Design and Energy Consumption Analysis of a Custom Built Wireless Sensor Node for Environmental Monitoring

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ABSTRACT

Wireless sensor networks (WSN) have become increasingly important in recent times. Sensor nodes are the building blocks for a typical WSN. Due to their limited computational, communication and energy abilities, the sensor nodes serve as the deciding factor for a given network design. As the fabrication technology improves, highly powerful, yet energy efficient, components are available to realize a WSN while keeping the cost at an affordable level. This paper introduces a novel wireless sensor node based on the powerful 8-bit Atmel ATMega128L microcontroller unit (MCU) equipped with the CC2420 transceiver having complete compatibility with the IEEE802.15.4. This paper enlightens the design details of the new node; providing complete details of the components used and the sensor unit design. Towards the end, the power consumption measurement results are given along with the experimental setup details.

Categories and Subject Descriptors

B.4.1 [**Data Communication Devices**]: Data Communication Devices – *processors, receivers, transmitters*.

B.7.3 [**Integrated Circuits**]: Reliability and Testing – *test generation, testability.*

General Terms

Measurement, Design, Experimentation, Performance.

Keywords

Wireless sensor node, power consumption, energy model, extension port.

1. INTRODUCTION

Wireless sensor networks (WSN) comprise small wireless devices (nodes) that form a network to insure the timely delivery of sensed parameters to a central basestation (sink). The integration of a large number of sensors (even in millions) with machinery, or environment enables the availability of information, preventing any catastrophes. WSN are truly inter-disciplinary, requiring theory and practice from microelectronics, computer sciences, communications engineering and embedded technologies.

Processing abilities have been enhanced by the current success in the IC fabrication technologies. These successes mean the availability of highly diverse yet compact components to be utilized in the wireless sensor node design process. The earliest wireless nodes like the µAMPS [1] produced by MIT in 1997 used the Strong ARM SA-1100 processor. The node has acoustic and seismic sensors fabricated on-board and was used in the first ever modern WSN. Unfortunately, the heavy built and high energy costs meant that WSNs could not be commercialized using the µAMPS devices.

As the technology modernized, extremely small sized MCUs were produced. Atmel's ATmega128 [2] along with a couple of variants was the first 8-bit MCU with extremely small power dissipation figures. In addition, Atmel provided an on-chip analog-to-digital converter (ADC) along with a multiplexer to interface up to seven different devices to the same ADC. Crossbow used the ATmega128 in the Mica family of nodes which are still being used in research institutions worldwide. A more energy efficient variant of the Mica family, the Iris, also uses the same micro-controller for processing abilities. Another popular MCU is the 16-bit TI MSP 430 which is being used in the Telos family of sensor nodes being produced by Crossbow.

The earlier WSN platforms like the Mica [3] devices were equipped with the basic CC1000 transceiver units. Basic modulation and RF channel sampling were provided by the transceiver and all other activities required additional components. Crossbow replaced the CC1000 with the CC2420 transceivers on all the MicaZ and the Telos family of nodes. The CC2420 provides a complete direct sequence spread spectrum (DSSS) communication in the form of IEEE 802.15.4 protocol. In addition dynamic adjustment of transmission power, channel selection and power control were provided on this transceiver. On the software front, energy efficiency was ensured when Berkeley introduced the TinyOS [5] operating system providing special concurrency adjustments while ensuring energy efficiency.

However, there are some drawbacks of these nodes. The Mica and Iris [4] nodes, for example, do not carry any on-board sensors. This means that additional sensor boards, from Crossbow, must be purchased in order to actually perform the sensing operation. For environmental monitoring, especially in polluted areas, it is required to measure the gas concentration for different gases in the atmosphere. Currently, the sensor boards provided by Crossbow do not contain any gas sensors. The only option is to use the general purpose board (MTS101CA) [6] which costs round $90. For the case of Telos devices, only 3 sensors (temperature, humidity and light) are provided on board with requirement of interfacing cards to attach additional sensors. Since environmental monitoring is the main goal of this work, the project requires measurement of methane and carbon monoxide levels in industrial settings. Clearly the cost of deploying Mica/Iris and Telos nodes along with the gas sensors goes beyond the project allocations.

