Sub-1Ghz Low-Power Wireless Node For IoT Based Smart Home System

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Abstract*— Internet of Things (IoT) development is a very challenging topic, and the debate about the actual implementation is still wide open. Various studies have been conducted in term of smart home system based on IoT technology. However, resources that concern on how to practically implement the particular energy-saving and resource efficient technology for smart home need to be improved. In this study, presented the field experiment results related to implementation of low-power node modules using sub 1 GHz LPWAN (low-power wide area network) connectivity. LPWAN technology has unique characteristics, such as a transmit power that in SRD class (short range device) but cellular like coverage range. LPWAN network support star topology by default, so it can overcome the problem of power usage inconsistency, network delay and the complexity of the routing management process found on conventional mesh-based sensor networks. Based on the field experiment result, the furthest distance under outdoor condition could reach up to 350 meters (RSSI -85 dBm) and 150 meters (RSSI -95 dBm) under indoor condition. Based on the power usage test, life-span estimation could reach up to 1 year or 17 years depend on the scenarios and battery types.

***Keywords*— IoT, Sub 1 GHz, Wireless Sensor, Smart Home**

I. Introduction

Smart homes, or intelligent home are homes that use automation systems to provide control and monitoring of home functions for the occupants. For examples, smart homes can control lighting, temperature, multi-media, security, window and door operations, as well as other functions [1]. Through network management, smart homes can further enhance home security, convenience, ease of control and artistic, as well as achieves eco-friendly living environment [2]. Network management within smart homes can take advantage of Internet of Things (IoT) technology. The IoT paradigm is a paradigm that enables a wide range of devices such as sensors and actuators equipped with telecommunication interfaces, processing, and storage units to communicate with each other over the Internet. This communication paradigm should allow for seamless integration between any potential object with the Internet, allowing for the creation of new forms of interaction between humans and devices, or directly between devices based on what is commonly referenced by the term of machine-to-machine (M2M) communication paradigm [3].

IoT development is a very challenging topic, and the debate over how its implementation is still wide open[4]. The discussion involves all layers of protocol stacks, ranging from physical transmission layers to data representation and service composition [5]. Various studies have been conducted to develop IoT-based smart home systems [2], [6], [7]. It is known that the recording of environmental data and controlling devices and home instruments is a major activity in IoT-based smart home systems [8]. Therefore, the development of environmental sensing modules and home instrument controllers is the most basic requirement to develop a reliable smart home system. The smart home system is entirely dependent on the sensor nodes (node sensor-nose), as well as the instrument control nodes (node actuator-noac) for monitoring and controlling the home conditions [9], [10].

Connectivity is one of the most fundamental aspects of the nodes. Generally, connectivity between nodes can be either wired or wireless. In recent years, wireless connectivity have been in great demand worldwide and are one of the most studied areas of the past decade [11]. Wireless connectivity have advantages such as lower cost factors, extensibility, reliability, accuracy, flexibility, and ease of deployment in a wider application field. Nowadays, IEEE 802.11 (Wi-Fi), Bluetooth LE (Low Energy), cellular, ZigBee, Z-Wave and Thread become the most important de facto standards in the IoT wireless communication arena [12]. According to the result of some initial research has indeed revealed the limits of the multihop short-range network technology related to IoT based application, stressing the need for a place-&-play type of connectivity, making it possible to connect any device to the IoT by simply placing it in the desired location and switching it on [13].

Moreover, conventional methods for sensor networks (IEEE 802.15.4 / ZigBee) generally use mesh / multihop topologies to extend network coverage. The mesh architecture can also provide resistance to failure on a single node. But on the other hand, multihop routing generally produce a long communication delays and the maintenance

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of mesh networks requires non-negligible control traffic, also unequal and unpredictable energy consumption among devices [14], [15]. To overcome the long delays, a high raw bit rate (eg, 250 Kbps) is used in the link-level technology. But they are not robust enough to penetrate the building walls and other obstacles (even in the 868/915 MHz band). In other words, in a trade-off between rating and sensitivity, rating is usually preferred. In addition to issues of topological and sensitivity characteristics, Bluetooth, Wi-Fi and Zigbee technologies may be interfering because they all use the same frequency band (eg 2.4 GHz), especially with the increasing number of devices operating in these frequency bands [16]. Interference issues can cause severe network quality deterioration, leading to increased power consumption among devices, low Quality of Service (QoS) ratings, to failure to achieve deadlines in real-time applications.

