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Design of a versatile lowcost IEEE802.15.4 module for long term battery operation

Alexander Klapproth, Simon Bissig, Martin Venetz,
Stefan Knauth, Daniel Käslin, Rolf Kistler
Lucerne University of Applied Sciences
CEESAR – Centre of Excellence for Embedded Systems Applied Research
Technikumstr. 21
CH 6048 Horw / Switzerland
alklapproth@hta.fhz.ch

Abstract

We present an IEEE802.15.4 / ZigBee Module optimized for long term battery operation. The design leads to a very small module which operates several years on one battery, with an actual size of 31 x 14 x 3 mm including chip-antenna and without battery. The TI-CC2431 based module may be produced at costs below EUR 10 / module. Besides detailed design considerations and hints, we present examples from several application patterns which take advantage of the low power low size low cost properties of the module: A classical sensor application reads data from a local sensor and sends this data on a predefined interval. For Push services like a light-switch application an acknowledged transmission is applied to ensure that the requested operation is correctly received. Also the device may behave as an actor. In this mode data is polled at an interval of some minutes. For all three applications, the device may operate several years with an 160 mAh Lithium battery. Context sensitive applications may use CC2431 built-in localisation schemes.

Controller

The heart of the Module is the CC2431 System-on-Chip from TI / Chipcon [1]. The chip includes the proven CC2420 transceiver technology and an efficient 8051 based microcontroller. With 128 KB Flash, 8 KB RAM and a CPU core running at 32 MHz, possible application scenarios range from simple proprietary sensor applications up to full function ZigBee coordinator- or router devices. The CC2431 is almost identical to the pin compatible CC2430 but additionally features a hardware location detection engine. This engine allows RSSI based localisation with an accuracy of around 3 meters. For small applications and reduced function devices without localisation needs, the CC2430 is available with 64 KB or 32 KB flash.
The chip provides 4 different power modes from which the most restrictive – mode 3 - cuts the power consumption down to 0.6 µA. However, the module shall be able to wake up on its own on regular time intervals but power mode 3 only allows power on resets or external interrupts. In power mode 2,,at the cost of 0.9 µA, the only running component is a low power frequency oscillator. At a frequency of 32.768 kHz incrementing a 24 bit counter, the maximum sleeping time is around 8.5 Minutes. Waking-up here only means activating the MCU. It’s possible to leave the RF transceiver in stand-by mode, if no transmission/reception actions are required. While the RX/TX modes of the chip require 27mA/24.7mA, the MCU on its own only consumes 7mA running at full speed. To save an external component - and 32 kHz crystal oscillators can become quite bulky - the module design takes advantage of the internal low power RC oscillator option, which is precise enough for our needs (+/- 0.2% after

