually $target_{delta}$ value is set to decrease as the number of packets received and eventually saturates to a minimum $target_{delta}$ value which will give minimum possible prediction error. The minimum $target_{delta}$ ensures minimum receiving state which means minimum power consumption.

$$target_{delta} = \begin{cases} MAX, & n < 3 \\ Med, & 3 \le n < 10 \\ min, & n \ge 10 \end{cases} \quad (2)$$

where *n* represents the number of received packets, *MAX* the maximum value of waiting time threshold, *Med* the medium waiting time threshold and *min* the minimum waiting time.

$$timer1_{new} = \begin{cases} timer1\_initial, & if\ n < 3 \\ timer1_{prev} + (target_{delta} - timer2) \\ \quad -delta, & Otherwise \end{cases} \quad (3)$$

where $timer1_{new}$ is the newly updated value of the timer1. Fig. 1 shows the procedure of the target delta acceleration convergence algorithm between TX and RX unit.

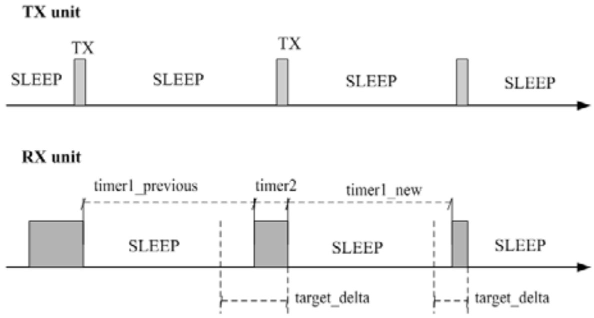

Fig. 1. Procedure of the target delta acceleration convergence algorithm

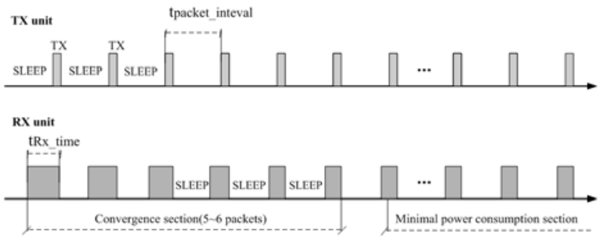

Fig. 2. Gradual reduction of the RX reception window

Fig. 2 shows the gradual reduction of the RX reception window as the number of packets received is increasing. As we can see, in less than 5 to 6 packet reception we reached stable state of minimal reception power consumption. For the case without the convergence acceleration algorithm, it takes more than 60 packet reception to reach minimal reception power state.

4.2 Scheme for not using DC/DC converter

The battery used in this paper has a nominal voltage of 3.0V, which will decrease constantly as the battery is discharged, when the battery is directly connected to a VLSI circuit without any form of DC/DC converter, the performance of circuits will start to degrade as the voltage across the battery decreases. An unregulated power supply may induce IR drop corresponding to the load current, whereas a regulated power supply keeps the same output voltage regardless of the load current variation. Moreover, when the battery's voltage reaches the minimum input voltage required by the circuit, the circuit will stop functioning even though there may be some capacity left in the battery. It is the role of DC/DC converter to provide a constant voltage to the circuit while utilizing complete capacity of the battery.

However, these roles are limited by a cut off voltage of batteries and a minimum input voltage of DC/DC converters. Minimum input voltages of converters used on sensor modules in [1], [17], [19] are 2~2.5V. The cut off voltage of CR2450 lithium ion battery used in experiment of this paper is 2V. Thus minimum input voltage of the converter to use on sensor module can be acceptable if it is about 2V. It is reported that there is always a non-trivial power loss in the converter, the amount of which is 10%~40% of the total energy consumed in the system [20]. According to [17], the more current discharges, the less current is utilized from the battery. This result comes despite the fact that the actual current discharge from the battery doesn't stay constant but fluctuates in discharge and relaxation cycles due to the pulse-frequency-modulation function implemented in DC/DC converter. Efficiency of converter used in [17] is about 70 %. Moreover, in the low duty cycle application that this node is designed for, the quiescent current used by DC/DC converter is very important.