A promising alternative solution, standing between short-range multihop technologies operating in the unlicensed industrial, scientific, and medical (ISM) frequency bands, and long-range cellular-based solutions using licensed broadband cellular standards, is provided by so-called low-power wide area networks (LPWANs) [4], [17], [18]. These kinds of networks exploit sub-gigahertz unlicensed frequency bands, and are characterized by long-range radio links and star topologies. Star topology mean the end devices are directly connected to a central node or gateway that provides the bridging to the IP world. The architecture of these networks is designed to cover wide area, ensuring a robust connectivity to nodes that are deployed in very harsh environments.

In this study, presented the field experiment results related to implementation of low-power node modules using sub 1 GHz LPWAN (low-power wide area network) as the communication method. The node operates in the 868 MHz ISM Band, with an 8-bit microcontroller compatible with the Arduino hardware development platform as a power-efficient processor. The network architecture uses a star topology, so it developed two types of nodes, namely central node (CN) and end node (EN). The characteristics of the modules are then analyzed to gain insight into transmission performance and duration of life in relation to the need of robust sensor and actuators node modules as a basic conectivity infrastructure of IoT-based smart home systems.

II. Research Method

A. Current Connectivity Standards for WSAN

Connectivity is a very important aspect in wireless sensor and actuator networks (WSAN) since it is closely related to the complete design of the node modules. Therefore, a mature study in designing the node architecture is essential to create a reliable smart home system. Generally the standard wireless communication methods used in IoT-based smart home systems are IEEE 802.11 (Wi-Fi), Bluetooth LE (Low Energy), cellular, ZigBee, Z-Wave and Thread [12].

In the wireless sensor network architecture that uses the ZigBee protocol, multi-hop mesh network topology were commonly used [19]. In addition to using mesh topology, ZigBee can also use star topology. The ZigBee protocols that use the IEEE 802.15.4 standard generally operate in the 2.4 GHz band, but there are also special frequencies that can run at 868/915 MHz with ranges ranging from a few meters to 100 meters depending on environmental conditions. The ZigBee protocol relies on the capabilities of a multi-hop mesh topology to be able to covers long range. When using a star topology, then the range area will be much reduced. Although mesh topologies have the advantage of handling nodes that fail to function, on the other hand wireless sensor networks with mesh topology are very difficult to maintain and require tricky traffic control. The multi-hop routing process also generates a lot of delay and power management that is difficult to predict on each node.

IEEE 802.11 protocol standard or commonly known as Wi-Fi also generaly used for WSAN connectivity. Its characteristics have a high data rate and coverage up to 32 meters by using the factory default antenna configuration for home use. But this technology is also less than optimal when applied to node module. In terms of quality, the 2.4 GHz frequency spectrum is already widely used so it is vulnerable to interference. Wi-Fi technology is also expensive in terms of resource usage, because the protocol that runs on it is based on TCP / IP that would require a large resources. The ability to operate in low-power mode is also not possible. Not to mention the security issues that need to be considered when using this technology.

To address weaknesses in the use of power and coverage ranges in 802.11 standards, the WiFi alliance developed a new 802.11ah standard (WiFi HaLow) operating in the 900MHz frequency band split into 26 channels. WiFi HaLow specification is quite interesting for IoT implementation because it has a wide coverage ranges up to 1 Km and low power capability. WiFi HaLow is not the only WiFi specification that offers connectivity for IoT, previously in 2014 the WiFi alliance also introduced the 802.11af standard, which is a network protocol standard operating in the bands 54 and 790 MHz. The range offered by 802.11af also matches the 802.11af range. But until now the products and chips that implement this technology are still rare and difficult to find in the consumer market.