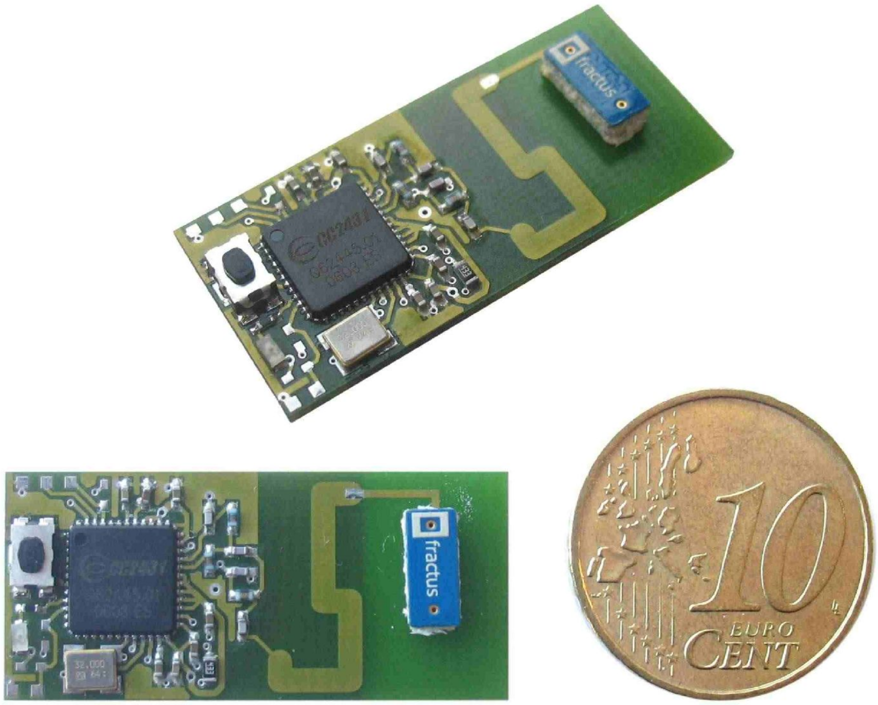


Fig. 1: The CC2431 based WeBee3 device

calibration).

Although the CC2430/31 chips appeared as the first true SoC solutions for IEEE 802.15.4 on the market (end of 2005), they were only available in sample quantities, due to pending revisions. Later on, when Texas Instruments acquired Chipcon, the future of the 8051 (and not MSP430) based design was unclear. However, while still marked as “PREVIEW” on the homepage, TI assures that the chips – the CC2430 with revision E – now work flawlessly, are soon available in large quantities and, if a SoC solution is featured, recommend these chips for new designs of mass market products.

In the meantime, other vendors such as Ember, RadioPulse, Jennic or Freescale have come up with their own 2.4 GHz IEEE 802.15.4 SoC or SIP (system in a package) designs. They mainly vary in their physical RF characteristics such as power output and receiver sensitivity which, together with the antenna, affect the overall link budget and in the end the RF coverage. Depending on the application, factors such as receiver selectivity, RX/TX currents, sleep modes, MAC hardware support (security, auto ACK, CSMA/CA etc.), and the microcontroller derivate affect the evaluation. Further, one should have a look at the development environment, debugging and monitoring facilities, the featured ZigBee Stack, technical support and of course the costs. The price of a chip largely depends on the ordering lot. Rumours from TI talk about 3$ for very high quantities. For Ember EM250 Chips, which are available in smaller quantities, we heard pricing from around 11.5$ for one piece down to 7$ for 2000 chips [2]. Of course one should always directly contact a distributor to get current and reliable pricing information. Table 1 shows a comparison of different SoC/SIP solutions for IEEE 802.15.4 available today. The information has been taken out of the data sheets publicly available.

Battery

As the CC2430/31 operates on power supplies ranging from 2.0 to 3.6V, it is directly driven by a 3V $Mn0_2$–Li Cell. The SANYO CR1/3NT1, initially thought for photo cameras, provides a capacity of 160mAh. This type of battery provides 60mA continuous discharge current (pulse current up to 80mA) from which around 27mA are needed when receiving IEEE 802.15.4 frames.

