Smart Structures and Systems, *Vol. 14, No. 4 (2014) 617-641*
DOI: http://dx.doi.org/10.12989/sss.2014.14.4.617

Energy efficiency strategy for a general real-time wireless sensor platform

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(Received August 13, 2013, Revised October 19, 2013, Accepted October 20, 2013)

Abstract. The energy constraint is still a common issue for the practical application of wireless sensors, since they are usually powered by batteries which limit their lifetime. In this paper, a practical compound energy efficiency strategy is proposed and realized in the implementation of a real time wireless sensor platform. The platform is intended for wireless structural monitoring applications and consists of three parts, wireless sensing unit, base station and data acquisition and configuration software running in a computer within the Matlab environment. The high energy efficiency of the wireless sensor platform is achieved by a proposed adaptive radio transmission power control algorithm, and some straightforward methods, including adopting low power ICs and high efficient power management circuits, low duty cycle radio polling and switching off radio between two adjacent data packets' transmission. The adaptive transmission power control algorithm is based on the statistical average of the path loss estimations using a moving average filter. The algorithm is implemented in the wireless node and relies on the received signal strength feedback piggybacked in the ACK packet from the base station node to estimate the path loss. Therefore, it does not need any control packet overheads. Several experiments are carried out to investigate the link quality of radio channels, validate and evaluate the proposed adaptive transmission power control algorithm, including static and dynamic experiments.

Keywords: wireless data acquisition; real time wireless sensor; energy efficiency; low duty cycle polling; adaptive transmission power control; path loss estimation

1. Introduction

Wireless sensors can provide a convenient approach to collect various physical variables from the surrounding environment, without the need of power and communication cables. Their application covers military surveillance, industrial monitoring and control, home/building automation, environment monitoring and so on. Among others, civil engineering structural monitoring is one of the important application fields. In this field, sensors are usually deployed far away from the central data acquisition device and do not have access to any grid. The conventional way is to deploy a long cable for power and signal transmission. However, it suffers installment difficulty, high cost, and limited distance due to attenuation. Therefore, a battery-powered wireless

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http://www.techno-press.org/?journal=sss&subpage=8 ISSN: 1738-1584 (Print), 1738-1991 (Online)

sensor is a good replacement of a wired configuration.

However, wireless sensors have some drawbacks, such as limited battery energy supply and unreliable radio communication. Radio communication is one of the main power consumption sources, which can be reduced by decreasingthe receiving duty-cycle and the transmission power. Reducing radio transmission power will decrease the link quality and thus increase the data loss. Increasing the radio transmission power will lead to higher energy consumption and also higher interference among different wireless sensors. How to optimize the transmission power becomes the issue on which attention has to be focused.

Although wireless sensors are often conceived for low power and long term monitoring application in the form of a dense wireless sensor network, it is also a good tool for short term and non-low power monitoring with simple star network topology. The low power property depends not only on the wireless data acquisition hardware, but also on the sensors. Recently, micro electro mechanical systems (MEMS) sensors become popular, because they have small dimension and low power, but for some applications, they are not appropriate due to their high noise floor. For example, in the civil engineering structural monitoring field, conventional sensors are still broadly adopted, such as the accelerometer EpiSensor FBA ES-T and FBA-11, since their noise floor are very low and they are able to detect a very small structural response with satisfactory accuracy.

There already exist many wireless sensor platforms in the structural monitoring field (Arms *et al*. 2010, Spencer and Yun 2010, Liu *et al*. 2011, Meyer *et al*. 2010, Swartz *et al*. 2010, Kim and Lynch 2012, Torfs *et al*. 2013), but most of them are customized for specific low power sensors or sensor boards and are not general. Since there are still many conventional high-performance sensors used for monitoring the small response of structures, a general wireless data acquisition platform is desirable. Therefore, based on the previous relevant effort (Casciati and Rossi 2007, Casciati and Chen 2011, Casciati and Wu 2012, Casciati and Chen 2012, Casciati *et al*. 2012), the author designs a new wireless data acquisition platform which bridges the gap between conventional sensors and low power dense wireless sensor networks.

The new energy-efficient wireless sensor platform can mount several kinds of transducers adopted in structural monitoring applications, with emphasis on achieving a good trade-off between power consumption and data loss by means of adaptive transmission power control. The platform can be interfaced with various sensors, including low power and non-low power sensors, by means of generic signal input and adjustable power supplies. The energy-efficiency is also achieved by a flexible and efficient power management and energy harvesting strategy. For reliability and real time, single hop communication is adopted. In case of long distance, a transceiver with a power amplifier and a relay transceiver can be used.

The paper is organized as follows: Section 2 reviews some related works about radio transmission power control technologies; in Section 3, the design of the whole wireless sensor system is briefly described; in Section 4, the proposed energy efficient strategy is presented in detail; Section 5 focuses on the proposed adaptive transmission power control algorithm, its implementation in the platform and its experimental validation and evaluation; lastly, some conclusions are drawn in Section 6.

2. Related work

Jeong *et al*. analyze the existing transmission power control algorithms and propose their own improved dynamic transmission power control (DTPC) algorithm based on the number of network neighbors for the Mica2dot platform and multi-hop networks(Jeong *et al*. 2007). It is found that (1) the energy saving of DTPC depends very much on the traffic pattern. It has not noticeable energy saving for aggregation traffic pattern, while it has around 16% energy saving for convergence traffic pattern. (2) the energy saving of DTPC should refer to the overall radio energy consumption, not only the transmission energy consumption. The overall radio energy saving depends also on the duty cycle of radio listening. Lower duty cycle will have higher energy saving. However, DTPC is not suitable for single-hop real-time convergent communication, since it requires the feedback of neighbor number.

Lin *et al*. propose an adaptive transmission power control (ATPC) technique for the MICAz using CC2420 transceiver, based on a linear predictive model between transmission power levels and received signal strength (Lin *et al*. 2006). It is found that the quality of radio communication varies significantly with time and environment even if the position of the wireless sensors are fixed, thus implying the ineffectiveness of fixed transmission power solution. TPC algorithms are categorized into three types, network level, node level and pair-wise. Their ATPC is pair-wise, which has an efficiency better than that offered by others. All the available transmission power levels are scanned and the approximate linear relationship between the transmission power level and the received signal strength is obtained. Thus, a predictive linear model is used to design the ATPC algorithm and to dynamically update the model parameters based on new measurement.

However a problem between the transmission power level index and the actual transmission power in CC2420 is ignored. They are not exactly linear in all the 32 transmission power levels. Instead, there are only 8 transmission power steps suggested in the datasheet of CC2420, instead of 32 steps. This phenomenon can be easily observed in Fig. 3 of the reference (Lin *et al*. 2006). Furthermore, their algorithm requires a lot of computation due to the calculation of model parameters.

Correia *et al*. propose a dynamic transmission power control technique, called Adaptive Exponentially Weighted Moving Average (AEWMA), for the wireless sensor network platform Mica2 using the CC1000 transceiver (Correia *et al*. 2007, Correia and Nogueira 2008). It employs calculations to determine the ideal transmission power based on the reception power, transmission power and average noise. The sender transmits a data packet to the receiver with the transmission power and when the packet is received, the receiver reads the received signal strength (RSS), calculates an ideal transmission power which can maintain the RSS higher than a certain threshold above background noise, and then send it to the sender by piggybacking it in acknowledge (ACK) packet. In order to reduce the fluctuation, an exponentially weighted moving average (EWMA) filter is used in the receiver to filter the ideal transmission power. The consequent data packet will be transmitted based on the latest calculated transmission power.