In this paper, we tried to operate stably prototype a communication system without using DC/DC converter for ultra low power consumption. In cases where the receivers are operating in battery operated conditions for long life time without battery replacement, battery tends to supply reduced voltage as the current is getting drained. This produces serious problem of increasing receiver timing window which results in the unnecessary power consumption. This phenomena is primarily caused by the longer timer period resulted by the reduced clock frequency. Normal silicon chip gives reduced clock frequency as the supply voltage reduces. We need to compensate the timer sample value for the supply voltage change. We suggest an empirical formula given in (4) where a true estimation error value is calculated to give larger value as sampled timer estimation is increased. Sampled timer estimation error increases as supply voltage reduces.

$$timer_{delta} = timer_{delta\_}measured \times 0.95 - 10 \qquad (4)$$

5. EXPERIMENTAL RESULTS

The experiments to show the validness of the proposed algorithm was performed based on a system using RF

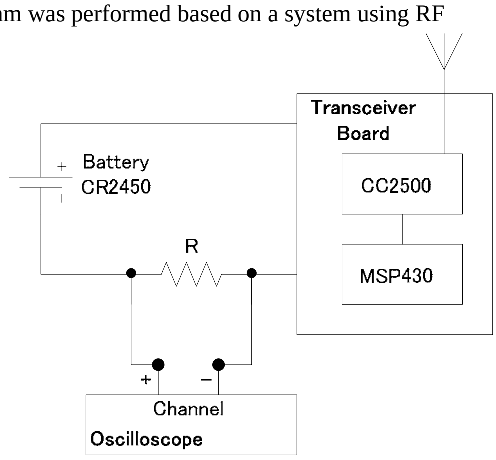

Fig. 3. Setup for measuring power consumption in TX and RX module

transceiver chip and a microcontroller chip. TI CC2500 (2.4 GHz carrier frequency) has been used as the RF transceiver chip and TI MSP430 MCU was used for the MCU which are integrated onto a single printed circuit board together with a chip antenna. We set up two identical transceiver systems each of which is comprised of a RF transceiver chip, an MCU and chip antenna together with passive components needed for BALUN and impedance matching. One of the two was used as the TX module and the other as the RX module. We used a very simple and efficient way of measuring the current consumption of both the RF transceiver and the MCU as shown in Fig. 3. The oscilloscope measures the voltage across the resistance R in between GND node of the transceiver and the power supply GND node. We can simply calculate the current by dividing the oscilloscope voltage reading by the resistance value of R. The MCU in TX module was programmed to generate identical packets every 1 second. The packet format is shown in Fig. 4. The MCU in RX module is programmed to implement the proposed algorithm. Fig. 5 shows the waveform of the TX packets samples at TX module. As we can see, TX packet appears every 1 sec with peak amplitude of about 160 mV on an average and the packet duration of about 1ms. Since we are using 10 ohm resistance for voltage sampling, we obtain 16 mA current consumption in the TX module which matches well with the 16 mA specification by 2500 data sheet. Tail of the packet waveform corresponds to the current consumption due to the MCU program execution in ACTIVE state. The period of low power state between each packet transmission has been achieved by sending the RF transceiver into sleep state. The low power state of the TX module consumes less than 20 uA, because the packet duration is about 1ms every 1 sec at 16 mA current consumption. Fig. 6 shows the waveform of the RX packets received in RX module. As we can see RX packets appear every 1 sec with amplitude of about 200 mV and the packet duration of about 2ms. The reason why the RX packet duration is longer than that of the TX packet is that earlier time duration

Preamble (4 byte)	SYNC Byte (4 byte)	Payload (4 byte)	CRC (2 byte)