	Chipcon	Ember	Freescale	Jennic	RadioPulse
Part Number	CC2430/31	EM250	MC13214	JN5139	MG2400-F48
Type	SoC	SoC	SIP	SoC	SoC
Package	QLP48	QFN48	LGA71	QFN56	QFN48
Supply Voltage [V]	2.0 – 3.6	2.1 – 3.6	2-3.4	2.2-3.6	1.7 – 3.6
Sleep Current [µA]	0.6	1	0.2..1	0.4	9
MCU Type	8051	XAP2b (16 Bit)	HCS08	RISC (32 Bit)	8051
I/O Pins (1)	21	17	32	21	20
Max. Flash [KB]	128	128	60	192 (ROM)	external
RAM [KB]	8	5	4	96	64
Max. Clock [MHz]	32	24	16	16	16
Current CPU [mA] (2)	7	8.5	6.5	9.2	-
Current Transmit [mA] 0dBm/Max (3)	24.7	33/41.5	30/35	39/43.5	27/36
Current Receive [mA]	27	35.5	37/42	39	26
Transmit Power [dBm] (4)	0	3/5 (5)	3	3	7
Receive Sensitivity [dB]	-94	-97	-92	-97	-99
Adijacent channel rejection [dB] low side/high side	29/41	35/35	29/34	31/33	32/32
MAC Hardware	Security, packet handling CCA, RSSI, LQI, ED auto ack	Security, packet handling, CCA, RSSI, LQI, auto ack	-	Security, auto ack, auto beacons, CCA, RSSI, LQI, ED	Security, RSSI
Favored Development Environment	IAR	Insight (Eclipse)	MetroWorks	GNU + IDE	Keil
Monitoring Software	Packet Sniffer	Insight HW Tracing	Daintree Network Analyser	Daintree Network Analyser, Packet Sniffer	Packet Analyser
Application Software	TI-MAC, Z-Stack, Free Object Download	EmZNet Stack, Only with Kit	BeeKit, Free Object Download	Jennic Stack, Examples Download	ZigBee Stack, Only with Kit

Table 1: Comparison of SoC and SiP IEEE802.15.4 solutions.
(1) All solutions provide GPIO, UART, SPI, ADC, Timer, DMA functionality. Many have batterie monitoring and temperature sensors on the chip. (2) CPU running at full speed, flash, RAM, no peripherals. (3) CPU and transceiver running, at 0dBm/maximal Output. (4) All chips allow to cut down the maximum transmit power. (5) Boost Mode.

Company	Fractus	RainSun	Antenova	Antenova	Antenova	TI	TI
Type	Chip (fractal)	Chip	Chip	Chip	Swivel	Folded Dipole (Print)	Inverted F (Print)
Bandwidth [MHz]	100	180	100	180	310	N/A	N/A
Efficiency [%]	70	N/A	55	65	85	N/A	N/A
Gain	1 dBi	1 dBi	0.2 dBi	4.1 dBi	4.1 dBi	0.3 dBi	3.3 dBi
VSWR	2:1	2:1	1.5:1	1.6:1	1.2:1	N/A	N/A
Size [L/W/H]	7/3/2	8/3.5	6.1/3.9/1.1	12.8/3.9/1.1	20/19/48	47/9	15.2/5.7

Table 2: Parameters of selected antennas.