However, their algorithm has two problems: the first one is that, the calculation is done in the receiver and the time taken by running the algorithm delays the return of the ACK packet; the second problem is that the transmission power of a new data packet is based on the calculated ideal transmission power of the last data packet, therefore if the signal attenuation between two adjacent data packets is significantly increased, the transmission of the new data packet might never succeed. In addition, in the evaluation of radio energy saving, the power consumed by the radio receiver is not taken into account.

Addressing the abovementioned problems, in this paper, a new adaptive transmission power control algorithm is proposed and implemented in the wireless data acquisition unit adopting the TI transceiver CC2430, as a part of the proposed energy efficiency strategy. The algorithm is pair wise and similar to the AEWMA, with some improvements for the real time continuous wireless data acquisition applications. Firstly, the algorithm is implemented in the sender (wireless sensors) based on the RSS and background feedback piggybacked in ACK packets from the receiver. Secondly, when a wireless data acquisition activity is started, the algorithm is restarted from using the highest transmission power, thus ensuring the success of initial communication. Thirdly, the energy consumed by radio receiving and lost packets are taken into account in the evaluation of the algorithm in terms of energy saving. In addition, the calculation of a new ideal transmission power level is based on the moving average of the eight latest signal channel path loss estimations.

3. System architecture

The proposed system consists of 3 modules: wireless sensing unit, base station unit and data acquisition software. The wireless sensing unit performs the data acquisition from connected sensors, thentransmits the acquired data to its base station through the wireless network. Once having received the data, the base station unit sends them to the data acquisition software through a USB virtual serial port. Finally, the data acquisition software stores the collected data into a text file, displays them in an edit box and also plots them.

This section provides the description of the three modules.

3.1 Wireless sensing unit

The wireless sensing unit is the key module in the wireless data acquisition systemand it forms a wireless sensor when Combined with a sensor. Usually, it is installed in a not easily accessible place and powered by a battery, and requires high power efficiency and low power features so as to avoid frequent replacement of the battery.

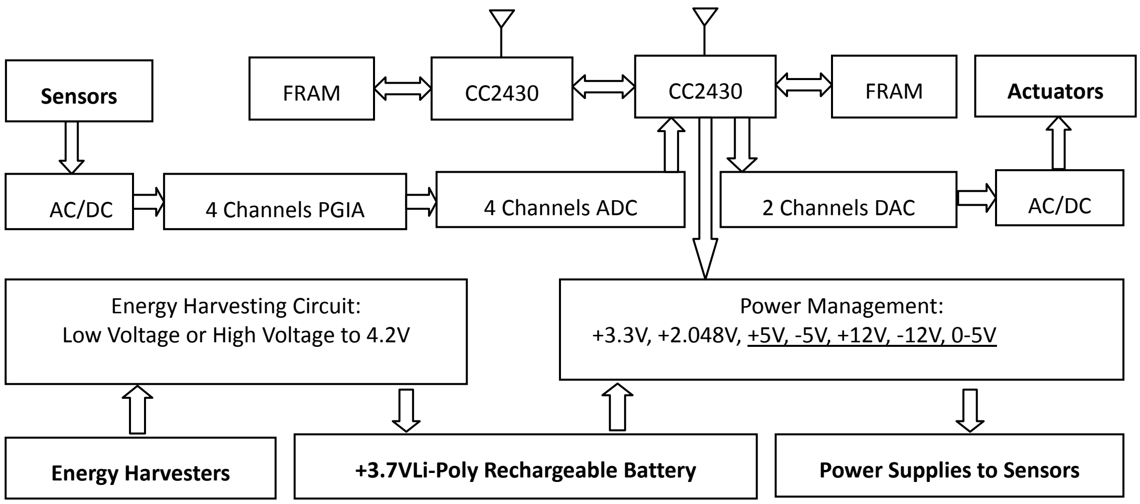

Fig. 1 Block diagram of the new wireless sensor and actuator unit

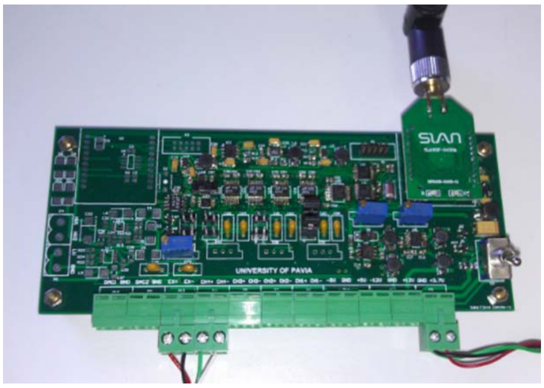

Fig. 2 prototype of the wireless sensing unit

The block diagram and prototype of the wireless sensor unit is shown in Figs. 1 and 2 respectively, where FRAM means "ferroelectric random access memory"; AC/DC indicates alternative current coupling or direct current coupling; PGIA means "programmable gain instrument amplifier"; ADC denotes the analog to digital converter and DAC the digital to analog converter. The blocks labeled in bold are external modules, which are not included in the circuit board. In the block of power management, the voltages underlined can be used as power supplies for external sensors and actuators. The power management and energy harvesting circuit is discussed in Section 4.

3.2 Base station unit

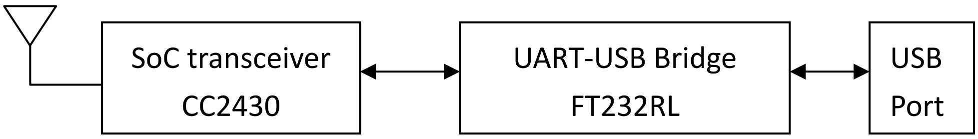

Fig. 3 Block diagram of base station unit

Fig. 4 Prototype of the base station unit

In the wireless data acquisition system, the base station unit (BSU) serves as a transparent bridge between wireless sensing unit (WSU) and computer. Commands from computer will be first passed to and stored in the base station unit. When wireless sensing unit polls BSU, it can fetch the command from the corresponding buffer. Since there is no energy constraint for the BSU, it will usually stay in radio receiving mode waiting for polling from WSU.

As shown in Figs. 3 and 4, the hardware of the base station unit mainly consists of a CC2430 transceiver and an UART to USB converter FT232RL which can create a virtual serial port in the computer through USB connection.

The BSU uses the same simple packet protocol as the one used in the WSU. The WSU packs the data of 10 sampling (80 bytes) with a packet sequence number and transmission power level into a data packet. When the BSU receives the data packet, it will check the sequence number. If the sequence number is different from the previous one, it will pass the data together with packet sequence number, transmission power level, received signal strength indicator (RSSI) and link quality indicator (LQI) values to the computer software, or else it will discard the packet, so that repeated data packets can be avoided.