As a complement to existing standards, LPWAN solutions are indeed examples of short-range devices with cellular-like coverage ranges [4], [20]. LPWAN has low-rate, long-range characteristics with transmission technology running on a freely licensed 1 GHz sub-frequency spectrum and using a star topology. LPWAN operates in 868/915 MHz, 433 MHz, and 169 MHz band, depending on the operating region [21]. Since the sub 1 GHz frequency has better penetration capabilities and cleaner propagation spectrum than the 2.4 GHz and 5 GHz frequencies, the spectrum below 1 GHz is not particularly susceptible to interference [22]. In terms of transmit power, LPWAN fall in the category of SRD (short range devices) or devices that do not cause interference to other devices, but has coverage as mobile technology (10-15 km in rural areas and 2-5 km in urban areas). This is possible because of the new design on the physical layer, aimed at very high receiver sensitivity. Network topology that is used also supports star topology or single-hop network to facilitate the expansion and flexibility.

TABLE I. THE COMPARISON OF COMMUNICATION CHARACTERISTICS FOR DIFFERENT PROTOCOLS

Wireless Standard	Range		Bit Rate (Mbps)	Throughput (Mbps)	Frequency (GHz)	Topology
	Indoor	*Outdoor*				
NFC	<0.2 m		0.424	0.22	0.014	p2p
Bluetooth	1-1000 m		1-3	1.4	2.4-2.5	scatternet
BLE	~100 m		1	0.3	2.4-2.5	star, scatternet
BT v5	300 m		2	1.5	2.4	N/A
ZigBee	<20 m	<1500 m	0.25	0.15	2.4	star, tree, mesh
802.11 b/g/n	<70 m	<230 m	>1	2-50	2.4/5	star
802.11ah HaLow	<700 m	<1000 m	0.15-40	>0.1	0.9	star
LPWAN	<10 Km		<0,05	<0.5	sub-GHz	star
3G	>5 Km		0.17	N/A	0.8-1.9	N/A
LTE	>5 Km		75-300	N/A	2.1	N/A

TABLE II. THE EFFECTIVENESS OF EACH COMMUNICATION PROTOCOL FOR DIFFERENT KIND OF APPLICATIONS

Wireless Standard	Use Case					
	Medical	*Smart City*	*Smart Building*	*Automotive*	*Industrial*	*Local Network (M2M)*
NFC	medium	high	low	low	very low	medium
BLE	very high	low	low	low	very low	high
ZigBee, BT v5	medium	high	very high	very high	low	high
WiFi b/g/n	low	high	medium	medium	medium	high
HaLow	high	very high	high	high	high	very high
LPWAN	low	very high	high	high	high	high
Cellular (3G, LTE)	low	high	high	high	high	very low

Based on the comparison between their characteristics, sub-1 GHz wireless connectivity has a high compatibility for application in the field of smart building [15]. In Table 1, the characteristics of the basic parameter of each common wireless communication technology used in wireless sensor network applications are summarized. However, it is important to note that the physical design of the node can strongly affect the final performances. For example, even if the devices operate in the same protocol, if the design and size of the antenna and the power transmission settings are different, the final performance are also affected. In Table 2, the compatibility of each wireless communication technology for different kind of application areas are reported.

B. Network Architecture and Node Module Designs for Smart Home System

Smart home system requires the node module to perform sensing of environmental conditions and controlling particular instruments. In this study prepared two types of nodes (central node and end node) to accommodate those needs. End node can act as a sensing or control module (noac & nose), and the central node acts as a gateway. The installation of a noac is generally intended to control actuators such as switches, electric valves (solenoid valves), door lock solenoid, PWM (pulse width modulation), motors and other. To achieve this goal, the noac is generally integrated with external driver or relay circuit. Nose is a sensing devices. Therefore, nose is equipped with sensors that have a variety of functions. Such as gas and smoke detector sensors, light intensity, temperature, humidity, ultrasonic, infrared, level, flow, current and voltage. An overview of the proposed network architecture for IoT-based smart home systems is shown in Figure 1.

