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Abstract: Wireless sensor and actuator networks have expanding applications which requires better throughput, power efficiency and cost effectiveness. This study intends to contribute to the growing pool of knowledge on WSAN especially in the design for novel applications such as image or video over WSANs, and solar energy and RF energy harvesting for the WSAN nodes. Two basic scalable wireless sensor and actuator networks were implemented and characterized in terms of throughput and power consumption. The two WSANs are the Zigbee-based WSAN which is based on the IEEE 802.15.4 protocol, and the ISM-based Zigbee which makes use of the industrial, scientific and medical (ISM) radio bands. The star topology was used for both WSAN implementations. The throughput is quantified with varied factors including distance from node to node, obstructions in between nodes and co-channel interference. As distance and obstructions between nodes are increased, the throughput for both networks decreases with varying degrees. Co-channel interference is also considered. The ISM-based WSAN network is weak in dealing with co-channel interference and error rate as compared to the Zigbee-based WSAN, thus requiring it to have a better data encryption. Power consumption is generally larger for the ISM-based WSAN as compared to its Zigbee-based counterpart. However, the ISM-based nodes consume the same power even up to a few hundreds of meters distance and are thus practical for covering large distances. Therefore, the Zigbee-based WSAN system is more appropriate for closed environment, such as in room automation and home automation applications where distance from node to node is relatively shorter. The ISM-based WSAN prototype, on the other hand, can be developed further for applications in larger areas such as deployment in fields and cities, since transmission is not generally limited by distance and obstructions.

Key-Words: sensor, actuator, WSAN, Wireless Sensor and Actuator Network, power consumption, throughput

I. Introduction

A Wireless Sensor and Actuator Network (WSAN) is a network of sensors that monitor a particular environment and makes use of actuator nodes to either alter that same environment, or produce a physical action that is a response to parameters in that environment as described in [1]. In that regard, WSANs are extensions of wireless sensor networks (WSNs) whose only objective is to observe phenomena in an environment without affecting it.

Section 2 first discusses the design issues of WSANs in terms of throughput and power consumption. The analysis of the characteristics of throughput and power consumption of a WSAN involves observing these parameters in varying environments.

Throughput is the rate at which a network sends or receives data. It is essential to look into throughput because of the possibility of interference when the number of devices that uses air as a transmission medium increases. On the other hand, power consumption refers to the amount of electrical current a WSAN requires for operation. Mastery of the power consumption of WSAN allows insight as to when nodes would fail and when their batteries should be replaced. The results of observing these two parameters are discussed in Section 3.

Section 4 summarizes the observations on the system and recommends the suited applications. Furthermore the cost of the Zigbee-based WSAN and the ISM-based WSAN is compared. In studying WSAN processes and protocols, parallel implementation may be found to perform the same functions without having to employ expensive equipment.

II. Design Opportunities of WSAN

The following questions are asked to further explore factors that may or may not affect the reliability, efficiency and availability of a WSAN: "How is wireless transmission affected by the environment and the presence of other devices that make use of air as a transmission medium?", "How much power does each node consume?", "How much do these networks cost to implement?", and "Is there a cost-effective way to implement WSANs?"

A. Throughput Design Issues

A significant fraction of the world's population now carries mobile devices in their pockets – be it a cellular phone with Bluetooth technology, or music players that can access the internet through WiFi. In fact, many homes nowadays have at least one working wireless router. We are seeing an increase in the use of frequency channels globally. As such, it becomes important for us to be able to see how wireless devices interact and affect each other in an environment.

Furthermore, the amount of open space available in the environment is dramatically decreasing. Waves in general propagate less effectively in the presence of obstacles as opposed to free space, it is important to observe the effects of such obstacles to the accuracy of received data transmissions. It is important to study throughput because as the number of devices that make use of air as a transmission medium increases, so does the possibility that interference can occur.

Furthermore, novel applications of WSANs such as image or video transmission, processing and actuating such as described in [2] requires WSANs to transmit more data accurately than the normal low data transmission of WSAN. WSAN applications such as monitoring stresses within buildings and bridges such as described in [3] require data to get across several barriers of different materials such as wood and concrete and thus affect the strength of the signal. Such issues also arise in the industrial environment as discussed in [4].

Such new applications are relevant to the Philippines in managing large areas such as farms, dams and rainforests.