The data frame from computer to BSU consists of a length byte and data bytes. BSU will use direct memory access (DMA) to receive the data frame, in order to reduce CPU burden. However, the data frame from BSU to computer is of fixed length for simplicity, since the software running in the computer can use the number of available bytes in the serial port input buffer as the interrupt event.

3.3 Data acquisition and configuration software

The software consists of three modules, as shown in Fig. 5. It has a graphical user interface (GUI) to control the system, as shown in the Figs. 6 and 7. Through the GUI, user can configure serial port, wireless sensor parameters, power on/off wireless sensor, start/stop data acquisition and create a file to store data. Moreover, the software uses the serial port interrupt to process the data from wireless sensor. For simplicity, the interrupt event of the serial port is configured to available data bytes of a specified number in the receiving buffer.

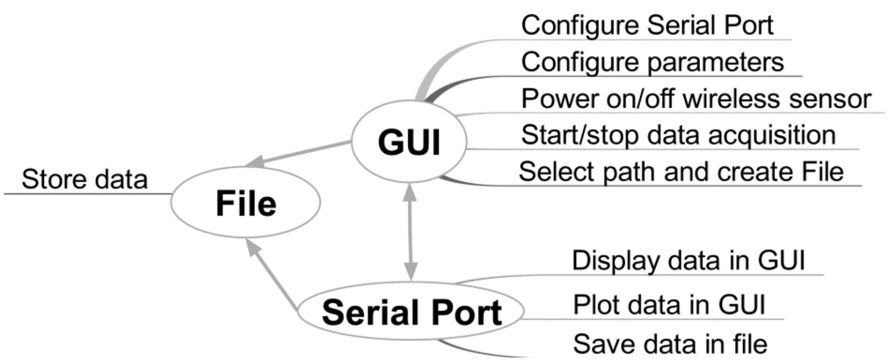

Fig. 5 Functions of the software modules

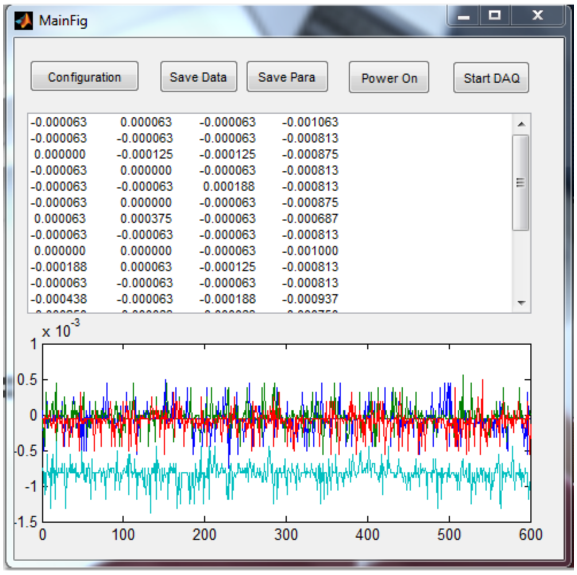

Fig. 6 Main window of the software

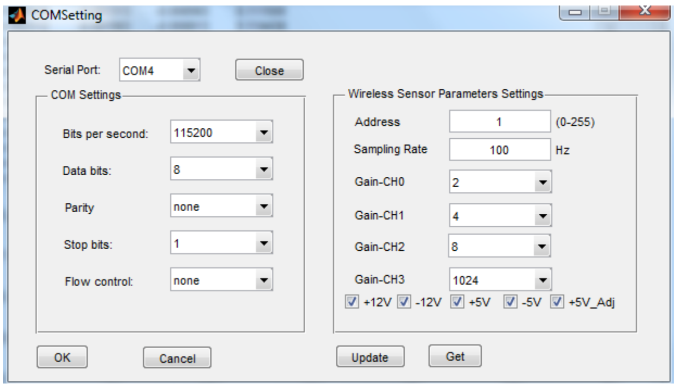

Fig. 7 Configuration window of the software

When configuring a wireless sensor, the software will send the new configuration data in GUI to BSU through the serial port. When receiving data from the serial port, the callback function of the serial port will display the data in the edit box of the GUI, plot them in the axis of the GUI, and save them in the created file.

4. Energy efficiency strategy

Since the wireless sensing unit is designed for both low-power and non-low-power sensors, power efficiency is pursued instead of a low power property.

The power efficiency strategy consists of three parts: part 1 is to adopt efficient, low quiescent current consumption, and switchable power management ICs; part 2 is to define three operational states for wireless sensors: the asleep state with most circuit switched off and low duty cycle radio polling, the awake state with all circuits on, and the data acquisition state. The power consumptions in the three states are quite different, since the switch state of electronic modules is different; part 3 is to adopt a new adaptive transmission power control technique to reduce the radio transmission power in the data acquisition state. The last part will be discussed in detail in Section 5.

4.1 Flexible and efficient power management

The flexible and efficient power management is another feature of this wireless sensor unit. It adopts different low-power high-efficiency voltage regulators to produce different power supplies, as shown in the power management block in Fig. 1. The types of the adopted regulators include LDO (low dropout), DC-DC switching regulator, DC-DC charge pump. Except the LDO for 3.3V, which is the power supply of the main CC2430, all the regulators can be shut down. Therefore, the power consumption of this unit in sleep mode can be greatly reduced.

In addition to the power management circuit for generating various power supplies from the original battery power supply, an energy harvesting circuit is also integrated in this unit. In fact, it consists of two DC-DC regulators with the 4.2V output voltage, one of which is a stepping-up regulator for low voltage energy harvesters (like thermo electric generator and solar panel), another one is a stepping-down regulator for high voltage energy harvesters (like piezoelectric and electromagnetic devices).

Table 1 the adopted voltage regulators

Voltage Regulator	Model	Quiescent Current	Conversion Efficiency	Description
+12 V	MAX618	500 μA	93%	switching converter
-12 V	MAX765	120 μA	80%	Switching Converter
+3.3 V	MCP1700	1.6 μA		LDO
+5 V	MAX1722	1.5 μA	90%	Switching Converter
	LT1762	25 μA		Low noise LDO
-5 V	MAX1673	35 μA	75%	Switching Charge Pump
	LT1964	30 μA		Low noise negative LDO
+2.048 V	LT1790	60 μA		Voltage Reference
+4.2 V	LT3971	2.8 μA	88%	Switching Converter
	LTC3105	24 μA	90%	Switching Converter

All the voltage regulators adopted in the design and their quiescent current and conversion efficiency are summarized in Table 1.

4.2 Three operational states of the wireless sensor

In order to efficiently use the energy of the wireless sensor battery, three operational states are defined: asleep state, awake state and data acquisition state. The hardware of the wireless sensing unit can be roughly divided into three modules: analog module (including amplifiers, voltage reference and ADC and their power management circuit), microcontroller (MCU) and radio. In different operational state, the activity of hardware modules is different, as shown in Table 2. In the asleep state, the wireless sensor consumes very little power, since all the modules are inactive for most of the time in a given period. In the awake state, it consumes the highest power, since all the modules are on. In the data acquisition state, it consumes less power than the awakeone, thanks to the radio off between two adjacent packets' transmission.

The state transition is shown in the Fig. 8. When the wireless sensing unit is powered on, it will enter the asleep state. It will transition to the awake state only if an ACK packet with the 'WAKE_BIT' bit equal to 1 is received, from its base station unit. In the awake state, it will return to the asleep state only if a sleep command packet from its base station unit is received.