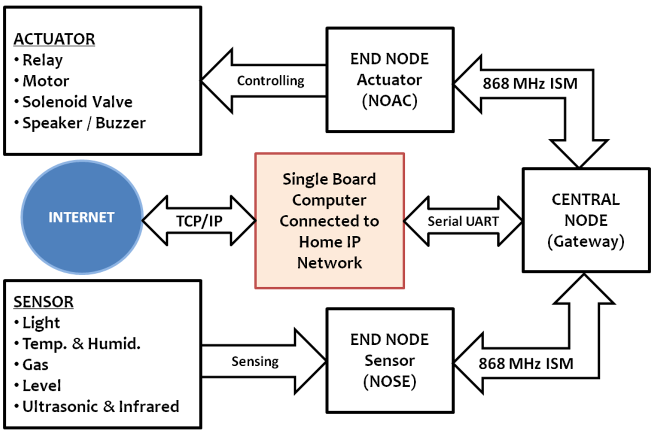

Fig. 1. Network Architecture for IoT-based Smart Home Systems

The proposed sub 1 GHz network architecture use a star topology since its offers an ease of design and network management. The central node becomes the gateway of a sub 1 GHz wireless network. Central nodes can connect to a TCP / IP or Internet via the Serial UART interface on a single board computer. Thus it can be integrated with data loggers, as well as intelligent home services and system interfaces. The addressing protocol used in the sub 1 GHz node network is almost similar to the addressing protocol of IP Address v4 on the TCP / IP network. Each node is assigned a unique identifier number, network number, and network key in the form of 128 Bit AES encrypted password. Any node that has the same network number and encryption password can communicate with each other. All nodes operate wirelessly at a frequency of 868 Mhz that has a fairly clean radio propagation band compared to the 2.4 and 5 GHz band dedicated to general communications. In Figure 2, a full description of the device installation along with the network for the smart home system is shown.

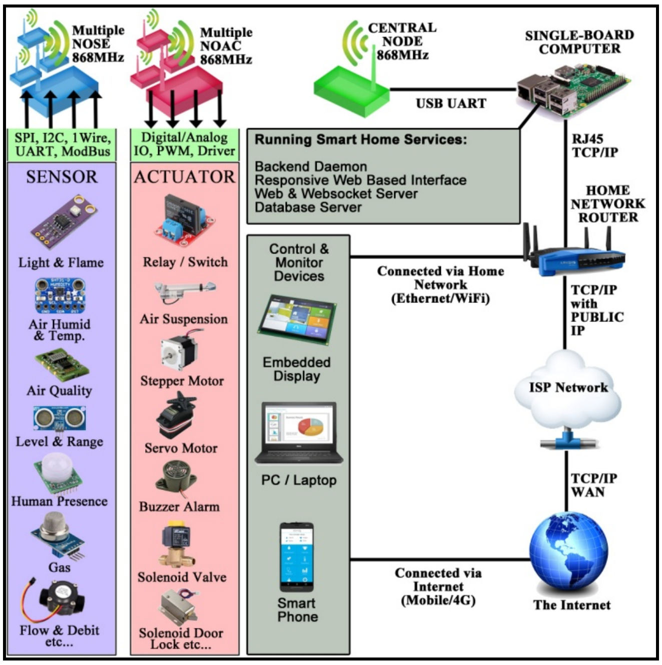

Fig. 2. Installation of Devices & Networks for Smart Homes

For the node itself, an 8-bit microcontroller chip ATmega328-AU is used as the low-power processor. This chip can meet the needs of the system and is the same chip used by the Arduino Uno hardware development board that is widely used in various open source hardware projects. Thus, all the advantages of Arduino Uno such as software libraries and great community support can also be utilized. The block chart that composes the node module is shown in Figure 3.

