International Journal of Smart Home
Vol.8, No.5 (2014), pp.63-86
http://dx.doi.org/10.14257/ijsh.2014.8.5.07

Constructing Energy Aware Home Automation within the IPv6-USN Architecture

Ardiansyah Musa[1,2], Dokyeong Lee[1], Isyana Paramitha[2], Kalamullah Ramli[2] and Deokjai Choi[1]

[1]*Electronics and Computer Engineering, Chonnam National University*
[2]*Electrical and Computer Engineering, University of Indonesia*
{ardisragen, isyanaparamitha}@gmail.com, ldk7175@nate.com, k.ramli@ee.ui.ac.id, dchoi@jnu.ac.kr

Abstract

The Internet of Things idea and the rapid expansion of IPv6, moreover after IETF defined 6LoWPAN as a technique to apply IPv6 into IEEE 802.15.4 low-power wireless network standard is added potential of the USN connected to Internet and it made up IPv6-USN as the new architecture. However, if we implement IPv6-USN to home automation, the energy consumption of IPv6-USN node operation is bounded. There is the need to periodically replacing its batteries because it commonly used AA batteries as power source, but the complexity of home building characteristics make it is not easy. In this paper, we present our study to develop energy aware home automation in IPv6-USN infrastructure. Our goal is to develop a system that is robust which aware with energy consumption. We designed the home automation nodes with smart and energy efficient oriented RPL routing. By having efficient control transmission and optimal objective function, we can maintain operation performance level of our IPv6-USN home automation with energy consumption reduction around 20%, average latency about 1.0875s, and packet delivery rate above 88.875%.

Keywords: *home automation, IPv6-USN, 6LoWPAN, RPL routing, energy consumption, energy efficient oriented*

1. Introduction

The Internet of Things (IoT), is the biggest challenge and opportunity for the Internet today. This idea made up of the IP-enabled embedded devices and smart object connected to the Internet. This trend has continued with Ethernet and IP becoming ubiquitous. One interesting example application of the IoT is home automation system. By home automation process in the household environment, we can give additional functionalities through the integration of sensors and actuators into non-automated systems like lighting, heating, air conditioning and even regular appliances. There has been a lot of solution in the field of home automation, but almost all of them existing in the market employ wired networks such as X-10, UPB, MODBUS, and Ethernet. They all have been available for at least a couple of decades and, while technologically and functionally proven, they offer some disadvantages that hindered their widespread adoption. For example, the X10 industry standard for communication between electronics devices, providing limited control over household devices through the home's power lines but suffer from low bandwidth and high error rate communication. MODBUS and Ethernet require physical wiring which is expensive, need intrusiveness of the installation and aesthetically displeasing.

ISSN: 1975-4094 IJSH

Nowadays, home automation systems have been challenged with the two outstanding needs: the need for the high interoperability between home devices and the need for accessing to the system from different end points. To develop and improve solution for this, researchers from academia give much attention into the field of home automation. [1] introduced a Bluetooth based home automation system, by connecting each home device to a local Bluetooth sub-controller. This system reduces the amount of physical wiring required and the intrusiveness of the installation through the use of wireless technology. However, due to the sharing of a single Bluetooth module between numerous devices has the disadvantage of incurring an access delay. [2] defined a ZigBee-based home automation networks, a flexible home automation architecture, trough adoption and evaluates the potential of ZigBee. However, this sys-tem still have problem with, evolvability, scalability, and internet integration. End to end paradigm where only the end to end points participate in the application protocol exchanges cannot be implemented with this solution. ZigBee needs intermediate local proxy server to enable communication between embedded home devices and Internet.

A possible strategy to solve the problem listed above could be adopting Internet of Things idea by implementing an all-IP solution based on IPv6 over low-power and lossy network [16,17]. Growing sup-port for IPv6 and its large address space enables the integration of large numbers devices to the IP net-work. The introduction of 6LoWPAN protocol enables home automation device based-on 802.15.4 wireless sensor network standard to be compatible with IPv6 while maintaining low power consumption [3]. It taking the nature of wireless networks into account and made up IPv6-USN as the new architecture. The improvement of 6LoWPAN standard also has been emerging and attracted the interest of other research groups in this field so that the ZigBee Alliance, a special research group in the ad hoc and 802.15.4 network, announced the integration of IETF standards such as 6LoWPAN and RPL into its specifications in march 2013 [7]. Moreover, this protocol is added potential for Internet communication and remote accessing of home automation devices from anywhere on the globe.