Fig. 4. Packet format in TX module

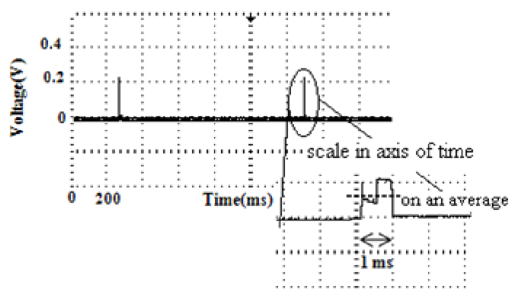

Fig. 5. Measured waveform of the packet in TX module

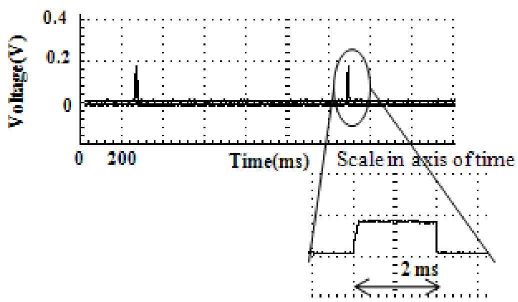

Fig.6. Measured waveform of the packet in RX module

of about 1 ms comes from the margin set by the prediction algorithm, this margin is the result of the converged target delta value. These results give also the same current consumption of 20mA specified by CC2500 data sheet. The RX pulse wave form has also the tails which corresponds to the MCU execution of program codes comprising the packet prediction algorithms in ACTIVE state. However the long period between each packet reception, we have very small current consumption of less than 40uA while the RF receiver is in SLEEP state.

Table 2 compares the power consumption of MicaZ[2], Telos[3], Eco[4] mentioned in Section 2 and Ours. In both TX and RX, Ours consumes less power than others.

Table 2. Power consumption comparison

	MicaZ	Telos	Eco	Ours
Total Active TX	22mA	19.5mA	16mA	16mA
Total Active RX	27.7mA	21.8mA	22mA	20mA

6. BIDIRECTIONAL COMMUNICATION CASE

For some applications such as active RFID tag, we need to implement RX function in both the tag and the reader. In this case we need to find the way to minimize TX and RX power both for tag (slave) and reader (master) especially for tag side. Since most of the cases stay in RX state without knowledge of packet arrival time will create huge amount of power consumption because all the blocks comprising the receiver structure in the transceiver chip should be alive. One of the best ways to minimize power consumption in both transceivers could be to use the packet arrival time prediction algorithm in either of the receiver. However due to the program size required to implement the prediction algorithm, it is better to implement the algorithm in the receiver of the master only since slave should be cheap. We propose a packet transfer algorithm between the master and slave. Fig. 7 shows the Procedure of the packet transaction for master and slave respectively after packet prediction convergence. Firstly slave TX module transmits a packet containing ID number and goes into RX state after estimated response time from the master. At first, master opens up the receiving window and waits for the first incoming packet. Once the receiver of the master finds the transmitted packet, arrival time prediction algorithm is activated and calculates the prediction and load the timer with this value. Then master put a acknowledge information into a TX packet and transmits back to the RX mode. After finishing the packet transmission, RX module of the master goes into SLEEP mode.

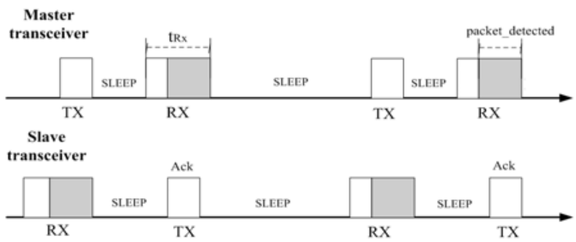

Fig. 7. Procedure of the packet transaction for master and slave respectively after packet prediction convergence

Then the acknowledge packet is received by the slave which makes the slave enter into sleep mode. Fig. 8 shows the waveform of packet transaction for slave and master respectively. For the slave, the earlier peak corresponds to the TX packet and the later one represents the RX packet. The time duration between the two pulses corresponds to TX to RX delay time in the slave. For master, the first peak pulse and the second pulse represents the RX packet and TX packet respectively.