This constraint gives rise to a completely new wireless sensor node design that provides interfacing facility for additional sensors (gas, temperature etc.) and is interoperable with all the existing nodes in the market. This paper provides the design details of the custom built wireless sensor node. A complete energy consumption measurement has been carried out to formulate an energy model that relates the payload size to the energy consumed. The formulated mathematical model can then be used in estimating the overall operating life of the wireless sensor network.

The rest of this paper is organized as: Section 2 presents the details concerning hardware design, Section 3 contains the design and implementation details of medium access control (MAC) and routing protocols, Section 4 has the demonstration summary and the paper concludes with the WSN deployment model in Section 5.

2. DESIGN OF THE SENSOR NODE

Considering the limitations of the commercially available wireless sensor nodes, we have developed a novel device (shown in Figure 1) using the 8-bit Atmel ATmega128L MCU providing high performance and multiple energy consumption modes. The CC2420EM is chosen as the transceiver of choice considering it is the latest, most affordable and highly versatile among the rivals. Like all the commercially available devices, three multicolored light emitting diodes (LEDs) are provided on board for testing and debugging. The designed node has a TSL13S light-to-voltage sensor and a digital SHT11x temperature/humidity sensor fabricated onboard. Six extension pins are provided for external sensors and programming is done using the low cost AVRISPMKII programmer produced by Atmel.

Figure 1. The designed wireless sensor node (top view).

2.1 Processing Unit

The main processing abilities of this node are centered on the 8-bit, 8MHz ATmega128L [2] MCU produced by Atmel. The chosen device offers six different power-save modes; from turning the ADC off to putting the complete device in the sleep mode. An extendable 128Kbytes of onboard programmable flash enables the largest of application files to be downloaded easily to the MCU. ATmega128 has eight 10-bit ADC lines available on chip with an internal multiplexer making the source selection easier. The device offers a calibrated internal oscillator for quick, fairly accurate clocking with the ability to get synchronization from any external oscillator. The provision of internal and external interrupt lines enable the ATmega128 to be triggered by both software and hardware as and when required. The MCU also has two serial peripheral interfaces (SPI) SPI interfaces termed as SPI0 and SPI1.

2.2 Wireless Communications Unit

The CC2420 evaluation module (CC2420EM) has been chosen to serve the purpose of providing communications to the node. The said transceiver board operates at a frequency of 2.4 GHz providing an effective data rate of 250 kbps while conforming to the IEEE 802.15.4 ZigBee standard.

The primary purpose of selecting CC2420EM for the new design is its interoperability with the existing ZigBee based sensor nodes. In addition the CC2420EM provides greater versatility both at medium access control (MAC) as well as at the physical (PHY) layer. This transceiver enables auto acknowledgement for every packet it transmits, special encoding is used at MAC layer to provide enhanced data security. The transceiver has the ability to append the group and the node IDs automatically when transmitting multicast or unicast packets respectively. This ability makes it transparent to the programmer and eases the burden of packet encapsulation. At the PHY layer, the transceiver has the ability to extract the received signal strength (RSS) of the incoming packet as well as the link quality (LQ) to estimate the channel conditions. The provision of an externally attachable antenna makes it easy to change antennas as required. Figure 2 summarizes the configuration details [11] of the CC2420EM.

CC2420 Configuration
- MAC
  - Open auto-ACK
  - Close security-enable
  - Configure RXFIFO threshold
  - PAN address
  - Node Address
- PHY
  - Configure/select the channel
  - Adjust Transmit power

Figure 2. CC2420 configuration.

2.3 Power Supply Unit

The power supply of the node consists of three AAA size batteries that provide a combined 4.5 V DC for the seamless operation of the node. Although the transceiver and the MCU can operate at 3 V, a 4.5 V supply has been included to help power some to the sensors that require higher operating voltages. Additionally an ON/OFF switch is provided to control the battery consumption.

2.4 Expansion Ports

Five pins constitute the expansion port interface on the platform as shown in Figure 3.

