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Physical layer design of wireless sensor network nodes

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Abstract: Major consideration dimensions for the physical layer design of wireless sensor network (WSN) nodes is analyzed by comparing different wireless communication approaches, diverse mature standards, important radio frequency (RF) parameters and various microcontroller unit (MCU) solutions. An implementation of the WSN node is presented with experimental results and a novel "one processor working at two frequencies" energy saving strategy. The lifetime estimation issue is analyzed with consideration to the periodical listen required by common WSN media access control (MAC) algorithms. It can be concluded that the startup time of the RF which determines the best sleep time ratio and the shortest backoff slot time of MAC, the RF frequency and modulation methods which determinate the RX and TX current, and the overall energy consumption of the dual frequency MCU SOC (system on chip) are the most essential factors for the WSN node physical layer design.

Key words: wireless sensor network node; physical layer; radio frequency; energy consumption; node lifetime

The wireless sensor network (WSN) has been shown to be a promising prospect in various applications. Initial research on WSN was mainly motivated by military applications: e. g. smart dust[1] funded by the Defense Advanced Research Projects Agency (DARPA). With the explosive development of micro electro-mechanical systems (MEMS), integrated circuits and wireless communications, low cost, low power consumption and tiny size components are off the shelf now. WSN has become more available in civil applications: e. g. animal observation[2], glacier monitoring[2], nuclear power plant monitoring[3], etc.

The design of WSN nodes presents a big challenge because of the limited resources of each node. A lot of work has been done in this area, such as the "Mote's family" in the smart dust project in Berkeley, the PicoRadio project, also in Berkeley, the iBadge in UCLA, MIT's PushPin, and WiseNet in Switzerland. Massive deployment of the nodes requires the cost of each node to be as low as possible; the inconvenience of replacing the batteries and the relatively slowly improved battery technology advocate minimal power consumption or energy extracting techniques; small size is always a good advantage during deployment. In the WSN, the communication data rate is usually not an essential factor since WSN is deployed usually not for data transmission but for event detecting.

In this paper, WSN node physical layer design considerations are discussed in detail and an implementation is presented followed by test results and analysis of the node's lifetime estimation.

1 Design Consideration Dimensions

Without doubt, a good WSN node design needs not only consider the physical layer, but also other optimized design spaces[2] such as the optimized MAC layer algorithm, the smart route strategy, and the efficient software system, etc. In this section, we will concentrate on some basic consideration dimensions for the design of the physical layer. Massive manufacture can settle the cost problem; here energy is the major factor.

1.1 Architecture of the node

Fig. 1 shows the system architecture of a generic WSN node.

The basic parts are composed of four entities. The power supply and management model, usually some kind of battery, provides the nodes electrical energy.

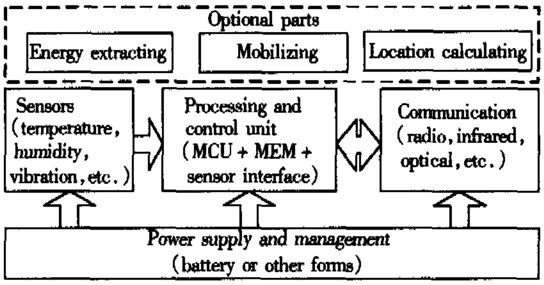

Fig. 1 WSN node architecture

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The communication block comprises a wireless communication channel in the forms of radio, laser, infrared, etc. The processing and control unit should at least include a microcontroller, a storage memory and the interface to the sensor block. The last block is a group of sensors or other devices which collect the desired data. Since different applications employ diverse sensors, this paper will not go further than the sensor part.

1.2 Communication approaches

For the WSN, according to specific application scenes, large quantities of nodes might be deployed either indoors or outdoors, either deliberately or randomly, either fixed or with mobility. Therefore, the wireless communication approaches used in the WSN should meet various and even rough environments. Here, five common wireless approaches are listed and analyzed.

1) Infrared

Infrared is widely used in remote control applications. The advantages of infrared are as follows: the cost of the infrared devices is extremely low; no antenna is needed, so a tiny size of the node can be achieved. The defects are as follows: not energy efficient (a 10 m 20° directional transmitter consumes about 60 mW); short communication range (usually less than 1 m of the diffused type and several meters of the directional type); poor ability of traveling round or penetrating the obstacles. In sum, infrared is not a good solution for the WSN.

2) Laser (optical methods)

The merits of laser are as follows: energy efficient because of its extremely focused energy; security due to no broadcasting transmission; no antenna is needed; a small laser emitter is also cheap. The shortcomings are as follows: line of sight (LOS) is needed; the nodes must be carefully placed so that the laser beam can be received; it is sensible to atmospheric conditions. Due to those shortcomings, laser is not attractive in the WSN.