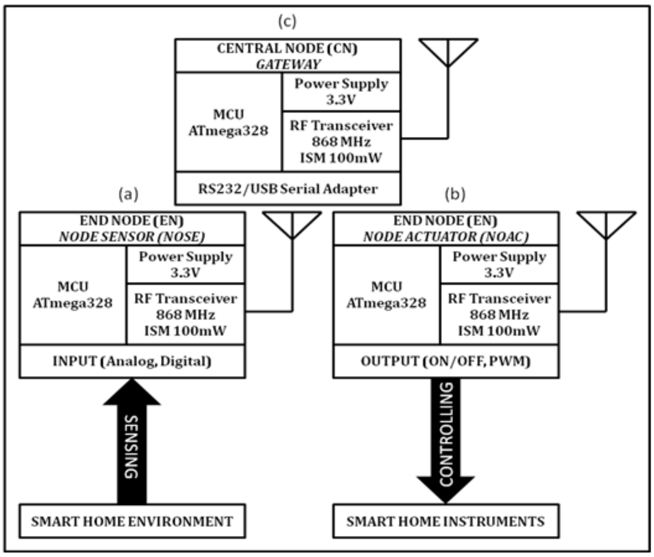

Fig. 3. (a) Node Architecture Block, End Node NOSE, (b) End Node NOAC, (c) Central Node

On the antenna part, a monopole or whip antenna is used. This antenna is suitable for simple, compact and relatively inexpensive use. The size of the monopole antenna used in this work is 8.6 cm. The wavelength is calculated based on the frequency of the radio wave, as in (1):

$$\lambda = \nu / F \quad (1)$$

Where λ is the wavelength, ν is the speed of light in an open air or vacuum space, and F is the frequency. Thus obtained the wavelength of 345.62 mm. However, if full size is used then the antenna will be too long, so a quarter wavelength option is selected that is 86.405 mm or 8.6 cm.

In the software section, the node module firmware is designed to use a star topology. Based on the hardware capability of the transceiver component (RFM69HW) that use a Semtech SX1231 / 1231H chipset, 256 networks can be formed containing 255 nodes on each network. The RF transceiver module also supports hardware encryption with AES 128 Bit. Although in a single transmission only 61 bytes of data can be transmitted, a small package can shorten the delivery time so as to minimize impact in the air and avoid packet loss. This condition still met node transmission need for IoT application that does not require large packet. The RFM69 packet transmission structure is shown in Figure 4.

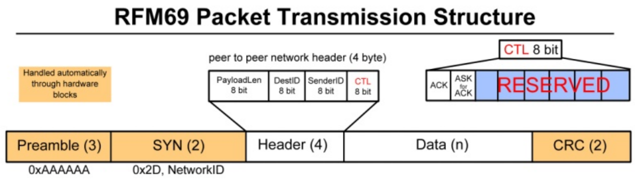

Fig. 4. RFM69 packet transmission structure

For power saving features, some parts of the node modules such as ATmega328AU microcontroller are set to power down mode, flash memory and transceiver can be disabled and all pins are set to low. The node module then can be awakened from deep sleep mode through the Watch Dog Timer (internal WDT) without having to use external circuits, or through interrupts sent by the Transceiver RF module in the event of a new packet received. So that node module can sleep forever if there is no activity of sending / receiving data.

C. *Performance Test Methodology*

As a proof of concept, transmission performance and power usage test was conducted. Transmission performance test are conducted in indoor and outdoor areas (permanent building & public park). But an initial test was done first to make sure the nodes is ready. Transmission performance test is done by sending sample data in form of string while the end node were moved away by walk from central node until no more data received. The sending process occurs every one second from end node to central node that is connected to a computer running data logger. The size of the data sample is 1 byte and 61 bytes to represent a minimum and maximum transmission throughput, thus on each area two test was conducted. The output of this test is a RSSI value of every received packet and the maximum range that could be reached.

Power usage test is done by measuring the current drawn (in mA) and duration (in milli seconds) of running process that consist of reading ADC (analog-to-digital converter) 100x, sending data, receiving data and deep sleep. Thus the avarage current usage (*Imean* in mA) related to system activity or the running firmware can be calculated. After getting the *Imean* value, then the life-span of the battery powered nodes can be calculated, as in (2):

$$T = BattCaps \,/\, Imean \qquad (2)$$

Where T is the possible life-span (in hours) based on the node activity, *BattCaps* is the capacity of the battery (in mAh), and *Imean* is avarage current usage related to system activity or the running firmware.