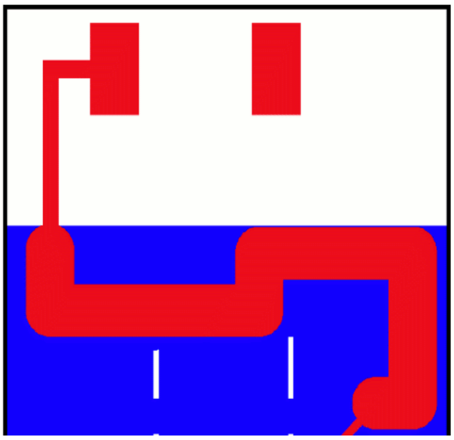


Fig 3: PCB Layout

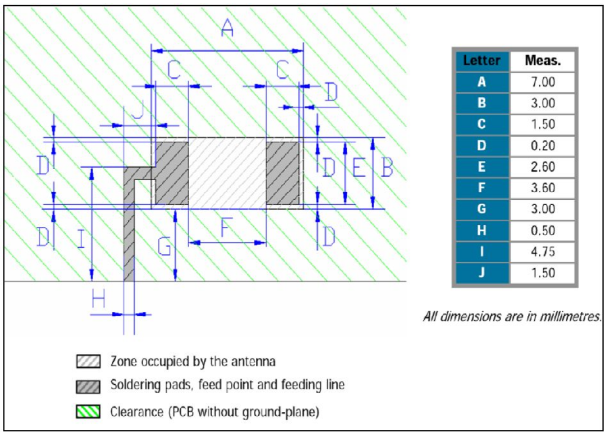


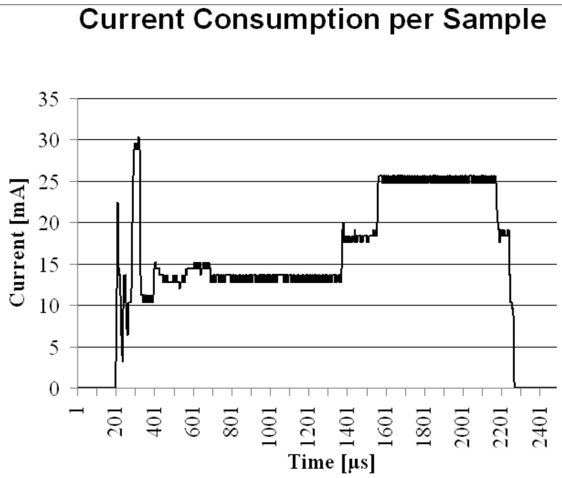
Fig. 4: Antenna PCB layout detail

Surface Microstrip Line			
Parameter		**Unit**	**Value**
	PCB Material	-	FR-4
H	PCB Height	mm	0.8
T	Copper Thickness	mm	0.035
W	Strip Line Width	mm	1.49
L	Strip Line Length	mm	16.9
ε_r	Dielectric Constant	-	4.40
Z_0	Impedance	Ω	50
f	Frequency	GHz	2.442
v_p	Propagation Velocity (fraction of c)	-	0.550

Table 3: Parameters for the antenna feed strip line

$$L=\frac{cv_p}{4f}=\frac{\lambda}{4}=\frac{299792458\frac{m}{s}\cdot 0.55}{4\cdot 2.442\cdot 10^9 Hz}=16.88\,mm$$

Equation 1: Calculation of the length for the antenna feed strip line



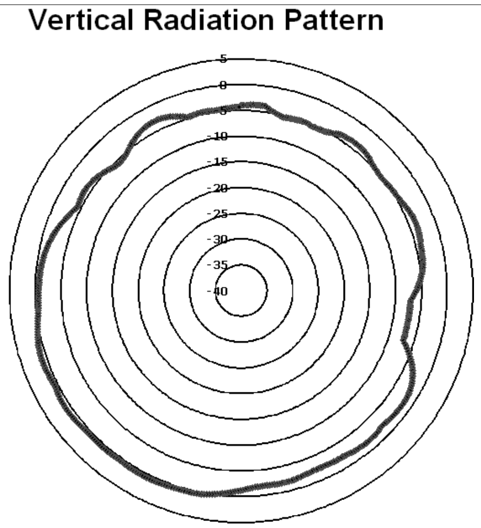


Fig. 5: Recorded current consuption per sample
Fig. 6: Measured vertical radiation pattern of the module

This requirement excludes the direct use of ordinary coin cells from such designs as their maximal discharge currents lie in the order of a few milliampères. With the chosen cell, the sample temperature sensor application developed for the module should be able to send its values for several years (see table 4), taking into account also the self discharging constant. The calculation was made based on the current consumption diagram shown in figure 2. It depicts the transmission of a packet containing one temperature sample.