B. Power Consumption Design Issues

Looking at the angle concerning power, it is reasonable to say that wireless sensors do not have the same access to power as wired sensors. It is important to characterize power consumption behaviour of wireless sensor network so that one could provide an accurate timeline for battery replacements and give insight on how to design energy harvesting systems for the nodes. Such systems involve harvesting solar energy for deployments which allows for sun exposure or even harvesting of RF energy as described in [5].

One way of reducing power consumption is to employ wake-up strategies such as the one described in [6] wherein the focus is space diversity wake up strategy. In [6], a star topology was used wherein a master node scans the surrounding and creates a map of the positions of the distributed sensor nodes. This kind of wake-up strategy may be affected by the variations of environment a sensor node may be placed. Another way of reducing power is in the protocol used such as discussed in [7].

C. Cost Issues

Another growing concern is the cost of the WSN and WSAN devices that are currently in the market today. Sensors are cheap, but the interfacing devices connected to these sensors have prices in the hundreds of dollars, resulting to expensive WSNs and WSANs. In studying WSAN processes and protocols, a way may be found to implement the same functions without having to use more expensive equipment. Microcontrollers and demo boards manufactured by most companies generally have functions that aren't needed in specific applications, while certain protocols are not necessary in low traffic environments. Trimming functions down for certain applications, lessening throughput requirements or shortening network lifetime could help make WSAN implementations cheaper in applications that do not need such features.

III. Results and Discussion

Two basic WSAN deployment were constructed, tested and compared, the ISM-based WSAN and the Zigbee-based WSAN.

A. Constructing the ISM-Based WSAN

The first attempt at a wireless sensor and actuator network was based on the Industrial, Scientific and Medical (ISM) frequency band (433 MHz.) This WSAN was designed to approximate a Zigbee-based sensor network as much as possible in terms of function. In keeping with the network architecture of a Zigbee-based WSAN, the ISM-based WSAN will have at least three nodes: a sensor node, a coordinator node and an actuator node in a star topology as shown in Figure 1.

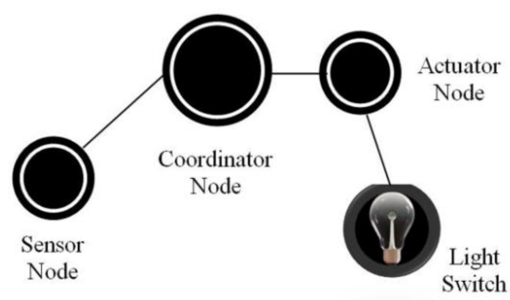

Figure 1: WSAN Topology

The three nodes – sensor, coordinator and actuator – each have two common components. The first component is the Z8 microcontroller by Zilog, which is used to process all the incoming data and perform a node process. These microcontrollers are programmed using the Z8 Encore! Development Studio (ZDS II), which uses the C language. The second component is the JZ863 wireless transceiver by Shen Jizhuo Technology Co. which allows the microcontrollers –and in this case, the nodes – to communicate with each other wirelessly. These transceivers have a range of over 500m when placed above 2m, and makes use of the 433 MHz ISM frequency band. It can operate at a maximum baud rate of 19200. These can be programmed to change their operating frequency, channel, baud rate and other parameters.

All of the nodes will make use of this microcontroller-transceiver set. The entire node is powered by a single 9V battery. Figure 2 shows a typical network node.