IPv6-USN promises the fulfillment of the emerging trend of embedded Internet technology in all aspects of everyday life [4], mainly because of its low costs, low power, scalability, and possibility to adapt existing technologies. [5, 6] has been analyzed and implemented IPv6-USN in home automation, however between the features of any 6LoWPAN-based home automation systems are long periods of life. We need to design 6LoWPAN home device with effective control transmission and efficient energy consumption. We believe is very important due to optimize the system because the power management design should achieve two fundamental requirements: energy-efficient operation and node operation performance level.

In this paper we propose and analyze our energy aware IPv6-USN home automation system with smart and energy efficient oriented RPL routing. The rest of this paper is organized into five sections. Section 2 discusses about 6LoWPAN-based IP-USN home automation and its implementation issues. Section 3 presents the setting to building energy aware environment in our system. Section 4 provides evaluation and management of our system. Finally, Section 5 will conclude our study and our plan to improve our energy aware IPv6-USN home automation.

2. IPv6-USN Home Automation System

According to [4], home automation (HA) consists of interlinked home component that has a set of characteristic properties and attributes as following:

- Future-proof. A HA system cannot be easily up-graded or uninstalled during the lifetime of a building, so it needs to use a stable, proven and future-proof technology.
- Moderate cost. For the HA system to be effective, a compromise between cost and functionality must be achieved, while at the same time maximizing the benefits.
- Low installation overhead. Any modern HA sys-tem has to have a low installation overhead, requiring little or no modification to the existing home environment.
- Configuration effort. System configuration should be easy and time-efficient. Adding new functions or modules to the system should be facilitated by a paradigm that is similar to plug-and-play.
- Connectivity. All entities of the system need to be connected, either through a unified interface or through a specialized one that allows bridging differ-ent technologies and hardware. Connectivity with the outside world is also a desired functionality.
- User interaction. Special care must be taken with interface ergonomics. The user should not be asked for ambiguous or repetitive commands and the inter-face must have familiar controls that need little or no training even for an inexperienced user.
- Security. The system must be aware and protect its users from threats like unauthorized access, privacy invasion or destruction.

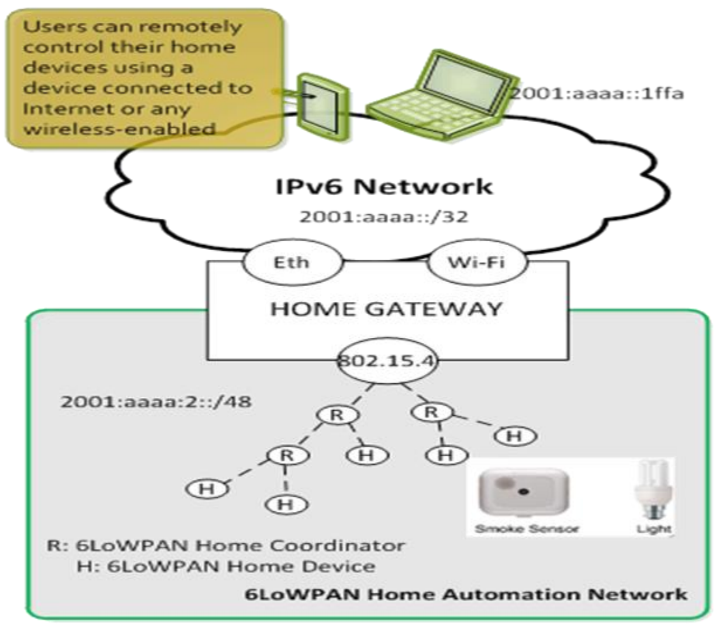


Figure 1. IPv6-USN Home Automation System Architecture

Our goal is to develop a home automation system that is robust, future-prof, low cost, ease to use and has a wide range of capabilities. We belief, 6LoWPAN is a well-suited solution for future IPv6-USN home automation systems. Thus, after having elaborated 6LoWPAN-based IP-USN [26], we argue that it is ready for HA considering the ongoing trend of ever decreasing cost and increasing level of ICT in home environments, as well as the features of IPv6. Our conceptual design of an energy aware IPv6-USN home automation network using 6LoWPAN is depicted in Figure 1.