III. Results and Analysis

A. Transmission Performance Test Result

In this research, two prototypes was constructed to represent central node and end node. The nodes installation in testing process and the maximum range recorded on each areas are shown in Figure 5. Tests on outdoor conditions conducted in public parks that located in the middle of the city, there are trees, people's activities and surrounding external noises. For indoor conditions conducted in the campus area located far from the city, with alot of permanent building. As shown in Figure 6, transmission with large data (61 bytes) in outdoor conditions has a greater chance of being lost in the air, causing fewer packets to be received. But in the indoor conditions as shown in Figure 7 the package size is not so influential, the number of packets received almost the same. If in the indoor conditions the RSSI final value is in the range of -90 dBm, in outdoor conditions even exist in the range of -80dBm at the maximum distance. This may be due to outdoor testing conditions where there are other activities that also involve the use of radio frequency (close to a powerful FM radio transmitter, loudspeakers, wireless microphones).

In addition, weak transmission power and external noise on a longer distance range (350m) causes the transmission to fail to reach the receiver, so that the recorded RSSI stops at a relatively high values. In indoor conditions (150m), RSSI value can reach -90 dBm due to the condition that is full with obstacles. Thus it can be concluded in addition to physical obstacles such as buildings and trees, other environmental conditions such as a more powerful radio transmitters also affect the performance. Based on the maximum distance, both in the worst environmental conditions, the transmission performance offered by the node module has a high prospect to be used as a sensing and controlling nodes in a smart home environment with a diameter up to 300 meters indoor, and 700 meters outdoor.

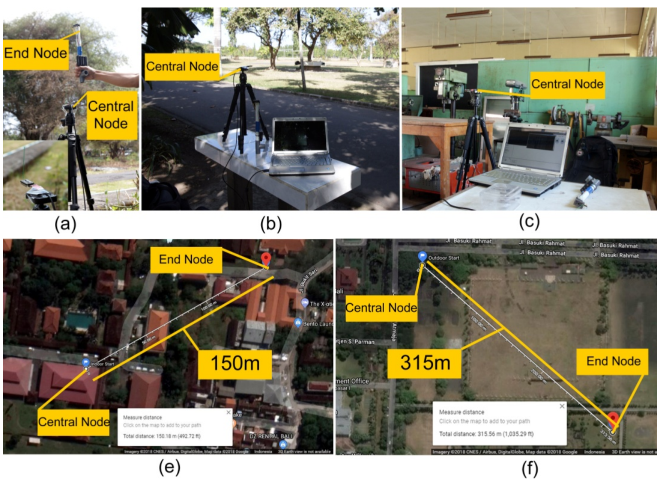

Fig. 5. (a) Device Installation in Transmission Test, (b) Outdoor area, (c) Indoor area, (e) Indoor Maximum Range, (f) Outdoor Maximum Range

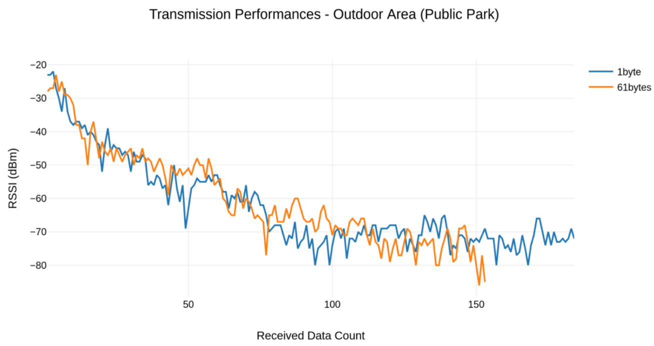

Fig. 6. RSSI vs Number of Received Packet in Outdoor Area (Public Park)