3) Inductive and capacitive coupling

Most passive RFID systems use this approach. Its disadvantage is small working distances, usually only about tens of centimeters. The WSN requires a communication range from several meters to hundreds of meters.

4) Sound

Sound or ultrasound is typically used for communication under water, but not for most WSNs.

5) Radio frequency (RF)

The benefits of RF are as follows: omni-direction transmission with ability of diffracting or penetrating the obstacles (NLOS); lower power consumption than that of infrared; relatively long function range (1 ~ 100 m @0 dBm). The biggest challenge for RF is the antenna design. To optimize the antenna gain, the PCB antenna needs $\lambda/4$ in length for whip or stub shape (λ is the wavelength of the carrier), which adds to the size of the node. The advantages of RF have made it an ideal testing platform for the WSN. Actually, most of the WSN projects employed the RF solution.

1.3 Radio communication solutions

1) Mature short distance radio standards

WPAN (wireless personal area networks, IEEE 802.15 Group) and WLAN (wireless local area networks, IEEE 802.11 Group) are nowadays major short range wireless networks. The 802.11 series (802.11b/a/g, etc.) is developed for a "wireless Ethernet", which does not take into consideration the energy but has a high data rate (11 to 54 Mbit/s, consuming more than 1 W in active mode and more than 50 mW[4] in power saving mode). Therefore, the WLAN devices are not suitable for the WSN nodes. 802.15 series includes 802.15.1/2 (Bluetooth), 802.15.3 (UWB), and 802.15.4 (ZigBee). The UWB aims at multimedia applications and is not energy saving. Some projects did use Bluetooth to implement WSN[5], but because of its short range (about 10 m) and lack of extreme power efficiency (refer to the Bluetooth chip BRF6150 in Tab. 1), the Bluetooth is also not a remarkable solution. ZigBee is regarded as the most suitable standard for the WSN. The PHY layer of ZigBee is almost suitable for WSN (not the best, see the ZigBee chips in Tab. 1). The MAC layer is not energy efficient enough for its traditional CSMA-CA algorithm[6].

2) Off the shelf components

Lots of SDR (short distance radio) chips are available today. Tab. 1 lists several market leading chips with their features.

3) RF device considerations

There are mainly five dimensions needed to be considered to make a good choice for the RF part.

① Operation frequency The WSN is expected to operate in the 433 MHz/868 MHz/2.4 GHz/5 GHz ISM bands. In general, higher bands can provide higher data rates and allow for smaller antenna size, but a higher frequency needs a higher clock rate[7], which means higher power consumption, and brings greater oscillator phase noise[7], which reduces the reception sensitivity. In Tab. 1, the 2.4 GHz devices generally consume more power especially in RX mode, and with lower RX sensitivity.

② Modulation The more complex the modulation is, the more power is needed. Constant envelope modulations that allow high-efficient nonlinear PAs are favored[7]. Therefore, FSK is a good solution for WSN's stringent low power requirement.

③ Startup time With regard to the MAC layer strategy, the nodes in WSN will be in a periodic listen and sleep cycle[8] in order to save power. According to the research on our MAC layer protocol, we conclude that the startup time of the component plays an essential role in the WSN. Since the startup time is the time period that the node needs to switch between sleep state and active state, it determines the best time ratio of sleep mode in the cycle, the evoking time needed for waking up the neighboring nodes and the minimal time slot of the MAC backoff strategy.

④ Sleep current The node in WSN will be in sleep state most of time; therefore, the sleep current is an important parameter in the design.

⑤ RSSI (receive signal strength indicator) The RSSI signal is useful for fast carrier sense, which is an indispensable part in the MAC backoff algorithm.

Tab. 1 Radio components comparison

Components	CC1010(8051 + RF)	CC2420(ZigBee)	nRF24E1(8051 + RF)	BRF6150(Bluetooth)	MC13192(ZigBee)	TDA5250
Frequency/GHz	0.3 to 1	2.4	2.4	2.4	2.4	0.868
Modulation	FSK	O-QPSK(DSSS)	GFSK	GFSK(FHSS)	O-QPSK(DSSS)	ASK/FSK
Voltage/V	2.7 to 3.6	2.1 to 3.6	1.9 to 3.6	1.7 to 3.6	2.0 to 3.4	2.1 to 5.5
TX current/mA	10.4 (0 dBm/433 MHz)	17.4 (0 dBm)	13 (0 dBm)	25	30 (0 dBm)	9.4 (6 dBm)
RX current/mA	9.1 (433 MHz)	19.7	18 (250 Kbit/s)	37	37	9 (3 V FSK)
RX sensitivity/dBm	−107@1.2 Kbit/s	−94	−90	−85	−92	−109
Data rate/(Kbit · s^{-1})	76.8 (max)	250	1 000 (max)	723.2	250	64 (max)
Startup time/μs	250 (RX)/270 (TX)	< 192	<200	NA	2.5×10^4	1.2×10^4
Sleep current/μA	0.2 (RF only)	1	2 (8051 + RF)	25	2.5	9
RSSI	Yes	Yes	No	NA	No	Yes