In the awake state, the wireless sensor will enter the data acquisition state only if it receives a start data acquisition (DAQ) command packet from its base station unit. In the DAQ state, the wireless sensor will return to the awake state only if it receives an ACK packet with the 'STOP_DAQ_BIT' bit equal to 1, from its base station unit.

The detailed behavior of the wireless sensor in the three states is presented below.

Table 2Activity of the hardware modules in the three states

State	Analog	MCU	Radio
Asleep	Off	Low Duty Cycle On	Low Duty Cycle On
Awake	On	On	On
DAQ	On	On	Intermittent off

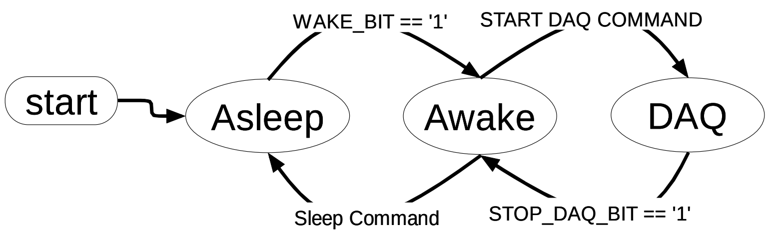

Fig. 8 The finite state machine of the wireless sensing unit

4.2.1 Asleep state

When the wireless sensor is in the asleep state, it will only remain the power supply for microcontroller and radio, and cut off other power supplies to other analog circuits, such as sensor, signal conditioner, and ADC. In this state, the MCU mainly stays in power mode 2 and the radio mainly stays in idle state, consuming only a current of 0.6 μA. The MCU periodically wake up to send a short polling packet to the base station unit for a waking command which is piggybacked on one bit in the ACK packet. Therefore, in this state, the average power consumption is very little, depending on the polling period. So far, this period is set to 1 second and the operating time can vary among, 10mS, 20ms and 30 ms, depending on the polling packet transmission timeout retry number.

4.2.2 Awake state

In the awake state, the wireless sensor will switch on all the hardware modules and wait for the starting data acquisition command from its base station. The base station broadcast the starting data acquisition without requesting an ACK packet to ensure the synchronization of data acquisition among different wireless sensors. This is also the main reason why wireless sensor should always switch on its radio receiver in the awake state.

In this state, the wireless sensor can also be configured and commanded to enter the asleep state by its base station.

4.2.3 Data acquisition state

In the data acquisition state, the wireless sensor will sample all the four channels at the specified rate, and pack 10 sampled data (80bytes) into a long data packet. Taking into account the communication overheads, the data packet should be as long as possible. Thus the averaged power consumption of 1 data bit can be reduced.

It is also worth mentioning that the power consumption of radio receiving is even higher than the one of radio transmission for the CC2430. Therefore, in order to minimize the power consumption, the radio receiver is switched off between two adjacent data packets transmission. The energy saving rate by adopting this measure varies with the sampling rate and link quality. Assuming a sampling rate of 100 Hz and perfect link quality, the sampling time for 10 data points is 100ms and the transmission time for 1 data packet is 10ms. Therefore, in this case, the radio energy saving by the measure is at least 90%.

4.3 Current consumption measurement and battery working time estimation

In this section, the actual current consumption of some wireless sensors and its components are given and the working time of the adopted battery is also estimated. The wireless sensing unit is powered by a Li-ion polymer battery with a capacity of 5000 mAh.

The measurement of current consumption is performed by using an external power supply (Model: E3620A) which is capable of showing its output current. The output voltage is set to 3.9V. Therefore, the current values in the tables represent the overall current consumption from the battery, instead of the actual current flowing into the components.

Table 3 gives the average current consumption of the wireless sensing unit without being connected to any sensor. It matches well the author's estimate. In the asleep state, i.e., standby state, the wireless sensing unit consumes a current as low as 0.3 mA, which is measured when the polling period is 1 second, and can be further reduced by prolonging the period. Therefore, the standby time of the wireless sensor is estimated to be 16666 hours, by simply dividing the capacity of the battery with the standby current consumption. In the awake state, the current consumption reaches the highest since all the components are powered on, but it is just a transitional state. The wireless sensor is supposed to work on this state only for a short time, e.g., few seconds. In the DAQ state, the current consumption is only 23 mA when the sampling rate is 100 Hz, thanks to the shutdown of the radio receiver between the transmissions of two adjacent data packets.

Table 3 Average current consumption of the whole wireless data acquisition unit without any sensor connected

State	Asleep	Awake	DAQ
Average Current Consumption (without any sensor)	0.3 mA	43 mA	23 mA

Table 4 Current Consumption of the wireless unit's modules

Module	Analog	MCU	Radio Receiver	Radio Transmitter
Current Consumption	12 mA	11 mA	20 mA	17.7 mA

Table 5 Current consumption of some sensors

Sensor Model	Current Consumption Increment (mA)	Description
CXL01LF3	8	MEMS triaxial accelerometer
FUTEK LTH350	12	Load cell
FBA-11	20	Monoaxial accelerometer
Episensor FBA ES-T (low noise)	313	Low Noise Triaxial accelerometer
YT89MGV80	707	Laser Range Sensor (voltage 20V)

Table 6 Continuous working time estimation of different wireless sensors

Connected Sensors	Total Current Consumption(mA)	Working Time Estimation(Hour)
CXL01LF3	31	161
FUTEK LTH350	35	143
FBA-11	43	116
Episensor FBA ES-T (low noise)	336	15
YT89MGV80	730	7

Table 4 shows the current distribution in the components of the wireless sensing unit, where the analog includes the power management circuits and the signal conditioning circuit, the MCU also includes its peripherals, e.g., timer. Table 5 shows the current consumption increase when the sensors are connected and table 6 shows the estimated continuous working time of the wireless sensors, obtained by simply dividing the capacity of the battery with the current consumption in the DAQ state. The continuous working time mainly depends on the power consumption of the sensors. However, in the asleep state, the current consumption is not affected by the connected sensors, since their power supplies are shut down.

5. Adaptive transmission power control

The power efficient technique for the data acquisition state is a new adaptive transmission power control algorithm which will be introduced in detail in this section. Although the maximum transmission power will have best link quality, excessive power will consume more energy without an obvious improvement wireless link quality, and lead to a higher interference with other devices. The control objective is to achieve an optimal tradeoff between power consumption and data loss. In other words, one has to find and maintain a minimal transmission power for a satisfactory link quality. Furthermore, a wireless link quality mainly depends on the signal power, the distance and the environment. Since the distance between the wireless sensor and the base station depends on the application and might change from case to case. Even if the distance will not change, the environment will change, such as temperature, humidity and so on. In other words, the radio channel property should be regarded to be time varying, and the link quality is also time varying even when the transmission power is static. Therefore, a transmission power control mechanism should also be able to dynamically adapt to the changes.

For the transceiver CC2430, the transmission power control is feasible, because it provides programmable transmission power levels and some hardware metrics to measure the link quality of the wireless channel, including received signal strength indication (RSSI) and link quality indication (LQI). The packet reception rate (PRR) can be calculated in a statistical way, by the ratio of the number of actually sent and received data packets.