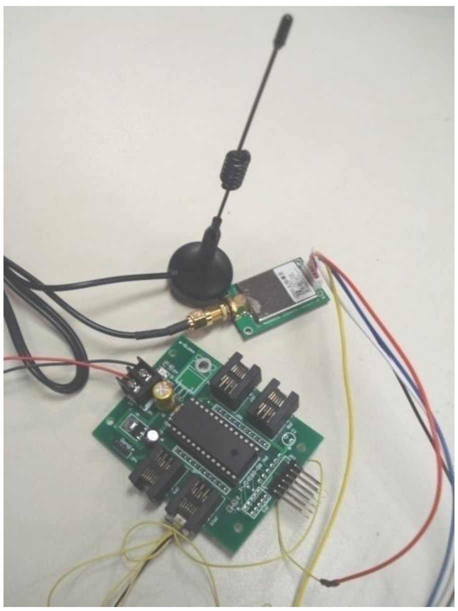

Figure 2: Typical Network Node

The sensor node performs all the sensing functions of the network. In this application, the sensor used to detect the presence of a person in a room is a microwave motion sensor. The output of the motion sensor was connected to the input of the microcontroller. The sensor node microcontroller was programmed such that when it receives logic 0 from the motion sensor (indicating sensed motion), it reports to the coordinator node. It reports wirelessly by sending a report byte to the UART for transmission to the coordinator node via the transceiver. Likewise, as it receives a logic 1 from the motion sensor (indicating no motion), it reports this to the coordinator via the UART and transceiver. Figure 3 shows the flowchart of the sensor node program:

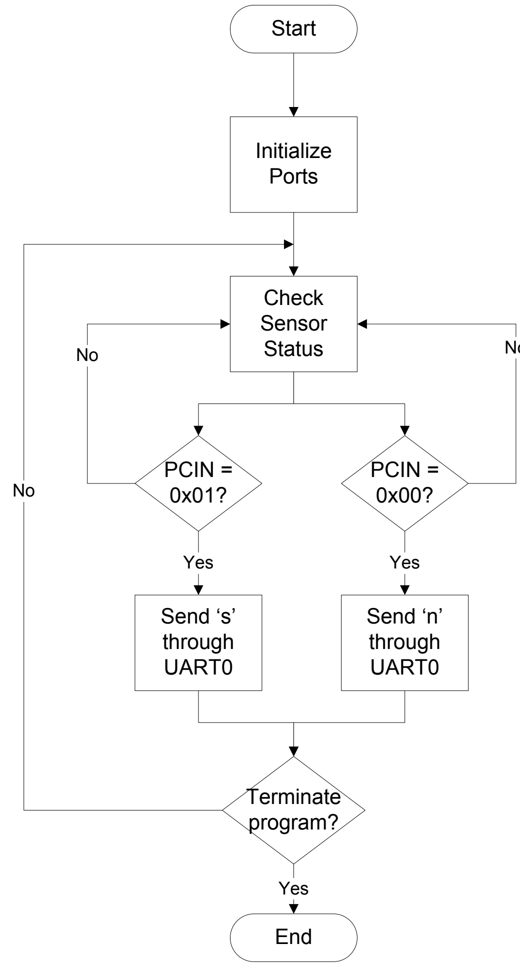

Figure 3: Sensor Node Flowchart

The coordinator node serves as the receiver of sensed information and processes that information to formulate a command to be sent to the actuator node when necessary. The coordinator microcontroller is programmed to receive the information sent by the sensor node (i.e. reports on whether there is sensed presence or not), and to formulate a command to be sent to the actuator node via the UART and transceiver. When the coordinator receives a report by the sensor node that there is movement in the room, it immediately sends a command to the actuator network to turn the lights on. When the coordinator receives a report that there is no movement in the room, it continues to check after sometime if indeed all movement has died down. After a certain amount of time of no-movement has elapsed, it sends a command to the actuator node to turn the lights off.

Figure 4 shows the coordinator node flowchart:

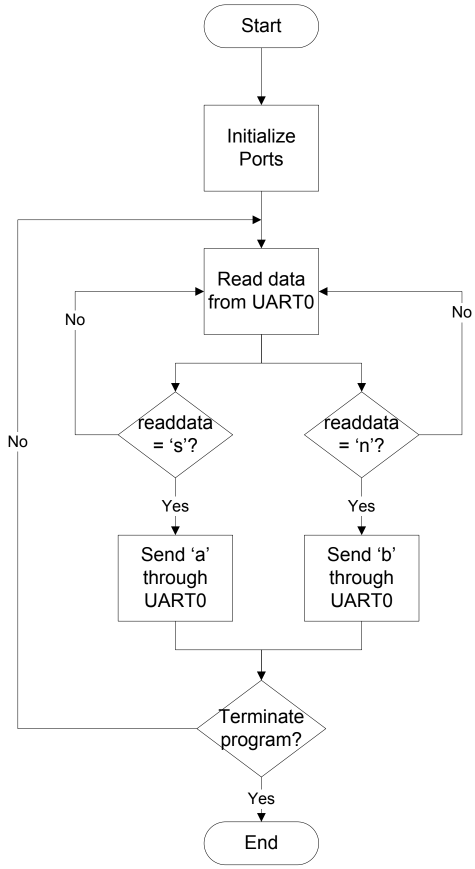

Figure 4: Coordinator Node Flowchart

The actuator node is responsible for executing the commands coming from the coordinator (and the coordinator only) – in this case, it is the turning on or off of the lights. For this purpose, the actuator node was interfaced with the lights. When the actuator node receives a command from the coordinator to turn the lights on, it outputs logic 1 to the relay driver. This "1" then toggles the switch, closing the circuit and turning the lights on. On the other hand, when the actuator node receives a command from the coordinator to turn the lights off, it outputs logic 0 to the relay driver which then opens the circuit and turns the lights off.

Figure 5 shows the flowchart for the actuator node program.

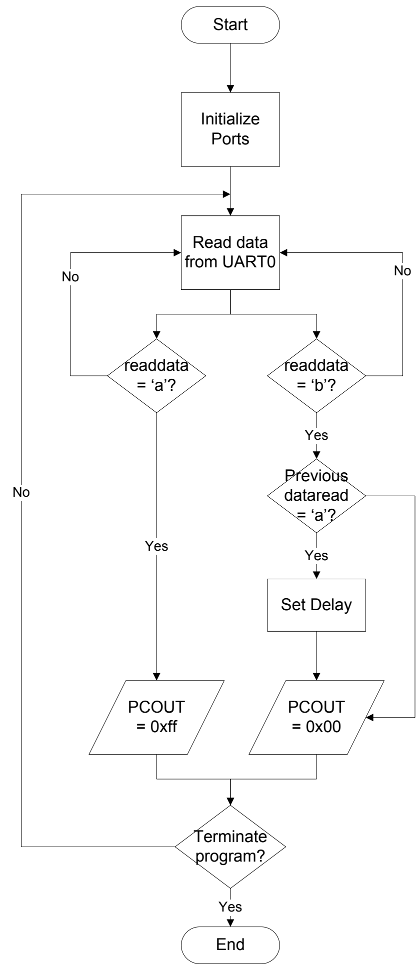

Figure 5. Actuator Node Flowchart

For the purposes of this application, the actuator node was interfaced with study lamps using an Omron relay driver. Figure 6 shows the relay driver used for this experiment.

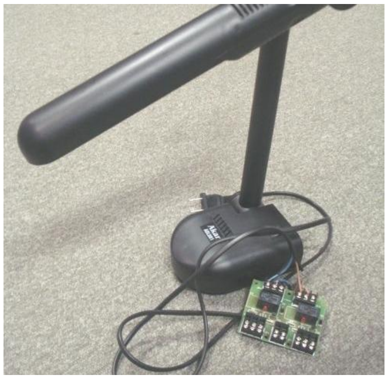

Figure 6: Lamp with relay driver

B. Constructing the Zigbee-based WSAN

A simple implementation of the Zigbee protocol is used in building the prototype of a wireless sensor and actuator network for the application of lights automation. This system is employed using three JN5139 Jennic modules that are Zigbee compliant and configured in a star topology similar to Figure 1. The same model of motion sensor board and relay driver were used for the sensor nodes input and actuator nodes output respectively. Figure 7 shows the sensor node together with the microwave motion sensor node.

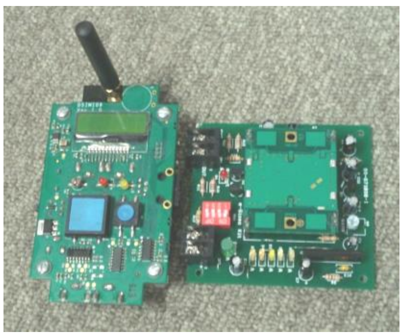

Figure 7: Sensor Node (left) and Microwave Motion Sensor (right)

The deployment of a wireless sensor and actuator network presented in this project consists of three nodes: the coordinator node, the sensor node, and the actuator node. Shown in Figure 8 is a flowchart for the entire system:

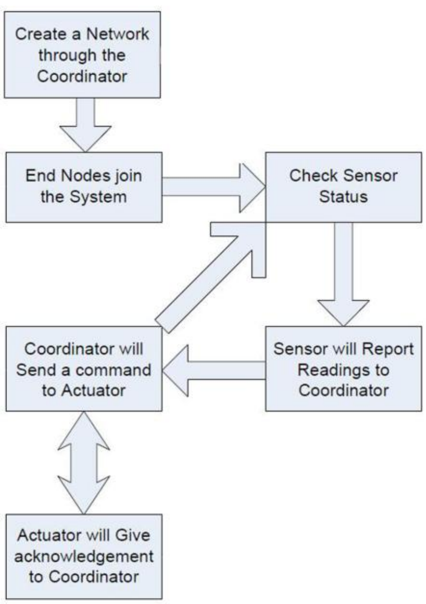

Figure 8: Zigbee-based WSAN System

In this experiment, the sensor used to detect the presence of a person in a room is a microwave motion sensor.

C. ISM-based WSAN Experimentation

1. Through-put Experimentation

The throughput was tested on varied distances and environments to test the performance of the set up given different ranges at a baud rate of 19200 bps. The different environments were open space, concrete/buildings and forest settings. Five (5) test spots were chosen for each environment with the sensor node placed at 60m, 100m, 140m, 180m and 220m away from the coordinator node at different times. Figure 9 shows the different testing spots for the through-put experiments.

Figure 9: Testing Spots

A test message was sent and the number of successfully received messages was counted in order to get the percentage received message. Among the received messages, the percentage of error messages was taken by dividing the number of error messages by the total number of received messages. Table 1 summarizes the percentage of successfully received messages while Table 2 summarizes the percentage of errors found in the successfully received messages.

Table 1: Percentage Received (ISM-based)

	Open Space	Forest/ Trees	Concrete/ Buildings
60m	99%	66%	0%
100m	95%	99%	0%
140m	82%	96%	0%
180m	81%	70%	0%
220m	65%	0%	0%

Table 2: Percentage Error (ISM-based)

	Open Space	Forest/ Trees	Concrete/ Buildings
60m	0%	3%	Not applicable
100m	1%	0%	
140m	5%	30%	
180m	4%	12%	
220m	6%	Not applicable	

The co-channel interference was also tested with two transceivers at different distances and obstructions. These set-ups are described in Table 3.

Table 3: Set-ups for Co-Channel Interference

Set-up	Description
Set-up 1	Distance = 1 m, No Obstruction
Set-up 2	Distance = 5m Obstruction: 1 Concrete Wall
Set-up 3	Distance = 5m Obstruction: 2 Concrete Walls
Set-up 4	Distance = 10m Obstruction: 4 Concrete Walls

For the first set-up, two transceivers were made to send data continuously at the different set-up points. The percentage of successful data sent is summarized in Figure 10.

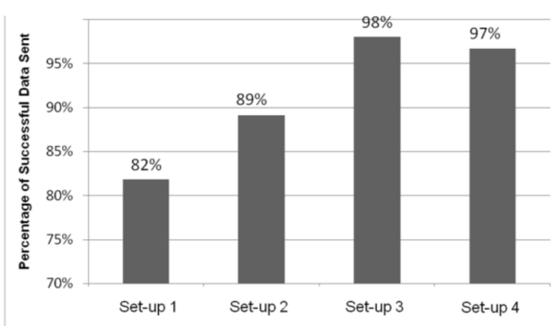

Figure 10: Co-channel interference while transmitting continuously

For the second set-up, two transceivers were made to send data alternatelyly at the different set-up points. The percentage of successful data sent is summarized in Figure 11.

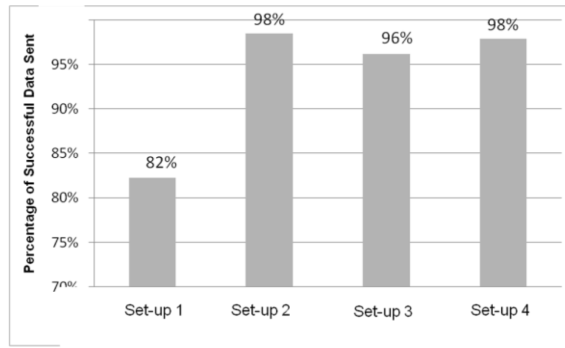

Figure 11: Co-channel interference while transmitting alternately

For both set-ups, the there is a strong co-channel interference when two transceivers are placed near each other. However, the presence of a dividing concrete wall is enough to protect the data from co-channel interference and boosts the number of successful data sent to around 96-98%.