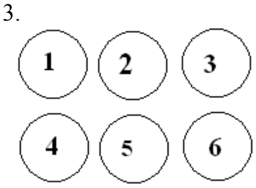


Figure 3. Expansion port pin layout.

These pins provide the ability to interface external sensors to the node. Table 1 shows the pin configuration of this expansion port.

Table 1. Pin functionality of the expansion port

Pin Number	Functionality
1	DC ground
2	ADC connection for analog sensor
3	RX line for digital sensor operating on a 2-wire interface
4	TX line for a digital sensor operating on a 2-wire interface
5	4.5 V DC supply

The expansion port enables the interfacing of an analog and a digital sensor requiring a maximum operating voltage of 4.5V simultaneously. For the analog sensor, the output voltage is converted to digital by the MCU and is then utilized. The digital sensors already provide an output in the digital format. Using the SPI0 of the MCU, this digital output is transferred to the MCU using the two-wire interface.

2.5 Onboard Sensor System

Among the onboard sensors, only the light sensor needs ADC since the SHT11x already provides a digital value at its output. Referring to the datasheet [10] of TSL13s light-to-voltage sensor, we use the following relation to convert the voltage output of the sensor to the corresponding light intensity, I.

$$I = 0.0387\ R \qquad (1)$$

In (1) R indicates the digital output of the ADC corresponding to the voltage output of the TSL13s sensor.

3. POWER MEASUREMENT

3.1 Why Measure?

The operating life of any WSN plays a very important part in its design. Since the lifetime of the network is governed by the energy consumption at the individual nodes [8], it is of utmost importance to study the power dissipation of the member nodes in a network. This analysis helps to provide an estimate of the network life prior to the actual design and deployment of the network.

Two techniques, theoretical and practical are used for network life time estimation.

3.1.1 Theoretical Method

This method makes use of the current and voltage consumption figures provided in the datasheets of all the individual components of the wireless sensor node. By making use of the adopted protocol, these figures are used to come up with the total current consumption of the node. By using this calculated current consumption and the rating of the node's battery supply, the approximate operating life of the node can be calculated. Since this method does not take into account the losses due to interconnects, printed circuit boards (PCB) imperfections and antenna radiation, the results are usually close but do not accurately represent the operating life of the node.

3.1.2 Measurement Method

This method is used to actually measure the current consumption of the node under different operating conditions (idle, transmitting, receiving etc.). The node is programmed in the various modes and the measurements are done. This technique provides accurate consumption figures and hence is more useful for efficient network design. The measurement method provides much accurate network lifetime figures as done in [9].

3.2 Power Measurement

To measure the power consumption of the node, we use the TinyOS [5] programs to operate the node in different modes. In order to measure the actual power consumed by the node, we have adopted the shunt resistor methodology [7]. Figure 4 shows the complete circuit setup for the experiment. The main idea here is to use a small ($R_{SHUNT} = 10\ \Omega$) shunt resistor to measure the current in the loop. Once the current is measured, the power can be calculated by the relation in (2).

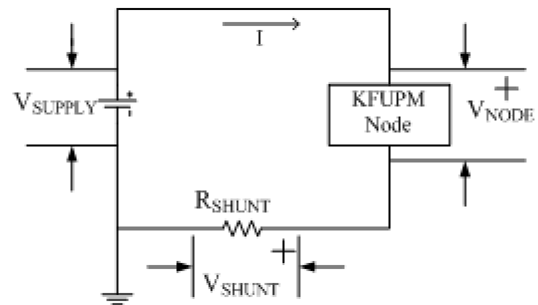


Figure 4. Shunt resistor energy measurement circuit.

$$P_{NODE} = \left(V_{SUPPLY} - V_{SHUNT}\right) \times \frac{V_{SHUNT}}{R_{SHUNT}} \qquad (2)$$

where P_{NODE} is the power consumed by the node
V_{SUPPLY} is the supply voltage (= 4.5V)
V_{SHUNT} is the voltage across the shunt resistor
R_{SHUNT} is the shunt resistor (10 Ω)
$\frac{V_{SHUNT}}{R_{SHUNT}}$ is the current, I, consumed by the node.