In this section, the link quality under different transmission power levels and communication ranges, is investigated. Based on the result, a new adaptive transmission power control algorithm is proposed and its implementation and experimental validation are discussed.

5.1 TXCTRLL register setting, Transmission power and current consumption

In current literature about transmission power control for CC2430, 32 continuous levels are usually adopted. However, the increase in the transmission power setting register TXCTRLL of CC2430 does not always lead to an increase in output power. In the design note DN020 from Texas Instrument, programming output power on CC243x, a table shows the relationship among the TXCTRLL register setting, the output power and the current consumption (Seem 2007). It states that a decrease in the output power level not necessarily means a decrease in the current consumption, and the output power versus the different TXCTRLL values is not linear.

Therefore, instead of using continuous 32 power levels from 0xE0 to 0xFF for the output power setting register TXCTRLL, the 8 transmission power level recommended in the datasheet of CC2430 is used in this paper, as shown in Table 7, where the current consumption is only due to the CC2430 radio transmitter.

5.2 Link quality investigation

The first objective of the experiment is to find the correlation among the transmission power level, the communication distance, RSSI, LQI and PRR, by recording and analyzing their data from actual communication. The second objective is to propose the control target parameter and its threshold value for the transmission power control algorithm, based on the correlation among the link quality metrics.

Table 7 Transmission power levels and current consumption of CC2430 radio

Transmission Power Level	TXCTRLL Register	Transmission Power(dBm)	Current Consumption (mA)
0	0XE3	-25	8.5
1	0XE7	-15	9.9
2	0XEB	-10	11.2
3	0XEF	-7	12.5
4	0XF3	-5	13.9
5	0XF7	-3	15.2
6	0XFB	-1	16.5
7	0XFF	0	17.4

5.2.1 Experiment setup

The experiment is carried out in a line of sight place. In order to take weather condition into account, the experiment is repeated in two different weather conditions, sunny and foggy. The photos of the experiment site with sunny and foggy weather condition are shown in Fig. 9. In the foggy condition, the relative humidity is up to 100%.

In the experiment, the 8 different transmission power levels recommended in the datasheet of CC2430 and 3 different line of sight communication ranges are tested, as shown in Table 8. One wireless sensor unit (WSU) and one base station unit (BSU) are used. The WSU continuously sends 21 data packets on each power level, periodically from the highest level to the lowest level. Each data packet is of 96 bytes length in total and the packet rate is around 10 Hz. The process lasts around 1.5 minute. In addition to the data acquired from ADC, each data packet includes a packet number and transmission power level number. When a data packet arrives at the BSU, its packet sequence number, the transmission power level, RSSI and LQI are sent to computer and recorded into a text file for further analysis. Through the packet sequence number, the actual sent number can be shown in the computer.

Fig. 9 Experiment site with foggy and sunny weather condition

Table 8 Experiment Description

Condition	Experiment 1	Experiment 2
Weather	Sunny	Foggy
Relative Humidity	65%	100%
Distance	25, 50, 75	25, 50, 75
Transmission Power levels	8	8

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5.2.2 Correlation among Transmission Power Level (TPL), RSSI, LQI and PRR

Based on the obtained data, 5 types of curve are plotted, TPL versus RSS, TPL versus LQI, TPL versus PRR, RSS versus PRR, and LQI versus PRR, as shown in Figs. 10 and 11. All the data sets are plotted together for comparison purpose. In the plots, ‘Sunny25m’ means the weather is sunny and the communication range is 25 meters line of sight, and so on.

The TPL-RSS curve shows that: (1) the 8 recommended power levels are not linear; (2) for the same TPL and distance, the RSS of sunny weather is better than the one of foggy weather, except the data sets of 50m.

The TPL-LQI curve shows that: (1) when the transmission power level is higher than a threshold, the link quality will maintain a good value; (2) below the threshold, the link quality change dramatically.

The RSS-PRR curve shows that when the RSS is higher than 85dBm, the PRR will be higher than 90%. This result is independent on the weather condition and the distance.

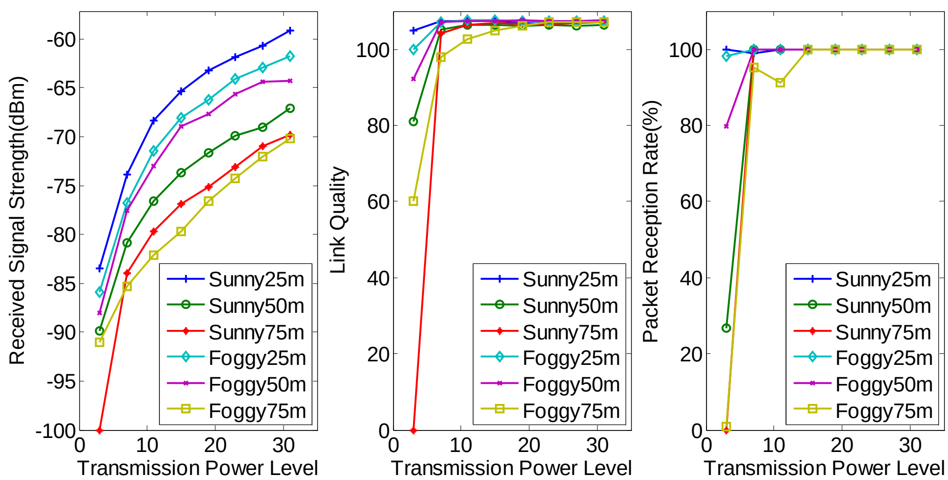

Fig. 10 RSS, LQI, PRR versus Transmission Power Level

The LQI-PRR curve shows that when the link quality index is higher than 90, the PRR will be higher than 90%. This result is also independent on the weather condition and the distance.

Based on the above observation from the plots, a conclusion can be easily drawn. The RSSI metric could be used as control object, since it changes in accordance with transmission power. The threshold value of RSS, below which the PRR will dramatically drop, can be used as control target. In fact, this RSS threshold value is referred as sensitivity.

Fig. 12 shows the variation of received signal strength under the same transmission power. The maximum peak to peak variation could be up to 5dB. The result is reasonable, since the wireless signal channel is noisy and the environment has some interference and multipath fading. This phenomenon suggests the use of a statistical average of RSS for transmission power control, instead of the instantaneous value. It also can be observed that the average trend of the RSS under the same transmission power is stable.