1.4 Processing units and sensor interfaces

The MCU in a WSN node serves as both the node controller and the data processor. Here, the processing ability of the MCU is not an acute issue, but since the MCU should never be turned off (most of the time in idle mode), it occupies a big part in power consumption. Thus, the power consumption in idle state is an important parameter for the choice of MCU. On the other hand, the cost, the power and the size limitations of the node argue that the MCU can only be an 8 bit or 16 bit low-end microprocessor SOC solution: the MCU chip integrates the code and data memories, the ADC converters and UART/SPI/GPIO interfaces.

There is another recently appearing solution: the MCU embedded in the RF chips such as CC1010, nRF9E5, nRF24E1, etc. Compared with the traditional solution of MCU connecting with an RF chip, the advantages of this integration are as follows: better system reliability due to fewer chips and fewer inter-chip connections; lower power consumption for inner chip data transfer and shared clock oscillation parts; smaller PCB size. Tab. 2 lists the comparisons of some practical MCU solutions.

Tab. 2 MCU comparisons

MCU	ATmega16L (8 bit)	P89LPC912 (8 bit)	MSP430F147 (16 bit)	CC1010 (8051 core)	nRF24E1(8051 core)
Maximum performance	8 MIPS @ 8 MHz	9 MIPS@18 MHz	8 MIPS@8 MHz	5 MIPS@24 MHz	5 MIPS@20 MHz
Flash/EEPROM/RAM	16 KB/512 B/1 KB	1 KB/0/128 B	32 KB + 256 B/0/1 KB	32 KB/0/2 KB + 128 B	0/0/4 KB + 256 B
ADC	8 channel, 10 bit	Comparator	12 bit ADC, comparator	3 channel, 10 bit	9 channel, 10 bit
IO	PWM, UART, SPI, IIC, GPIO	PWM, UART, SPI, GPIO	USART, SPI, GPIO	PWM, UART, SPI, GPIO	PWM, UART, GPIO
Voltage/V	2.7 to 5.5	2.4 to 3.3	1.8 to 3.6	2.7 to 3.6	1.9 to 3.6
Current(active/idle)	3.8 mA/1.2 mA@4 MHz, 3 V 1.1 mA/0.35 mA@1 MHz, 3 V	7 mA/1.5 mA@12 MHz, 3.6 V 4 mA/1 mA@7.373 MHz, 3.6 V	280 μA/1.6 μA @1 MHz, 2.6 V	14.8 mA/12.8 mA@14.745 6 MHz 1.3 mA/29.4 μA@32 KHz	3 mA/2 μA @16 MHz, 3 V

1.5 Power supply and management issues

The power supply block consists of a battery and relative circuits. Batteries can be divided into two classes: non-rechargeable and rechargeable. In general, the non-rechargeable has higher energy density and lower cost. It may be possible to extend the lifetime of a sensor node by extracting energy from the environment, for instance, solar light, vibrations, RF, etc. But the high cost of these techniques hinders the implementation.

Power management strategies are considered in prior research[7,9,10]. Although it is usually accomplished by the application layer, there are also some methods in the physical layer to reduce power consumption. In Refs. [9, 10], dual processor solutions are suggested for power saving because the power consumption of the microprocessor is in direct proportion to the frequency at which it works. One high frequency processor, which serves for the RF model, can be in sleep mode when there is no data to transfer; one low frequency processor controls the node and does some data processing. However, this design results in several problems: the cost of the node ascends; the reliability of the node descends; the size of the node PCB increases. There are some devices such as CC1010 that can use two crystal clock inputs (one is 32 kHz, and the other may be 3 MHz), and we can make the node with only one MCU but work at two different clock frequencies so as to achieve the same results as using dual processors. One processor working at two frequencies is a much better solution than dual processors.

2 An Implementation of the WSN Nodes

2.1 Solution and design

According to the considerations mentioned above, to minimize power consumption, node size and node cost, and to guarantee the reliability of the device, we prefer an SOC solution. For the frequency band, 433/868 MHz is chosen. It is best that there is no hardware or firmware MAC layer in the chip so that our own MAC and route protocols later can be deployed on this WSN node platform. So, the ZigBee devices are deserted and the existence of RSSI signal and short startup time are required. Finally we accomplished our prototype WSN node (see Fig. 2) using CC1010. The node integrated a compact PCB antenna, a temperature sensor, and a DC-DC converter. The RF part of CC1010 was configured to work at 868.277 MHz.