2. Power Consumption Experimentation

The ISM-based WSAN nodes are powered by a 9V battery. A sensor node is made to transmit continuously and was able to deplete the fully charged battery in 2 hours and 53.45 minutes. Continuous voltage readings of 10 samples per second were taken using a data acquisition device together with a simple LabView program in order to monitor the state of charge (SOC) of the battery. Table 4 summarizes the amount of time the voltage remained in a specific SOC interval while Figure 12 shows the Voltage vs. Time Graph as the battery is used by the sensor node.

Table 4: SOC Summary (ISM-Based)

SOC Interval	Amount of Time
100%	38.55 minutes
100% - 89%	115.33 minutes
89% - 78%	2.48 minutes
78% - 67%	12.27 minutes
67% - 56%	1.95 minutes
56% - 45%	0.52 minutes
45% - 0%	0 minutes

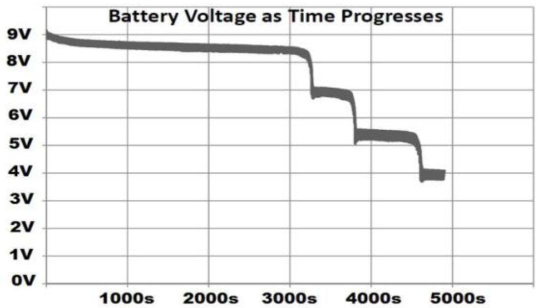

Figure 12: Voltage vs Time Graph (ISM-based)

D. Zigbee-based WSAN Experimentation

1. Through-put Experimentation

The throughput was tested on varied distances in open space. A test message was sent from a sensor to a coordinator at distances of 5m, 10m, 25m, 40m, 80m, 100m and 120m. The percentage of successfully received message is as shown in Table 5.

Table 5: Percentage Receive (Zigbee-based)

	Percentage Received in Open Space
5m	100%
10m	100%
25m	92%
40m	85%
80m	84%
100m	57%
120m	58%

2. Power Consumption Experimentation

A sensor node is programmed to send 1 packet every 500ms continuously and was able to deplete the fully charged battery in 1 hour and 47.33 minutes. Continuous voltage readings of 10 samples per second were taken using a data acquisition device together with a simple LabView program in order to monitor the state of charge (SOC) of the battery. Table 6 summarizes the amount of time the voltage remained in a specific SOC interval while Figure 12 shows the Voltage vs. Time Graph as the battery is used by the sensor node.

Table 6: SOC Summary (Zigbee-based, Sensor Node)

SOC Interval	Amount of Time
100%	66.75 minutes
100% - 83%	36.58 minutes
83% - 63%	3.08 minutes
63% - 54%	.92 minutes
54% - 0%	0 minutes

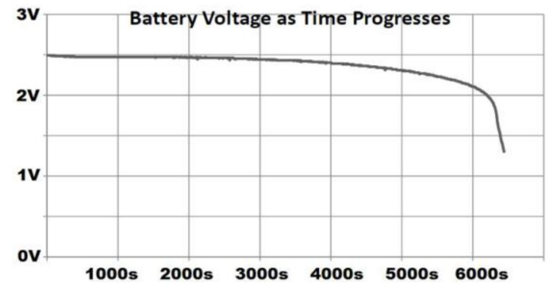

Figure 12: Voltage vs Time Graph
(Zigbee-based, Sensor Node)

The same power consumption was performed with a coordinator node running the create-a-network program. The coordinator node was able to deplete the battery in 4 hours and 7 minutes. Below is the summary of the coordinator nodes power consumption.

Table 7: SOC Summary (Zigbee-based, Coordinator Node)

SOC Interval	Amount of Time
100%	218.83 minutes
100% - 83%	23 minutes
83% - 63%	1.25 minutes
63% - 56%	3.92 minutes
56% - 0%	0 minutes

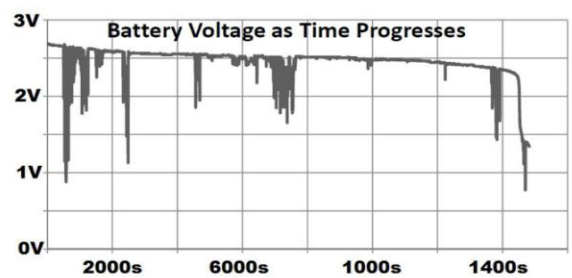

Figure 13: Voltage vs Time Graph
(Zigbee-based, Coordinator Node)