Our system allows home owners to monitor and control connected devices in the home, through any Wi-Fi enabled device. Additionally, users may remotely monitor and control their home devices using any Internet enabled device. A home gateway is implemented to facilitate interoperability between heterogeneous IPv6-USN with ordinary IPv6 network based on Ethernet and Wi-Fi. It is also facilitate local and remote control and monitoring over the home devices and provide a consistent interface, regardless of the accessing device. Remote user communications traverse the internet until they reach the home gateway. They are then wirelessly transmitted to the home devices using the 6LoWPAN protocol.

2.1. IPv6-USN Home Automation Network

As discussed, the proposed system architecture implements IPv6-USN home automation network with 6LoWPAN protocol. The use of 6LoWPAN offers certain advantages and provides a comprehensive home automation solution. The wireless nature of 6LoWPAN helps overcome the intrusive installation problem with the existing home automation systems identified earlier. The automatic installation and IPv6 addressing of 6LoWPAN provide novel solution end to end connectivity and ubiquitous Internet-based home automation system, helps tackle the expensive and complex architecture problems with existing home automation systems, as identified earlier.

In our architecture, a simple IPv6-USN is connected through home gateway to Wi-Fi and outside IPv6 home network. In order to develop home automation with IPv6-USN, one of the main elements is an appropriate working environment that will support software and hardware requirements. Contiki [13] specially used in lossy networks and provides new low-power standard 6LoWPAN stack. [15] CC2530 has been necessary as a IPv6-USN node due to this device allow the use of Contiki without using an upper layer application. This is, the user can configure the devices and the networks right from the beginning, and configure the network in a proper manner depending on the final application. The automatic installation and IPv6 addressing of 6LoWPAN provide novel solution end to end connectivity for IP-based home automation system.

2.1.1. Home Automation Gateway: Home gateway, as depicted in Figure 2, is based on our edge router [14, 8] with some extension configuration and it is charged with providing interoperability between different connecting networks. The home gateway provides data translation services between Internet based-on Ethernet/Wi-Fi with IPv6-USN. One way to integrate IPv6-USN into home gateway is to provide basic layer 1-3 functionality using a 6LoWPAN network processor, which is used 802.15.4 as low power wireless interface. In order to use IPv6-USN wireless interface with a standard IPv6 protocol stack, our home gateway functionality implemented 6LoWPAN adaption layer, 6LoWPAN–ND, IPv6 RPL routing, IPv6 interconnection.

In order to interconnect IPv6-USN home automation system, based on 802.15.4 and 6LoWPAN, with existing IPv6 Network, based on Ethernet/Wi-Fi, the home gateway can act as a bridge or as a router. In router mode, this home gateway acts as a full-fledged IPv6 router, interconnecting two IPv6 subnets. The home automation subnet is managed by the RPL protocol and the Ethernet subnet is managed by IPv6 NDP. In this mode, home gateway provides a virtual second interface to filter the packet. The router mode allows us to isolate IPv6-USN mesh into its own subnet, therefore clearly identifying the home automation nodes.

