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IEEE 802.15.4 Symbol Rate Timer for TelosB

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Abstract

A software implementation of the IEEE 802.15.4 MAC on the TelosB mote platform is impossible, because it lacks a clock with sufficient resolution and accuracy. We have developed and tested an add-on timer board that provides the required functionality and has a current consumption in the lower μA region.

Contents

1 Introduction

The popular open-source TelosB mote platform [4] is equipped with the CC2420 radio transceiver which provides an IEEE 802.15.4-compliant [3] physical layer. A software implementation of the MAC layer is, however, not possible, as it requires a local clock with *symbol* resolution. For instance, backoff periods in the CSMA-CA are expressed in multiples of symbol times, and in the beacon-mode packets may only be transmitted on 20 symbol boundaries after the last beacon. In the 2.4 GHz band used by the CC2420 radio, a symbol has a duration of 16 μs. Thus, an implementation of the 802.15.4 MAC protocol on TelosB requires a clock with 62.5 kHz frequency, and according to the standard it must have an accuracy of $\pm$40 ppm.

TelosB has two hardware clocks, but both of them are insufficient to be used as 802.15.4 symbol clocks: the internal oscillator of the microcontroller is highly temperature dependent and thus cannot meet the accuracy requirement, while the external 32.768 Hz oscillator has an inappropriate frequency.

Although the TelosB cannot generate the necessary timing itself, with some minor modifications (adding a 0 Ω resistor and cutting an ADC connection line) one of its timers can be sourced from an external clock attached to the TelosB 10-pin expansion connector. We identified the following requirements that such a "timer-board" must meet:

1. frequency of 62.500 Hz or small multiples thereof: the timer system provides input dividers,
2. accuracy of $\pm$40 ppm,
3. power consumption below 0.5 mA,
4. built using easily available components,
5. on-demand circuit dis/enable, and
6. matching the electrical characteristics of the TelosB mote.

A timer-board that meets these requirements is currently not available for TelosB. We discuss our solution (depicted in Fig. 1) in Sect. 2. In Sect. 3 we show that it meets the above requirements.

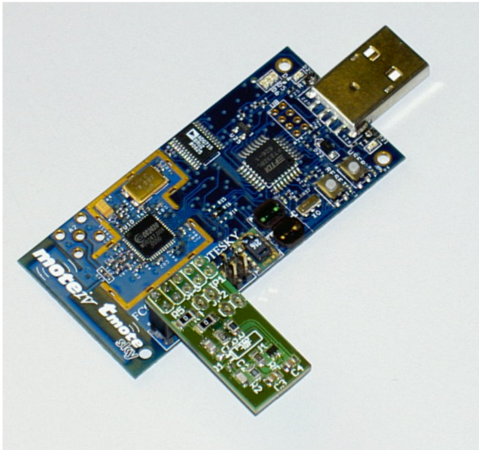

Figure 1: TelosB mote with timer board

2 Circuit Design

Due to its simplicity and robustness we realized the symbol timer as a Pierce oscillator (see e.g. [5]), a standard quartz oscillator. Its main advantage is that it can be built with very few components as shown in Fig. 2. It consists of a CMOS-inverter (Inv) that is put into amplifier mode using the feedback resistor (R), and two capacitors in series with the crystal. The two capacitors are chosen such that their series capacitance matches the capacitance of the crystal at its resonance frequency. In fact, their value is not critical and standard ceramic capacitors with 5-10 % tolerance are sufficient. For the quartz we chose an in stock 125 kHz crystal with $\pm 30\,\mu$s/s tolerance and as inverter we used an NXP 74HC1GU04 [1]. Unfortunately, this oscillator consumes an unacceptable 2.1 mA on average. Therefore we have developed an improved design.

In order to reduce the power consumption, we added two resistors to the circuit (see Fig. 3): one into the power supply connection of the inverter (R3) and one into the ground connection (R2). The values of theses resistors were difficult to find. Higher values reduce the power consumption, but also affect the signal amplitude and offset up to a point where the microcontroller cannot detect it any more.