3.2.1 Power Measurements for MCU in Different States

As mentioned in Section 2.1, the ATmega128L MCU can be clocked by either using the on-chip oscillator or by using an external crystal. This node has an external 8 MHz crystal oscillator fabricated on board to provide highly accurate clock pulses for the MCU and the radio. The on-chip oscillator option provides clock pulses with minimum delay but is fairly inaccurate. On the contrary, by using an external oscillator, highly accurate pulses can be produced but some amount of delay is introduced due to the finite amount of time taken by the external oscillator to initialize.

The power consumption of the designed node under the different modes of internal and external oscillators has been analyzed. The TinyOS programming suite gives the user the ability to select the oscillator (on-chip or external) and the required frequency at the programming instance. A simple TinyOS application, *TestApp* was written that periodically broadcast packets every 2 seconds with 50% duty cycle. Figure 5 shows a view of the V_{SHUNT} for the complete duty cycle. At the time of programming the sensor node, the oscillator value as well as the type was selected and the maximum, minimum and the average voltage drop across the node was measured using a multimeter. Since majority of the power is consumed while transmitting and receiving, two different cases for each oscillator configuration were considered. Initially the node was operated with both the MCU and the radio ON and after taking the readings the radio was turned off for the second set. From readings in Tables 2, 3, 4 and 5 we conclude that the internal oscillator modes consume less power regardless of whether the radio is ON or not.. However, for the external oscillator, when operating at less than the oscillator frequency (0.9 – 3MHz) some frequency limiting circuitry functions consuming more power as compared to the high frequency range (3 – 8MHz) as indicated in Tables 4 and 5.

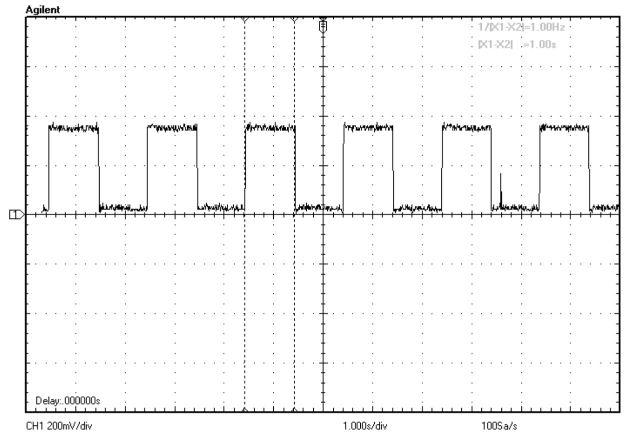


Figure 5. V_{SHUNT} measurement for 50% duty cycle.

Table 2. Power consumed using internal oscillator at 4MHz.

Configuration	V_{MAX} (mV)	V_{MIN} (mV)	V_{AVG} (mV)	P_{AVG} (W)
MCU (ON) Radio (ON)	372	352	361	0.149
MCU (ON) Radio (OFF)	56	40	48	0.021

Table 3. Power consumed using internal oscillator at 8MHz.

Configuration	V_{MAX} (mV)	V_{MIN} (mV)	V_{AVG} (mV)	P_{AVG} (W)
MCU (ON) Radio (ON)	440	380	391	0.160
MCU (ON) Radio (OFF)	56	40	48	0.021

Table 4. Power consumed using external oscillator at medium frequency (0.9 - 3MHz).

Configuration	V_{MAX} (mV)	V_{MIN} (mV)	V_{AVG} (mV)	P_{AVG} (W)
MCU (ON) Radio (ON)	432	376	402	0.164
MCU (ON) Radio (OFF)	248	48	76.1	0.033

Table 5. Power consumed using external oscillator at high frequency (3 - 8MHz).