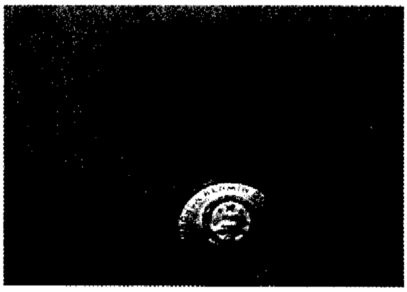

Fig. 2 WSN node

2.2 Experimental results

We conducted a node to node open air LOS data transfer test on November 20th, 2005. The results were the reliable communication distances between two nodes, which are shown in Tab. 3.

Tab. 3 Point to point communication range (LOS) m

Data rate/(bit·s^{-1})	RF power/dBm		
	-20	-10	0
19 200	25	36	46
9 600	33	37	49
2 400	47	48	58
600	48	49	81

3 Lifetime Estimation

There are four working states of each node and the power consumptions of each state are listed in Tab. 4. The time ratio in Tab. 4 means the assumed time percent of each state. We took into consideration the periodic listen and sleep cycles[8] required by the MAC layer algorithm, so state 3 owns a time ratio as high as 5% and 1%. The lifetime T_{lifetime} can be estimated as

$$T_{\text{lifetime}} = \frac{C_{\text{battery}}}{I_{\text{average}}} \tag{1}$$

$$I_{\text{average}} = \sum_{i=1}^{4} P_i I_i \tag{2}$$

where C_{battery} is the capacity of the battery (mA · h), I_{average} is the average current consumption (mA), P_i is the time ratio in the state i, and I_i is the current consumption in the state i.

Tab. 4 Four states of the node with the power consumption of each state (868. 277 MHz)

MCU	RF	State	Current/ mA	Time ratio A/%	Time ratio B/%	I_{avarage}/mA	Lifetime/h
Idle (29. 4 μA @ 32 kHz)	Power down (0. 2 μA)	1 Sleep	0. 029 6	93. 5	98. 8	0. 906	286 (CR2330)
Active(3. 7 mA@ 3. 686 MHz)	Power down (0. 2 μA)	2 Data process	3. 7	1	0. 1	(ratio A)	1434 (CR123A)
Active(3. 7 mA@ 3. 686 MHz)	RX(11. 9 mA)	3 RX	15. 6	5	1	0. 201	1427 (CR2330)
Active(3. 7 mA@ 3. 686 MHz)	TX(8. 6 mA@ -20 dBm)	4 TX	12. 3	0. 5	0. 1	(ratio B)	7138 (CR123A)

As shown in Tab. 4, the lifetime was calculated based on two types of batteries (CR2330 Li-Mn coin battery: 260 mA · h, max 3mA continuous current; CR123A Li-Mn column battery: 1 300 mA · h, max 1A continuous current) and under different state time ratios. From the lifetime estimation, we can confirm that the most essential design factors for power saving are as follows: the RF startup time, which decides which time ratio can be achieved by the MAC algorithm; the RX current (including MCU active current), since the node has to listen to the media periodically; and the sleep current, which occupies the biggest time part.

The lifetime evaluation in Ref. [9] is problematic for its lack of considering the node's periodical RX state. The multi-hop feature of the WSN requires that the node should act as both a data source and a network router, so each node should periodically listen to the media preparing for data relay. This error in Ref. [9] leads to the much longer but mistaken estimated lifetime (13. 1 years).

4 Conclusion

In this paper, the basic dimensions for the WSN node physical layer design are discussed, and an implementation is presented together with the test results and lifetime evaluation analysis.

To meet the energy, size and cost design challenges, every aspect of the node system should be carefully considered. For the physical layer, the startup time of the RF which decides the best sleep time ratio and the shortest backoff slot time of MAC can be achieved. The RF frequency and modulation methods which determinate the RX and TX current, the dual working frequency MCU SOC which contributes to the reliability and overall energy consumptions, are the three most essential factors for this challenge.

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无线传感器网络节点的物理层设计

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摘要:比较和分析了无线传感器网络节点物理层设计的各种无线通信技术、现有的成熟标准、重要的射频参数以及不同的处理器方案,对节点物理层设计的各个主要方面进行了较为全面的研究. 介绍了无线传感器网络节点的一种实现,给出了相关的测试数据以及一种"单处理器双工作频率"的新节能策略. 分析了符合传感器网络 MAC 算法中节点周期性侦听要求的节点寿命估算问题. 指出无线传感器网络节点物理层设计的关键考虑因素为:RF 启动时间(决定 MAC 协议可以实现的最佳节点睡眠时间比例和最小的退避时间颗粒)、RF 载波频率和调制方式(决定射频收发功耗)以及处理器工作在 2 个频率的片上系统的总体功耗.

关键词:无线传感器网络节点;物理层;无线电射频;能耗;节点寿命

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