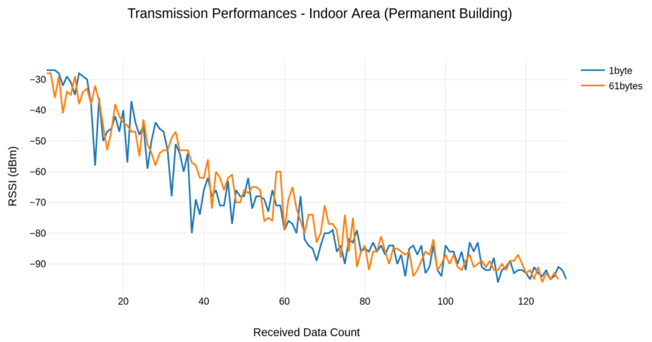

Fig. 7. RSSI vs Number of Received Packet in Indoor Area (Permanent Building)

If performance takes precedence over power usage, then a transmission algorithm can be applied that enables retransmission of lost packets as done by the TCP / IP network protocol. Also optimizing a dynamic transmission control algorithm to auto-adjust transmission power based on RSSI. In addition, optimization on the hardware side such as the antenna design can also be improved to get a better performance without having to rely on cost factor and simplicity.

B. Power Usage Test Result

The node module life-span is estimated up to eight hundred and fourty-five days or about two years and three months if using 2600mAh Li-Ion Battery and 0,23% firmware duty cycle (ADC readings (with 100 samplings), data transmission, data reception, and deep sleep once in a cycle). Node sensor (nose) is ideal if using a duty cycle of 0.23% with a total duration of 8018.47 milliseconds in full cycle. Given environmental data such as global temperature and light are not changing enough within 8 seconds which is the maximum sleep times based on the microcontroller specification if using internal WDT as the wake-up trigger. Indeed, other combination of process is also possible by repeating it to fit different condition. For example, in Figure 8 shown the life-span estimation by four different scenarios and battery types. Each battery types has its own characteristic such as form-factor, voltage, maximum current drain limit found on Alkaline, or self-discharge rate issues found on rechargeable battery that also need to be considered. Four different scenarios is categorized by its sleeps duration.

TABLE III. CURRENT DRAWN BY PROCESS AND LIFE-SPAN CALCULATION

No.	*Imax (mA)*	*Imin (mA)*	Duration (mS)	Process	Loop Count (LC)	Duration * LC	*Imax * (Duration * LC)*
1	8,3400	8,1000	11,2300	Read ADC (100x Sampling)	1	11,2300	93,6582
2	135,6000	135,3000	6,5200	Transmit	1	6,5200	884,1120
3	23,1200	21,7200	0,7200	Receive	1	0,7200	16,6464
4	0,0041	0,0041	8000	Deep Sleep	1	8.000	32,8000
					Sum	8018,47	1027,22
						Batt Caps. (mAh) 18650 Li-Ion	2600
						Imean (mA) = Imax * (Duration * LC) / Duration * LC	0,1281
						Dutty Cycle (%) = SUM(Duration * LC[1:3])/SUM(Duration * LC[1:4])*100	0,2303
						Life-span (Hours) = Batt Caps / *Imean*	20295,64