IV. Conclusion

Two WSAN implementations were characterized and compared in terms of power consumption and throughput reliability to determine networks quality of service. The following table shows the basic comparison between the two:

Table 8: General Comparison of WSANs

Comparisons	**Zigbee-based WSAN System**	**ISM-based WSAN System**
Protocol	108.13.4 (Zigbee)	UART
Frequency	2.4 GHz	433 MHz (ISM)
Components	Sensor, Coordinator, Actuator	Sensor, Coordinator, Actuator
Maximum Distance	133 m (open space)	394.44 m
Data Sending	Frames	Bytes
Programming Language/Compiler	C++ / Codeblocks	C / Zilog
Cost	$ 500 per module	$ 70

Power consumption is generally larger for the Zilog microcontrollers used in building up the ISM-based WSAN System. A microcontroller's current consumption reaches 200 mA while only 46.48 mA is measured for its Zigbee counterpart. Consequently, battery life is longer for the Jennic modules used in the Zigbee-based WSAN which lasts up to 2-2.5 hours as compared to 1.5 hours in Zilog for the same battery. However, this is true only for 5-8 meters of distance from node to node. The Zilog microcontrollers on the other hand, consume the same power even up to 394.44 meters distance. The power consumption observations for the two networks are summarized in Table 8.

Table 9: Power Consumption Comparisons

Power Consumption Observations	**Zigbee-based WSAN System**	**ISM-based WSAN System**
Current Consumption	46.48 mA	200 mA
Max distance at same power	5-8 m	394.44 m
Battery Life	2 – 2.5 hours	1.5 hours

Throughput was quantified with varied factors including distance from node to node, obstructions in between nodes and co-channel interference. Throughput for both networks is noticeably less as distance is increased. This also goes for increased number of obstructions in between nodes. For the Zigbee-based WSAN, wall thickness must be lessened at increasing distances to achieve maximum throughput. The difference in throughput observations between the two systems lies in the co-channel interference and error rate. While the ISM-based WSAN network is weak in dealing with these factors, Zigbee-based WSAN network is not affected by these. Zigbee has a way of encrypting data so other channels may not interfere with the data sending and receiving. This is done together with the creation of frames. The frames also ensure maximum reliability in the data being sent, hence no error rate. The throughput observations for the two networks are summarized in Table 9.

Table 10: Throughput Comparisons

Throughput Observations	**Zigbee-based WSAN System**	**ISM-based WSAN System**
Maximum Distance	= 133 m (open space) Less throughput at larger distances	= 394.44 m Less throughput at larger distances
Error rate	No error rate in MSG frames received	Less error rate at larger distances
Obstructions	Wall thickness largely affects throughput	Largely affects throughput
Co-channel interference	Does not affect throughput	Largely affects throughput

Throughput was quantified with varied factors including distance from node to node, obstructions in between nodes and co-channel interference. Throughput for both networks is noticeably less as distance is increased. This also goes for increased number of obstructions in between nodes. For the Zigbee-based WSAN, wall thickness must be lessened at increasing distances to achieve maximum throughput. The difference in throughput observations between the two systems lies in the co-channel interference and error rate. While the ISM-based WSAN network is weak in dealing with these factors, Zigbee-based WSAN network is not affected by these. Zigbee has a way of encrypting data so other channels may not interfere with the data sending and receiving. This is done together with the creation of frames. The frames also ensure maximum reliability in the data being sent, hence no error rate.

From the data gathered and from the analysis above, the group concludes that the Zigbee-based WSAN system is more appropriate for closed environment, such as in room automation and home automation applications, where distance from node to node is relatively shorter. The ISM-based WSAN prototype, on the other hand, is better for larger areas such as deployment in fields and cities, since transmission is not generally limited by distance and obstructions.

The Zigbee protocol has better throughput functionality which can be advantageous in security-intensive applications. The ISM-based WSAN, however, is more cost-efficient and could be used in diverse applications. The Jennic modules used in the

Zigbee-based WSAN system implementation are relatively low in power and thus more resilient in applications that require more consumption of energy.

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