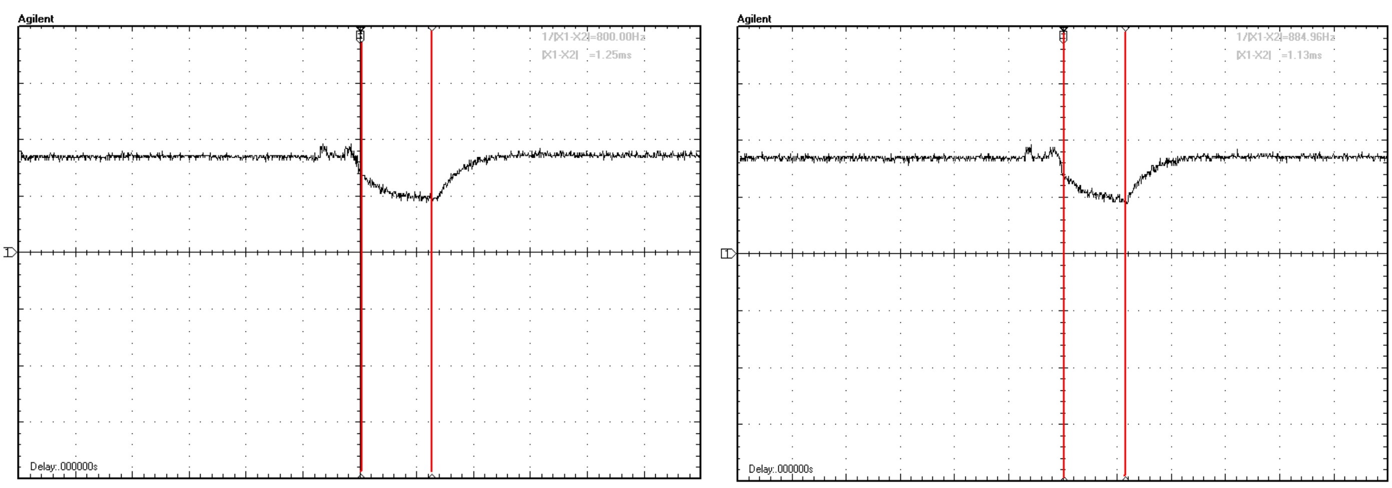
Configuration	V_{MAX} (mV)	V_{MIN} (mV)	V_{AVG} (mV)	P_{AVG} (W)
MCU (ON) Radio (ON)	424	368	407	0.167
MCU (ON) Radio (OFF)	128	48	65.4	0.029

3.2.2 Transmission Power Measurements

To measure transmission energy, a TinyOS application called the *SendingMote* was programmed onto one of the nodes. This application turns the node on and keeps transmitting packets of 28 byte payloads every second. The transmission power of the radio was changed between 0 dBm, -5 dBm, -10 dBm, -15 dBm and -25 dBm and the resulting P_{NODE} was calculated using (2), where V_{SHUNT} was measured from the circuit of Figure 3. We show some of the results for V_{SHUNT} at transmission power of -25 dBm and 0 dBm in Figure 6 and Figure 7 respectively. It is observed that V_{SHUNT} is, on average, 191 mV for -25 dBm transmissions and 320 mV for 0 dBm as indicated by the red lines in Figure 6 and Figure 7. Once the packet has been transmitted, the radio returns to the listen state where it consumes an almost constant current of 35mA (V_{SHUNT} = 350 mV).