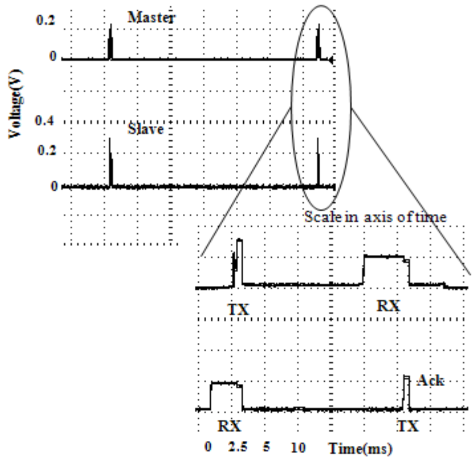

Fig. 8. Measured waveform of Packet transaction for master and slave respectively after packet prediction convergence

7. APPLICATION

There could be various kinds of applications utilizing proposed low power communication protocol. The advantage provided by this method compared to others is that both master transceiver and slave transceiver can be low power consumption system. This is extremely suitable to the

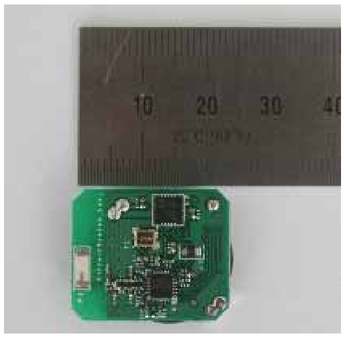

Fig . 9. TX module of the prototype system for mobile phone lost prevention system

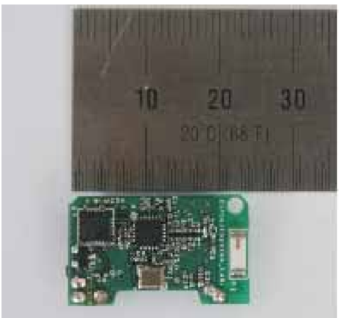

Fig . 10. RX module of the prototype system for mobile phone lost prevention system

application such as personal mobile management systems for various portable devices or objects. If we can embed or attach this system to portable devices such as mobile phone, digital camera, note book, wallet, travel luggage, passport, pets, and so on, we can track and record the presence and distance from the person carrying this system. This will allow us to protect portable articles from lost or theft in real time. What makes this system available is that the size and weight of both the master and slaves can be extremely small thanks to the use of small size batteries such as coin type lithium batteries. For portable devices having batteries inside we do not even need extra battery and the size of the system can be reduced further to be embedded inside the device. Another application could be the portable distance estimation systems. Slave can have capability of measuring the received signal power from the master. If we can translate the received power level into distance value between the two, various applications can be devised such as the alarm system warning dangerous items approaching, a system for notifying the presence of and distance to a target item for blind person or robot and so on.

We have developed a prototype system for mobile phone lost prevention system based on the proposed algorithm in this paper. Fig. 9 and Fig. 10 show the slave and master module respectively. The slave module is comprised of MCU (TI MSP430), RF transmitter (TI CC2550), chip antenna with balun/matching circuits. The total size of the slave is 20mm by 24mm by 1.5mm. Master module is composed of MCU (TI MSP430), RF transceiver (TI CC2500), chip antenna with balun/matching circuit, switch, led and buzzer. The total size of the master is 15mm by 24mm by 3mm. We used CR2032 lithium coin battery for slave and CR2450 for master for test the functionality and the distance of reach. The distance of maximum reach was about 20m at 2.4GHz.

8. CONCLUSION

Extremely low power communication algorithm for wireless communication is proposed and described using the test result based on the prototype implementation. Even though there are several competing technology such as Bluetooth and ZigBee, Proposed technology offers big advantage in systems consuming much less power and eventually less size and weight thanks to the small size battery. This algorithm will create a lot of new application area for near distance communication which has not been possible because of the power consumption and size and weight of the application device.

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