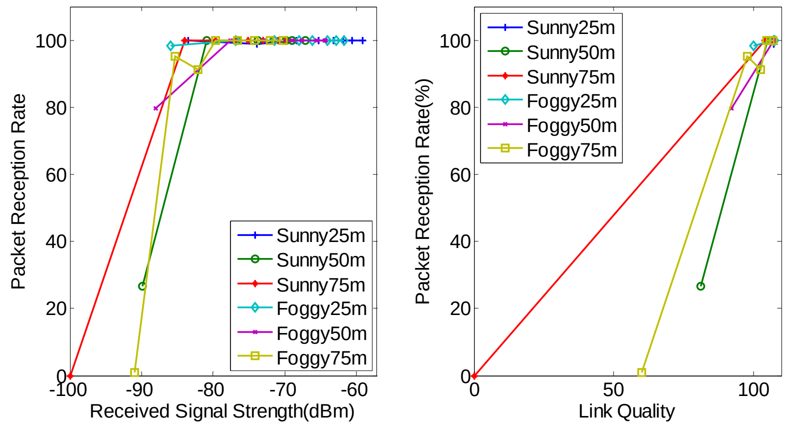

Fig. 11 RSSI, LQI versus PRR

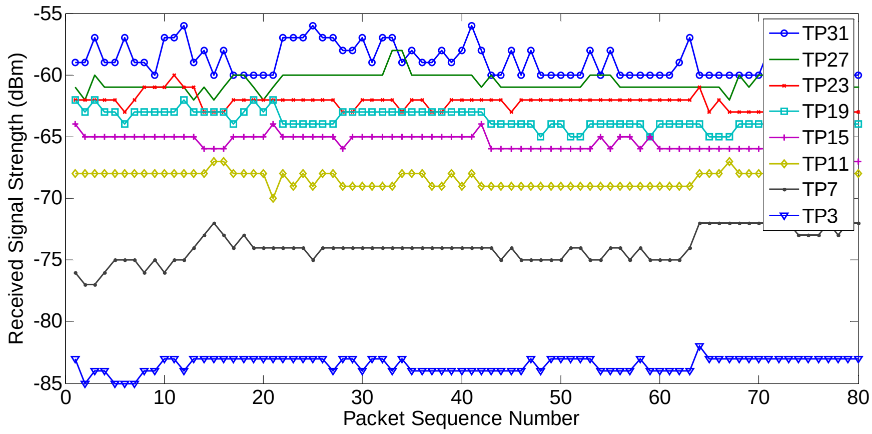

Fig. 12 RSSI of the packets of the 8 transmission power levels in the data set ‘Sunny25 m’

5.2.3 Background noise and sensitivity

CC2430 provides a hardware received signal strength index which is a relative metric. In order to have absolute RSS value, an offset should be added to the RSSI. The typical value for the offset is -45dB. Due to hardware and environment difference, the background noise of the RSS is usually different. Therefore, it is not suitable to use a same absolute RSSI threshold for all the wireless sensors. Instead, a threshold relative to noise floor is better. In order to have the relative RSSI threshold, the background noise RSSI should be observed by reading the RSSI when there is no communication.

5.2.4 Path loss

The Friis' transmission equation for free space propagation can be used to model the path loss (Kvaksrud 2008), as shown in Eq. (1).

$$Pr = Pt + Gt + Gr + 20\log\frac{\lambda}{4\pi} - 20\log d \quad (1)$$

Where *Pr* is the received power, *Pt* is the transmitted power, *Gt* and *Gr* are the transmitter and receiver antenna gains with respect to an isotropic radiator, d is the distance between transmitter and receiver, Lambda is the wavelength. The power is in the unit of dBm and the antenna gain is in the unit of dB.

$$P_{passloss} = Pt - \mathrm{Pr} = 20\log d - Gt - Gr - 20\log\frac{\lambda}{4\pi} \quad (2)$$

Therefore, the path loss can be expressed as the Eq. (2). One can assume that the path loss is a constant parameter when the transmitter and the receiver are fixed. However, there are many factors affecting the path loss, such as multipath due to the signal reflection, temperature and humidity variance. But these environmental factors change slowly.

Treating path loss as a slowly changing variable greatly facilitates the transmission power control. Path loss can be easily estimated by subtracting the received signal strength from the transmission power.

5.3 ATPC algorithm and its implementation

Based on the link quality investigation in the above sections, an estimated path-loss-based adaptive transmission power control algorithm is proposed in this section. The algorithm is implemented in the WSU which needs RSS feedback piggybacked on the ACK packet from BSU. Therefore, the algorithm is designed for reliable communication mode, with a ACK-TIMEOUT-RETRIES mechanism. The ATPC is only for WSU, since BSU has not energy constraint and it always use the maximum transmission power to communicate with WSU.

The algorithm consists of 2 parts: (1) to find and update the sensitivity threshold, as a reference input; (2) to calculate the new transmission power by the known transmission power and the received signal strength.

5.3.1 Link quality threshold selection

The link quality threshold mainly depends on the BSU. When the BSU is powered up, it will read some background RSSI values and take their average as the noise floor. In the following communication, every time after having received a packet from the WSU, the BSU will read again the new background RSSI to update the noise floor, since the supply voltage and the temperature can affect the background noise.

The sensitivity value of the BSU (P_s) is defined as the background noise floor (P_b) plus a signal to noise ratio (SNR, e.g., 10 dB), as shown in the Eq. (3). It is around -80dBm according to the empirical experience. However, the SNR value is configurable through the PC software.

$$P_s = P_b + SNR \tag{3}$$

5.3.2 Adaptive Transmission Power Control Algorithm

In this paper, a new path loss based adaptive transmission power control algorithm is proposed. This algorithm estimates the path loss by subtracting received signal power from transmission power, and calculates the ideal transmission power by adding the path loss to the sensitivity, as shown in Eqs. (4)-(6). The algorithm runs in the WSU, instead of BSU.

$$P_{pathloss} = Pt - Pr \tag{4}$$

$$P_{ideal} = P_s + P_{pathloss} \tag{5}$$

$$P_{\min} >= P_{ideal} \tag{6}$$

Since the transmission power of CC2430 is not continuously programmable and there are only 8 steps recommended in the datasheet of CC2430, one should choose the minimum available transmission power which is greater than the ideal transmission power.

The algorithm is only applied in the data acquisition state. In the asleep state, the WSU uses the highest transmission power level to poll the base station so as to make sure the success of polling. It has little impact on the overall power consumption of the WSU, since the polling packet is quite short and infrequent. The BSU always uses the highest transmission power level to send an ACK and command packet, since it has not power constraint. Once, having received a starting DAQ command from the BSU, the WSU starts data acquisition, sends the acquired data and restarts the ATPC algorithm, as follows:

(1) In the first 8 data packets transmission, the WSU uses the highest transmission power level to make sure that the ATPC is algorithm starts from the best link quality and the path loss estimation is always based on 8 samples. A 8 bytes path loss buffer is assigned to store the latest 8 path loss estimations. After having received a starting DAQ command, the WSU will clear this buffer to restart the ATPC algorithm.

(2) Once having received a data packet from the WSU, the BSU will put the RSSI value and its own background RSSI value into the ACK packet and send it back to the WSU to acknowledge the reception.

(3) Once having received the ACK packet, the WSU gets the RSSI value, computes the path loss by subtracting the known transmission power with the received signal strength, and then uses the path loss value to update the 8 bytes long path loss buffer. If the path loss value number in the buffer is 8 bytes, the WSU will take an average value of the path loss buffer, compute an ideal transmission power and select the minimum power level for the next data packet transfer,

according to Eqs. (4), (5) and (6).

(4) If the path loss value number in the buffer is less than 8 bytes, the WSU will use the highest transmission power level. This mechanism is quite useful when the WSU is mobile. If the WSU hadn't started from the highest transmission power to send data packets, it might always fail in data transmission when its position is moved from the BSU further than the last position of data acquisition. The mechanism can ensure that the data transmission always starts from the best link quality and then converges to the optimal level.