However, the resistors do not only influence the output of the oscillator: they also influence the gain which, in turn, influences the frequency of the oscillator. A higher gain (using smaller resistors) implies a higher frequency, while a smaller

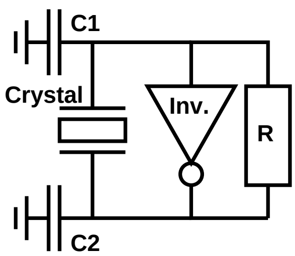

Figure 2: Pierce oscillator

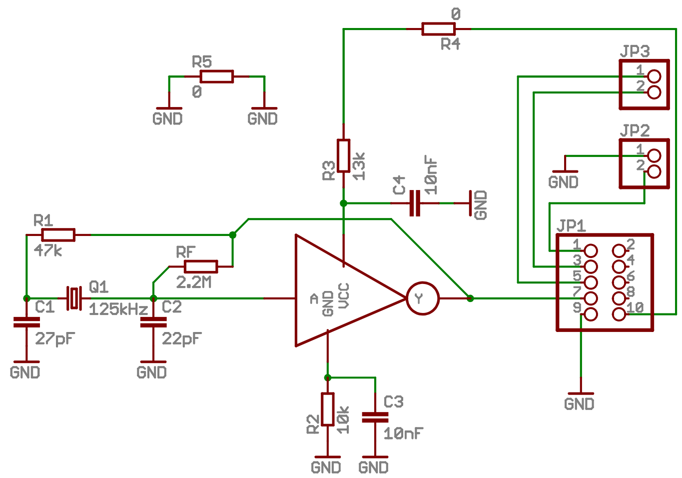

Figure 3: Low power Pierce oscillator

gain implies a lower frequency. To decouple the gain (and hence the frequency) from the resistor values, we introduced the additional capacitors C3 and C4, which also increase the oscillator's noise immunity. The capacitors allowed us to find the right values for R2 and R3 without having to worry about the frequency. In a second step, we adjusted the gain using C3 and C4 such that the frequency is 125 kHz. For a complete list, see Table 1.

3 Evaluation

The final circuit shown in Fig. 3 has a power consumption of 64 μA measured at 3 V power supply using a Fluke 189 Multimeter, a reduction by a factor of more than 30 compared to the initial Pierce oscillator.

We manufactured a small series of oscillators and used 7 boards to evaluate the accuracy. The oscillators were attached to TelosB nodes which sent packets to a PC every 0.5 s. The clock of the PC was kept stable using NTP. Over a time span of more than 24 hours we counted the number of oscillator "ticks" and compared their sum to the elapsed reference time on the PC. From this we calculated that the average frequency of the boards is 125001.6 Hz and their accuracy is $\pm$19.4 ppm[1]. This is within the required accuracy of 125000 Hz $\pm$40 ppm.

In addition, we compared the board with the 32768 Hz oscillator of the TelosB mote once every 0.5 s and found that there are no short-term discontinuities, the frequency did neither increase nor decrease suddenly.

We verified that the output signal of our oscillator meets the input requirements of the MSP430F1611 [2] microcontroller of the TelosB. At a supply voltage of 2.2 V the signal must rise above 1.5 V and fall below 0.4 V, while at a supply voltage of 3 V the signal must rise above 1.98 V and fall below 0.9 V. In Figure 4 we show the signal at 3 V, measured using an National Instruments NI-Scope 5102 Oscilloscope: it rises above 2.1 V and drops below 0.7 V – meeting the requirements.