Antenna

To restrict the physical size of the module to a minimum, only integrated antenna solutions were taken into consideration. Although other antenna types may beat today's smallest chip antennas concerning gain, compared to their small size, the chip antennas provide a very reasonable performance. Taking into account the physical size, the bandwidth, the radiation characteristics and the efficiency of the antenna, the Fractus Compact Reach Xtend Chip Antenna FR05-S1-N-0-102 has been evaluated [3]. Fractus takes advantage of the space-filling and multiple-scale properties of fractal geometries to optimize the performance of their multilayer chip antennas. Another plus of this geometry based approach is that fractal antennas can be manufactured from standard materials using standard processes.
As the antenna's impedance matches the one of the CC2430 RF interface – 50 Ohms – no external adaptation is needed. However, to connect the chip antenna to the chip, a balun circuit and an impedance matched antenna feed line must be designed. For this reason, we employed a 50 Ohm Surface-Micro strip on the PCB. If the impedance, the frequency and the special properties of the PCB material are given, the calculation of this strip can be easily done using free software tools. We used AppCAD from Agilent [4]. Table 3 shows the configuration including the parameters of our specific design. For the placement of the antenna, the vendor comes up with specific requirements (Fig. 4). Besides the geometry of the feed line and the feed point, these requirements mainly propose 3 mm distance between the antenna and the rest of circuit in form of a clearance zone. The clearance zone consists of copper free PCB material without ground plane (Fig. 3). Low power also means that by following these rules, the power loss between RF chip and the antenna can be minimized, thus maximizing the RF performance that can be achieved with a given output transmit power.

Battery Life

Samples	Duty cycle	Battery life
6/h	0.004‰	20 years
30/h	0.02‰	4 years
1/min	0.04‰	2 years
2/min	0.08‰	1 year

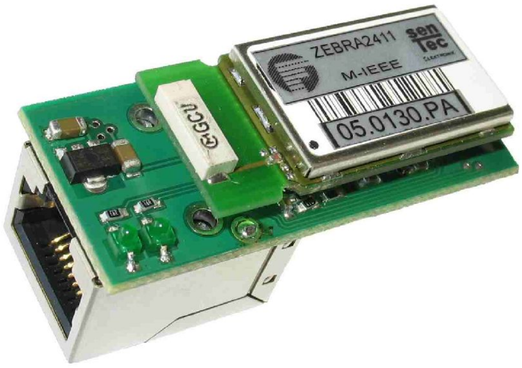


Table 4: Battery life for different sample frequencies

Fig. 7: “EtherBee 2”, a IEEE802.15.4 to Ethernet and TCP/IP Gateway

Board layout

The layout of the two layered PCB closely follows the reference design from TI/Chipcon implemented on their CC2430EM boards [6]. Special care needs to be given to the placement of the ground planes. The area below the chip for instance, must be kept free for such a plain. The balun circuit, on the Chipcon boards in the form of a curved feed line, has been replaced by discrete SMD components in order to save space. Of course, the standard rules for placing such components, such as not to put two coils right next to each other with the same orientation, need to be applied. Concerning the micro strip there are two rules 1) It must be at least 16.9 mm long. Equation 1 is used to calculate this length. In general, the longer this line, the better. 2) It should nowhere be nearer to other circuitry (or itself) than twice its width. Besides this, the layout of the strip does not matter too much.
All in all, without the small push button and the LED we placed for demonstration purposes, the bill of material for the module lists 25 parts. .

Software considerations

As already stated, the node has enough space and performance to host a fully featured ZigBee Stack. However, with very low power applications in mind, we fully tailored the firmware to shortest possible MCU and RF transceiver on-times. For instance, a long term temperature sensing application, we assumed has around a dozen nodes within RF range in star topology and a duty cycle of <0.004 ‰.
The time for the transmission of a temperature value from wake up back to sleep mode 2 is around 2ms. This time is very short, compared to our experiences using various ZigBee/IEEE 802.15.4 Stacks (Z-Stack/TI-MAC TI, MPZBee Microchip, BeeStack Freescale and EmberZNet from Ember). With a ZigBee Stack, such an action may run several dozens of milliseconds. Furthermore, the modularity of those stacks often lack the flexibility one would expect by looking at the interfaces (SAP) defined for the different ZigBee layers in the standard. It often takes considerable effort in getting to understand the stack framework at hand to write an application that directly utilizes the PHY/MAC or NWK interfaces without going through the application layer.
For the temperature itself, we took the on-chip temperature sensor together with a channel of the internal 8-14 Bit ADC. The circuit can be calibrated to measure the ambient temperature to an accuracy of about 0.5°C. The sensor’s temperature data is collected and displayed on the CC2430 Development Board from TI/Chipcon or over an USB Dongle from Integration [7] on a PC.