Since the RSSI value has a noise nature, a moving average filter for the path loss estimation is used; the statistical average of the most recent 8 path loss values for calculating a new minimum transmission power level is adopted.

5.4 Experimental validation and evaluation

In order to validate the proposed adaptive transmission power control (ATPC) algorithm, three types of line-of-sight experiments are performed: five static experiments and three dynamic experiments in the campus. For comparison purpose, the results using the fixed highest transmission power (FHTP) level were also obtained.

In all the experiments, the base station unit is always put at a fixed position. In the five static experiments, the wireless node is fixed at five different distances, 12.5 m, 25 m, 50 m, 100 m and 150 m. In the two dynamic experiments, the wireless node is held at hand and moved slowly. The experiments are repeated three times and an average result is used in the evaluation.

For the experiments in the campus, the base station and wireless node are in line of sight without any moving object in between and both of their antennas are put at 1.2 m height and vertical. In order to achieve long communication distances, 10dBi high gain antennas are adopted. The sampling rate of the wireless node is set to 100 Hz, and 10 data samples are put into a data packet. Therefore, every 100ms, one data packet will be created.

5.4.1 Static experiments

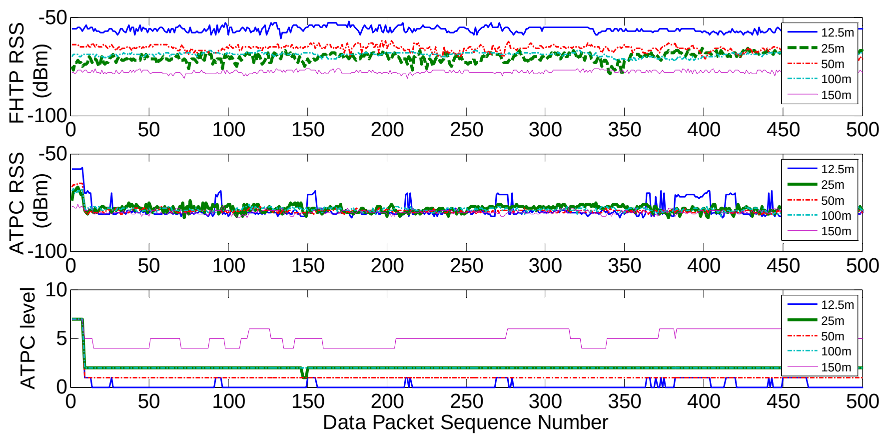

Fig. 13 FHTP RSS, ATPC RSS and ATPC TPL versus Data Packet Sequence Number

In order to evaluate the performance of the proposed ATPC algorithm, the fixed highest transmission power is first used to collect 1200 data packets, which results in aduration of 2 minutes, then the ATPC algorithm is enabled to collect the same data packets. Along with the data samples, some data packet parameters are also piggybacked and recorded by the Matlab software, including the actually transmitted data packet sequence number, the successfully transmitted data packet sequence number, the transmission power level and the RSSI reading. These parameters enable the evaluation of the ATPC algorithm. From the first two parameters, the packet reception ratio can be calculated.

As shown in in Fig. 13 and Table 9, the RSS of the FHTP method is quite stable with a small deviation. This result is obtained when there is not any moving object in between. The RSS of the ATPC method is successfully maintained near -80dBm with a small deviation, except for the distance 12.5meters. This is because of the 10 dB big transmission power difference between the transmission power levels 0 and 1, as shown in Table 7. In Fig. 13, one can also see the variations of transmission power level when enabling the ATPC algorithm. This demonstrates the effectiveness of the ATPC algorithm. When the path loss is higher, the transmission power level is higher.

Table 9 Received signal strengths at different ranges

Distances (meters)	FHTP		ATPC	
	Avg RSS (dBm)	STD RSS (dB)	Avg RSS (dBm)	STD RSS (dB)
12.5	-56.3	2.15	-79.1	3
25	-69.8	2.08	-78.3	1.65
50	-65.3	1.98	-79.1	1.07
100	-68.8	1.04	-78.6	1.06
150	-77.8	1.09	-80.0	0.98

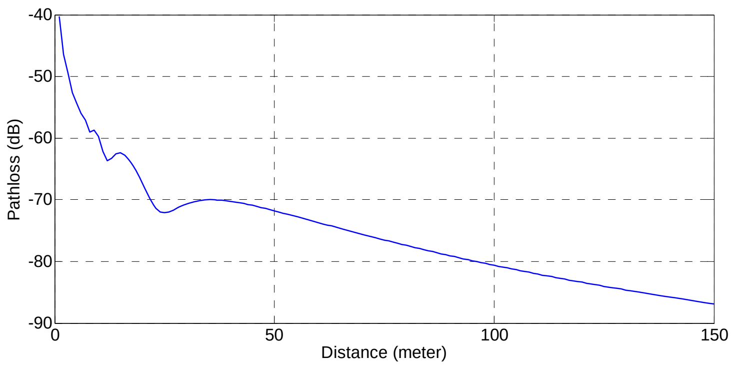

Fig. 14 Path loss estimation using the Friis equation with ground reflection

It is interesting to observe that the RSS decreases when the distance increases except for the distance 25meters. This unexpected result can be explained by the multipath effect of a radio signal transmission. The Friis transmission equation with ground reflection described in (Kvaksrud 2008) is used to simulate the path loss at different distances and Fig. 14 is obtained, in which the 25m is the valley point. Therefore, the simulation result matches the experimental observation.

In order to quantify the energy saving of ATPC method relative to FHTP method, an objective calculation method is proposed. The method takes into account the data loss. It accurately calculates the energy consumption of data packets transmission including ACK packets reception.

The length of a data packet including the communication overheads (including the preamble bytes, start of frame delimiter and frame control sequence bytes) is 96bytes, which means that the transmission time of a data packet is 3.072 ms, since the data rate of CC2430 is 250kbps. The timeout is set to 7 ms. The length of an ACK packet is 12 bytes including the overheads, which means that the transmission time is 0.384 ms. Once the BSU receives a data packet, it will reply the ACK packet with an approximate delay of 1mS. Therefore, if a data packet transmission succeeds, it consumes (TP * 3.072 ms + RP * 1.384 ms), where TP means transmission power and RP means receiving power. By contrast, if a data packet transmission fail, it consumes (TP * 3.072 ms + RP * 3.928 ms). In order to simplify the calculation, the transition time in different states of radio and the time to run the related firmware code are ignored.

The energy saving ratio is obtained by (EFHTP - EATPC) / EFHTP. The EFHTP and EATPC mean the total energy consumption of the radio when transferring a certain number of data packets, using FHTP and ATPC methods, respectively. Both of the energy consumptions take into account the energy consumed by lost data packets.

Based on the calculation method, the radio energy saving ratios are obtained as shown in Table 10, where the results are the average of three repeated experiments, so that a better confidence level is achieved.