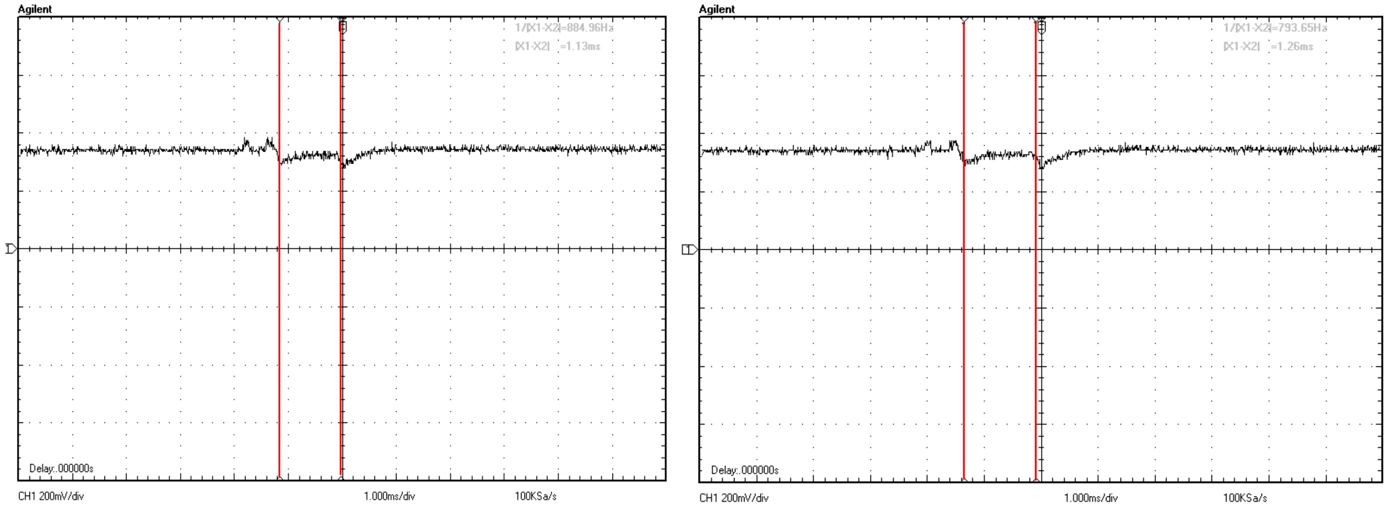
3.2.3 Transmission Power Measurements at Varying Payload Sizes

The amount of data to be transmitted has a direct impact on the energy consumption. As the payload size increases, the radio needs to be turned on for a longer time, thus consuming more energy.



(a) (b)

Figure 6. V_{SHUNT} measurement for transmission at (a) -25 dBm with 16 byte payload (b) -25 dBm with 22 byte payload



(a) (b)

Figure 7. V_{SHUNT} measurement for transmission at (a) 0 dBm with 16 byte payload (b) 0 dBm with 22 byte payload

Since TinyOS allows a maximum default payload size of 28 bytes, in order to quantify the energy consumption of the node at different payload sizes, we use the *SendingMote* application and for each of the five transmission powers mentioned in Section IV-B, we vary the payload sizes as 10, 16, 22 and 28 bytes. Observing the results of V_{SHUNT} for two different payloads in Figure 6 and Figure 7, the voltage remains the same, however, the duration of the transmission increases with payload size (Figure 6b and Figure 7b). From Figure 6 and Figure 7 we observe that it requires 1.13 ms to transmit 16 bytes as compared to 1.25 ms for 22 bytes payload regardless of the transmit power.

3.2.4 *Sleep State Power Measurement*

To monitor the energy consumption pattern during the sleep state, the *TestApp* application was used. This application operated the node in a cycle of 2s with 50% duty cycle, i.e., the radio is ON for 1s and OFF for 1s. The results shown in Figure 5 indicate a current consumption of 35mA (V_{SHUNT} = 350 mV) during the active state and 3mA (V_{SHUNT} = 30 mV) during the sleep state.

4. NODE ENERGY MODEL

The relationship between power and energy is characterized as:

$$E_{NODE} = P_{NODE} \times t_{MODE} \quad (3)$$

where E_{NODE} is the energy consumed by the node
P_{NODE} is the power consumed by the node (from (2))
t_{MODE} is the time spent by the node in a given mode

As observed from Figure 6 and Figure 7, V_{SHUNT} does not remain constant over the entire interval. Therefore, the average value of V_{SHUNT} has been considered in the calculation to provide a much stable result.

4.1 Transmission Energy Model

A node was programmed with the *SendingMote* application while each time the transmission power was changed between 0, -5, -10, -15 and -25 dBm. Table 6 contains the results of the energy consumption relative to the payload size.

Table 6. Energy consumption (µJ) vs. payload size for different transmission power levels.