Applications

The classical sensor application reads data from a local sensor and transmits it on a predefined interval to some gateway or “base” station. Another possibility to integrate the sensors into an existing IT infrastructure is to use a IEEE802.15.4 – Ethernet gateway (“EtherBee 2”, Fig. 7) which provides a sensor data interface on the TCP/IP side, allowing a standard PC to collect the data via a TCP or UDP connection. Using a star-topology, the simplest approach is to send a data packet without prior sensing the channel for activity (CSMA/CA), and without checking the transmission success by an acknowledgement. In this approach, no back channel is required and the receiver is actually not used for normal operation. As mentioned above, in this case the uptime of the transceiver is reduced to the sole transmission of the data packet, which makes the approach the most energy efficient. Of course, the probability for a single data item to reach the backend application is not 100%. But in a typical sensor network application like sensing the temperature in a warehouse, some percentage of measurement value loss is acceptable.

It may happen, that two devices interfere by transmitting at the same time such that the receiver may not be able to receive one or both packets. If the devices would use a constant sleeping time, then this would happen again in the next transmission period, and so on, depending on how aligned the effective frequency of the oscillators of the two devices would operate. Considering a packed duration of 2 msec, and a 20 ppm crystal accuracy, even 100 seconds after the first interference the transmitters may interfere. Since we actually use the built-in RC oscillator, the correlation will be only about one second. Nevertheless, the sleeping time of a module is slightly adjusted after each transmission with a pseudo-random value, which is seeded by a number unique for each device, for example by the device ID or the MAC ID.

Employing the presented module, transmitting a temperature reading every 10 minutes leads to a sensor lifetime of more than 20 years. As mentioned, we did not employ the full ZigBee stack but decided upon sending IEEE802.15.4 MAC frames, which are transmitted by directly interfacing the hardware.

The device is also ideally suited for push services like a light-switch application. Again employing a IEEE802.15.4 star-topology, an acknowledged transmission is applied to ensure that the requested operation is correctly received. In contrast to the sensor application, where the sensor reading is transmitted continuously with a given duty cycle, here a transmission is only necessary on a given event, like a user pushing the switch. On the other hand, the transmission must be acknowledged since each event shall not be ignored at all. Assumed normal usage, the battery lifetime of this application is limited by battery self discharging and typically lies beyond 10 years.

Combining the two above described applications, one gets a long battery life wireless actor. In this mode the device polls data from a router at an interval of some minutes. Equipping the module with a low power LCD display leads to a versatile long term available pager or information display, which may also be context-sensitive by using the CC2431 on-chip localisation feature.

Conclusion

We presented a versatile lowcost IEEE802.15.4 module and discussed specific hardware design details. The module enables a variety of sensor network applications to be run for years on battery powered devices. Using either a star-topology or continuously powered routers, the device may operate using IEEE802.15.4 MAC layer and a proprietary protocol, or may implement a ZigBee reduced functionality device. Beside typical sensor applications like temperature monitoring, also applications which require bidirectional transfer, can be realised. In the latter case there will of course be a trade-off between response time and power consumption. The CEESAR competence centre (www.ceesar.ch) at Lucerne University of Applied Sciences, besides contributing to a high education standard, provides consulting and has a broad experience in industry research partnerships. If you are interested or have questions, don't hesitate to contact us.

Contact

Prof. Alexander Klapproth
Head of CEESAR
Lucerne University of Applied Sciences
Switzerland

Tel.: +41 41 349 35 12
EMail: alklapproth@hta.fhz.ch
Web: http://www.ceesar.ch

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