Table 10 Energy saving ratios at different ranges considering data losses

Distances (meters)	FHTP PRR	ATPC PRR	ATPC AvgTP Level	Radio Energy Saving Ratio
12.5	100%	98.7%	0.07	31.7%
25	99.8%	98.6%	2.16	22.9%
50	100%	100%	1.08	29.2%
100	100%	99.8%	2.01	24.96%
150	97.4%	99.2	5.48	13.2%

5.4.2 Dynamic experiments

To further validate the adaptability of the proposed ATPC algorithm to communication range changes, three dynamic experiments are carried out. In the first dynamic experiments, the wireless node is held at hand and moved from 12.5meters to 150 meters and then moved back to

12.5meters, at a speed of around 1 meter/second; in the second experiment, the wireless node is moved from 12.5meters to 150meters; in the third experiment, the wireless node starts from 150meters to 12.5meters. Their transmission power levels and received signal strengths are plotted in Figs. 15 and 16.

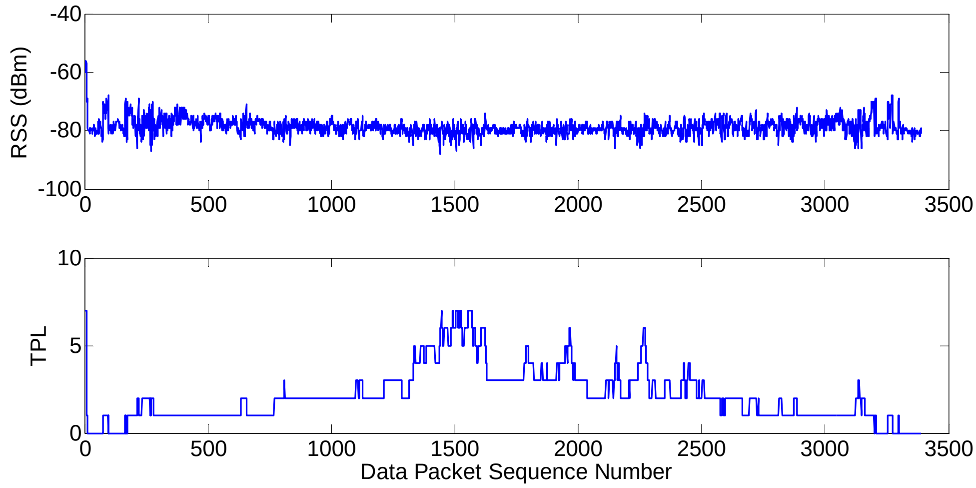

Fig. 16 Comparison of the results of the second and third experiments

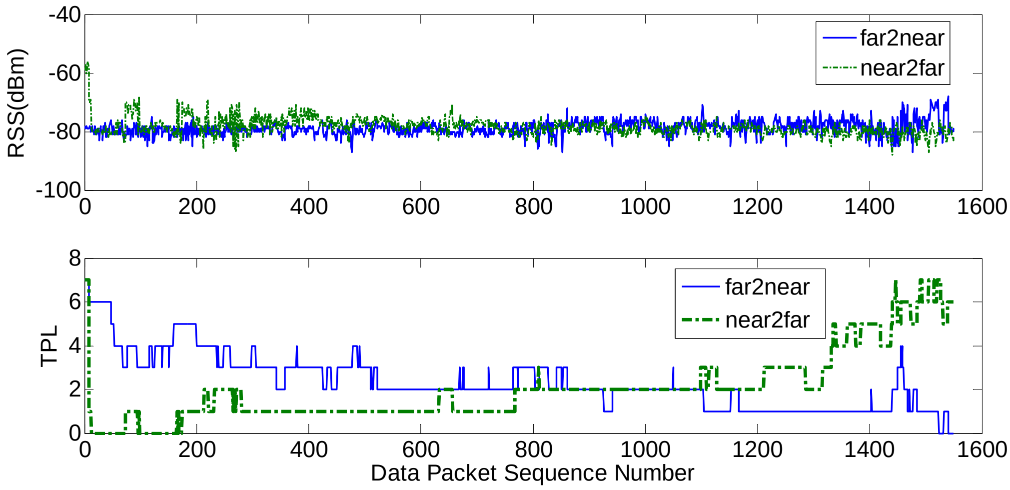

Fig. 15 Results of the first dynamic experiment

Table 11 Energy saving ratio in the different scenarios

Scenarios	ATPC PRR	ATPC AvgTP Level	Radio Energy Saving Ratio
12.5 m-150m-12.5 m	98.6%	2.12	22.8%
12.5 m-150 m	98.3%	2.07	22.6%
150 m-12.5 m	98.4%	2.24	22%

In Fig. 15, one can see that: (1), when the communication distance increases, the transmission power level tends to increase; when the communication distance decreases, the transmission power level tends to decrease as well. (2), except the initial and ending part, the averaged received signal strength is maintained relatively stable around -80dBm. At the initial and ending part, the RSS has an obvious fluctuation, since the wireless sensor is very close to the base station and the transmission power difference between level 0 and level 1 is up to 10dB. (3), due to the noisy nature of wireless signal channel and the movement of the antenna, the received signal strength of the dynamic experiment is noisier than the result achieved in static experiments. (4), for the whole process, according the calculation method, the radio energy saving ratio is calculated, as shown in Table 11.

In the second and third dynamic experiments, the data acquisitions start when the wireless node is at 12.5meters and 150 meters, respectively. The ATPC algorithm is restarted at the beginning of every data acquisition and it always use the highest transmission power level for the first eight data packets transmission. Therefore, the algorithm can work for any distance which is less than the maximum range.

6. Conclusions

Energy constraint is still one of the common issues in the application of wireless sensors. In this paper, a practical compound energy efficiency strategy is adopted in the implementation of a real time wireless sensor platform. The energy efficient techniques greatly reduce the overall power consumption of the designed wireless sensor and thus greatly prolongs the operating time.

The adoption of low power devices, especially low quiescent current and high efficiency power management circuits, reduces the power consumption in terms of hardware. The ability to switch off the power supplies of most circuit modules and the low duty cycle radio polling makes the estimated standby time of the wireless sensor as long as 16666 hours. Using a bit in the ACK packet to stop the data acquisition enables that the radio receiver can be switched off between the transmissions of two data packets, leading to a radio energy saving of around 90%, during the wireless data acquisition.

The proposed adaptive transmission power control algorithm can effectively reduce the radio energy consumption. The experimental results show that it is effective to stably maintain the received signal strength at an optimal threshold with little data loss increase. According to the proposed accurate radio energy saving calculation method which takes into account the energy consumption due to lost data, the radio energy saving ratio contributed by the algorithm varies from 13.2% to 31.7%, in the performed experiments. The expected result that a higher path loss results in a lower energy saving ratio, vice versa, is also observed.

In order to achieve a single hop long distance communication, the radio transceiver CC2430 module integrated with an external power amplifier CC2591 can be used. The proposed adaptive transmission power control algorithm will be more significant to this extended range transceiver module, since the current consumption difference between the lowest and highest transmission power levels is quite big. Furthermore, the packet reception ratio can be used as an input of the adaptive transmission power control algorithm to adaptively adjust the radio sensitivity threshold. Indeed, a noisy environment requires a higher signal to noise ratio.

Acknowledgments

This work was supported by the Marie Curie European project SmartEN. The author also would like to thank Daniele Bortoluzzi (a Ph.D. student of the University of Pavia, Italy) for his useful help during the experiments.

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