Transmit Power (dBm)	Energy Consumption (µJ)			
	10 bytes	*16 bytes*	*22 bytes*	*25 bytes*
0	126	151	168.46	192.53
-5	99.9	119.7	133.56	152.64
-10	90.47	108.48	120.96	138.24
-15	83.88	100.57	112.14	128.16
-25	77.94	93.45	104.20	119.08

By using the curve fitting toolbox in MATLAB, we find that the energy consumption changes as a linear function of payload size. Figure 8 shows the measured data and the fitted curves for the corresponding data set.

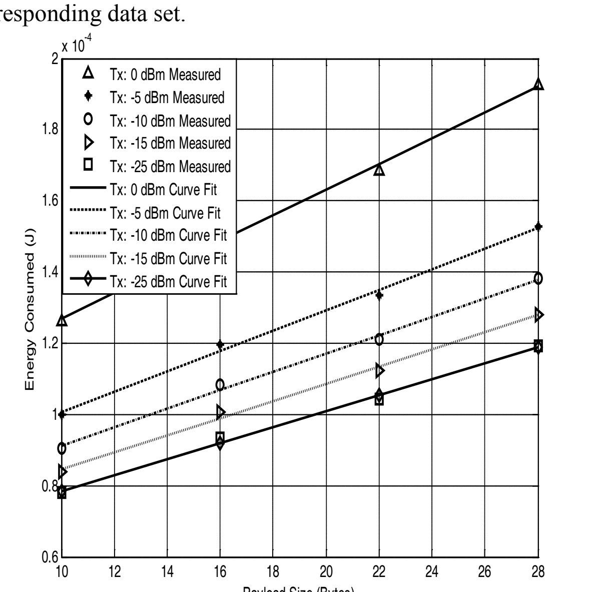


Figure 8. The designed node transmission energy model.

The fitting toolbox gives us a linear approximation of our measured data, the coefficients for the different power levels are given in Table 7.

Table 7. Transmission energy model equations for different transmit power levels.

Transmit Power (dBm)	p_1	p_2	$y = p_1x + p_2$
0	3.617e-6	9.077e-5	y = 3.617e-6x + 9.077e-5
-5	2.868e-6	7.196e-5	y = 2.868e-6x + 7.196e-5
-10	2.596e-6	6.520e-5	y = 2.596e-6x + 6.520e-5
-15	2.407e-6	6.046e-5	y = 2.407e-6x + 6.046e-5
-25	2.236e-6	5.618e-5	y = 2.236e-6x + 5.618e-5

4.2 Receiving Energy Model

Unlike the transmission process, the reception of a packet is independent of the payload size. Considering the node listens for 1s the energy consumed is:

$$P_{NODE} = V \times I = 4.5V \times 35mA = 157.5mW$$

$$E_{NODE} = P_{NODE} \times t_{MODE} = 157.5mW \times 1s = 157.5\ mJ$$

4.3 Sleep Mode Energy Model

Similar to the receiving mode, the sleep mode consumption is also constant as observed from Figure 5. Assuming the node stays asleep for 1s, the energy consumption is:

$$P_{NODE} = V \times I = 4.5V \times 3mA = 13.5mW$$

$$E_{NODE} = P_{NODE} \times t_{MODE} = 13.5mW \times 1s = 13.5\ mJ$$

5. CONCLUSION

Wireless sensor networks for environmental monitoring applications are being used worldwide because of their small size and no cable overhead. Some situations prevent the sensing nodes to be recharged, thus available power must be utilized in the most efficient manner possible. This paper presents the design details and the operating energy costs for the custom built wireless node for environmental monitoring. The measurement results show a linear relationship between the payload size and the energy consumed resulting in the formulation of a mathematical model. The formulated model can be used for accurate network lifetime estimation of large networks for optimum WSN design.

6. ACKNOWLEDGEMENTS

We would like to thank the Electrical Engineering department at K.F.U.P.M. for allowing us to use the labs that served as the basis for all the measurements for this paper. The authors also express their gratitude to Dr. Munir Al-Absi for his help in the fabrication of the device. We would also like to acknowledge King Abdulaziz City of Science and Technology (KACST) for funding this research under project number 2-6م ط .

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