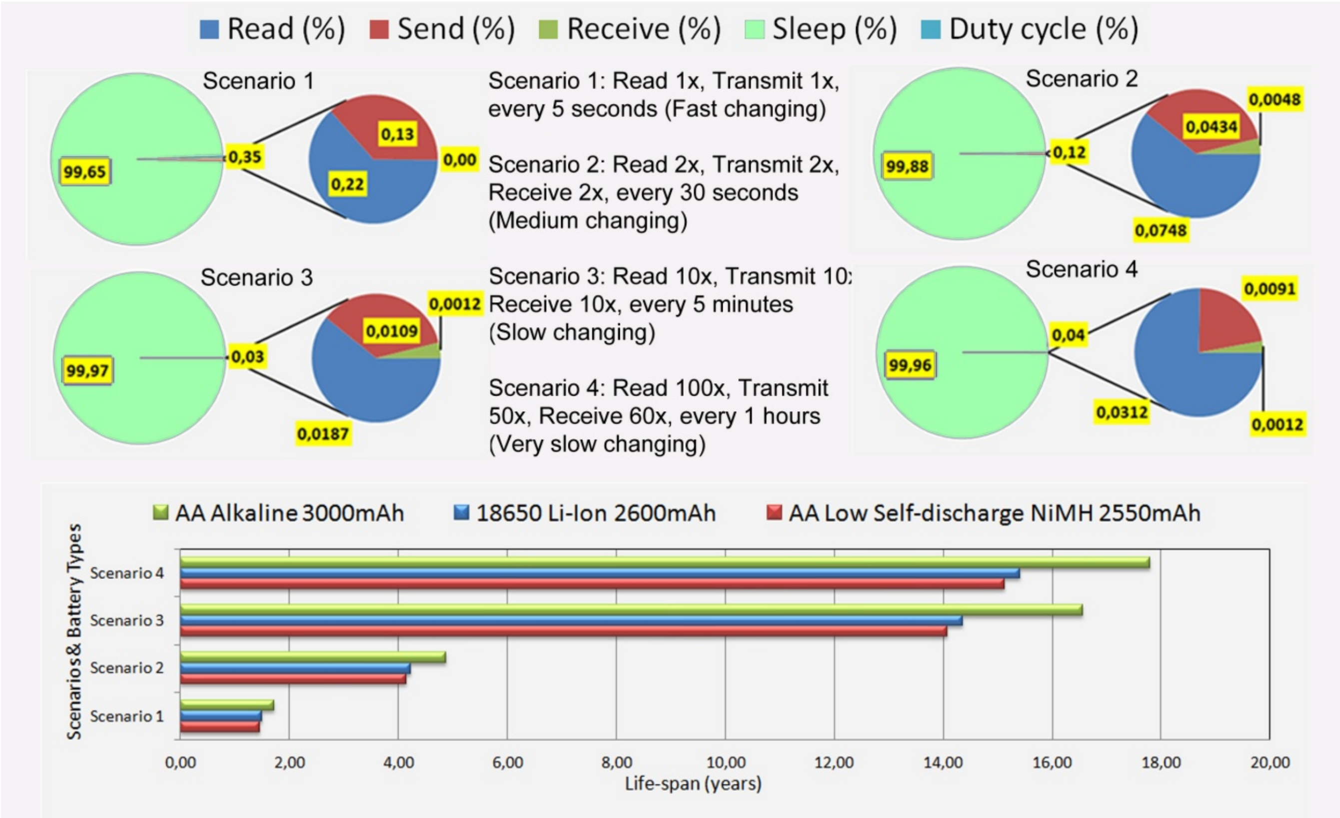

Fig. 8. Life-span Estimation by Scenarios and Battery Types

Scenario 1 suitable for a condition that requiring a sensing node to be placed in a remote areas, such as a remote alarm to detect a human or animal activity. Scenario 2 for a medium changing condition such as a water level, garage door, or power saving features of inactivity. Scenario 3 for a slow changing condition, such as a global condition (light and temperatures, weathers). And the last one, for a very slow changing such as a mailbox, a hourly or daily changing things and a long-term logging systems.

IV. CONCLUSION

In this research, presented the field experiment results related to implementation of low-power node modules using sub 1 GHz LPWAN (low-power wide area network) as the communication method. The sub 1 Ghz connectivity is selected because its characteristic is suitable for IoT application, has better penetration capability, and is not particularly susceptible to interference as in the 2.4 GHz frequency. The node modules architecture is designed using an ATMega328 microcontroller that is compatible with the Arduino open source hardware development platform. The Arduino platform has a large library resources and communities that facilitate further development and reduce production costs. To gain insight into transmission performance and life-span, two tests were performed. Based on the transmission test it can be known that the furthest distance under outdoor condition could reach up to 350 meters (RSSI -85 dBm) and 150 meters (RSSI -95 dBm) under indoor condition. Based on the power usage test, life-span estimation could reach up to 1 year or 17 years depend on the scenarios and battery types.

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