[1]90% confidence interval of the t-Distribution

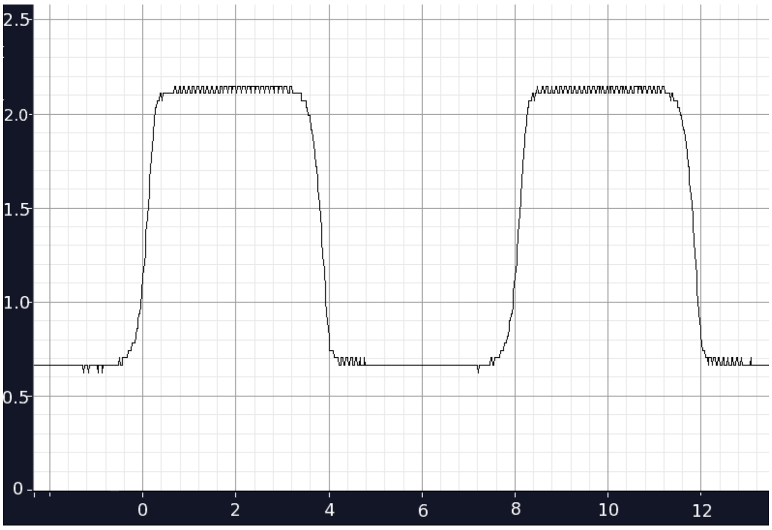

Figure 4: Output signal – y-axis is output voltage [V], the x-axis is time [μs]

We also verified that the oscillator meets the conditions at 2.2 V supply voltage: we measured 1.68 V and 0.395 V.

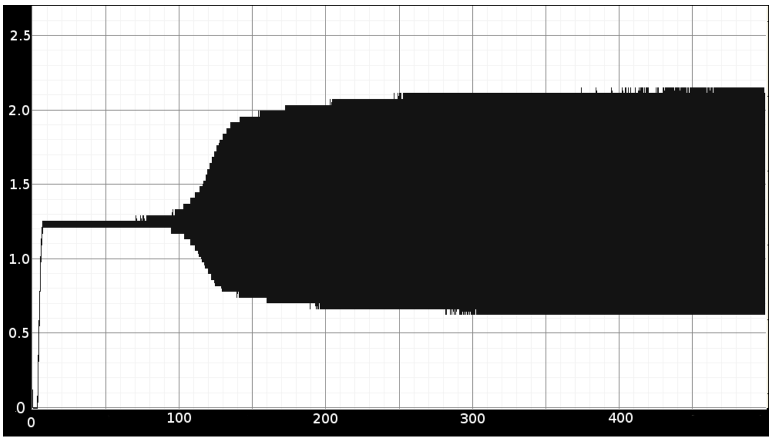

Figure 5: Settling time – y-axis is output voltage [V], the x-axis is time [ms]

Finally, we measured the settling time of the oscillator (the time to reach its steady state, Fig. 5), which is 0.4 s – a standard value for a crystal based oscillator.

References

[1] NXP 74HC1GU04 Inverter Datasheet.

[2] Texas Instruments MSP430F1611 Datasheet.

[3] LAN/MAN Standards Committee of the IEEE Computer Society. *IEEE Standard for Information technology – Telecommunications and information exchange between systems – Local and metropolitan area networks – Specific requirements – Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low Rate Wireless Personal Area Networks (LR-WPANs)*, September 2006.

[4] Joseph Polastre, Robert Szewczyk, and David Culler. Telos: Enabling Ultra-Low Power Wireless Research. In *Proceedings of the Fourth International Conference on Information Processing in Sensor Networks: Special track on Platform Tools and Design Methods for Network Embedded Sensors (IPSN/SPOTS)*, 2005.

[5] Ulrich Tietze and Christoph Schenk. *Halbleiter-Schaltungstechnik*, chapter 14, page 912f. Springer, Berlin, 1999.

A Bill of Materials

Part	*Value*	*Package*	*Remark*
C1	27pF	C0805	Capacitor 5% ceramic, 10V
C2	22pF	C0805	Capacitor 5% ceramic, 10V
C3	10nF	C0805	Capacitor 5% ceramic, 10V
C4	10nF	C0805	Capacitor 5% ceramic, 10V
JP1	2X05	0.1” 2X5	Pin header
Q1	125kHz	TC26H	Crystal
R1	47k	R0805	Resistor 5%
R2	10k	R0805	Resistor 5%
R3	13k	R0805	Resistor 5%
R4	0k	R1206	Resistor 5%
R5	0k	R1206	Resistor 5%
RF	2.2M	R0805	Resistor 5%
U1	74HC1GU04	74HC1GU04	Inverter

Table 1: Bill of materials