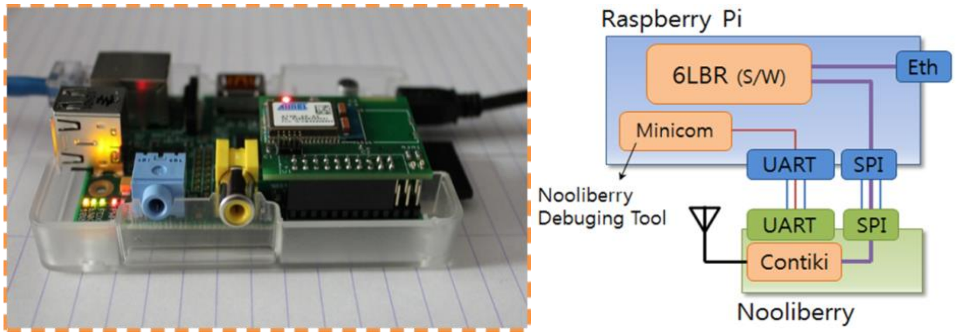


Figure 2. Home Automation Gateway

In bridge mode, this home gateway provide switching capabilities and allowing to interconnect a standard IPv6 based network with a RPL based 6LoWPAN mesh in one subnet. All incoming packets targeting an 802.15.4 interface or incoming multicast packets on the Ethernet interface are forwarded to the home automation segment. Conversely, all incoming packets targeting an Ethernet interface or incoming multicast packets on the LoWPAN inter-face are forwarded to the Ethernet segment. Home gateway is acting as a NDP proxy on the Ethernet side and is using NDP parameters to configure the 6LoWPAN mesh. Source and destination MAC ad-dresses are translated and addresses in ICMPv6 packets are also translated. This mode allow us to seamlessly integrate a 6LoWPAN mesh into an existing NDP based IPv6 network and aggregate several 6LoWPAN meshes into one virtual IPv6 subnet.

2.1.2. IPv6-USN Home Automation Node: The IPv6-USN node for this test-bed is based on TI CC2530 application board [15]. The CC2530, depicted in Figure 3 is true system-on chip (SoC) solution for 802.15.4 application based-on SmartRF05 Evaluation Board. It combines the 2.4 GHz RF transceiver with 8051 MCU, in-system 256 KB programmable flash memory, 8KB RAM, batteries and ambient/environment power source. In this environment, the application boards run Contiki [13], an open source operating system for memory efficient networked embedded system and wireless sensor networks. Contiki provides IP communication, both for IPv4 and IPv6, thanks to the embedded uIPv6 subsystem. The latter is an implementation of an IPv6/6LoWPAN stack, able to transmit IPv6 packets using the IEEE 802.15.4 radio of CC2530 chip. In our home automation system, this node has connections for LED sensor. In normal operation, typical current consumption of this sensor is 70μA and the power consumption can be reduced to less than 0.3μA when powered down.

Figure 3. 6LoWPAN Home Nodes based-on TI CC2530

2.2. Implementation Issues

Most of residences and apartments today's al-ready have Internet connectivity, so, by utilizing the existing Ethernet infrastructure as a backbone, implementing IPv6-USN network in our home automation is satisfies all of the home automation requirements. However, due to the home building characteristics, when implement this in the home automation network, we have been analyzed that there are several issues should be considered related with energy consumption [12].

Table 1. Routing Requirement of Home Automation Applications

Use Case	Requirement
Lighting Application in Action	Support Mobility, Scalability
Energy Conservation and Optimizing Energy Consumption	Constraints-based Routing
Moving a Remote Control	Support Mobility, Convergence Time
Adding A New Module to The System	Convergence Time, Manageability
Healthcare	Constraint-based Routing, Support of Mobility, Convergence Time
Alarm Systems	Scalability, Convergence Time

2.2.1 Routing Consideration: As depicted in Table 1, charterer in 2010, IETF Routing over Low-power and Lossy Network (RoLL) working group was analyzed unique routing requirement for home automation applications in 6LoWPAN described in RFC 5826 [21]. Unlike other application areas analyzed in ROLL, this space is consumer oriented, placing a different emphasis on requirements. Devices are cost sensitive, while at the same time required to be physically small with a long battery life. Important requirements include energy consumption, memory uses, mobility, scalability, and so forth. Successful solutions must take the specific application requirements into account, along with Internet topology and 6LoWPAN mechanisms.

An analysis of existing routing protocol algorithms such as OSPF, OLSR, RIP, AODV, and DYMO along with their applicability to wireless embedded applications is available in [22]. The result concludes that no existing routing protocol meets the requirements of this domain, all of existing algorithms needs modification to be used. Moreover, [23] survey available routing protocol with modification such as Ad-Hoc On-demand Distance Vector Routing (LOAD), Dynamic MANET On-demand for 6LoWPAN Routing (DYMO-low), and Hierarchical routing (HiLow) so it can be implemented in general 6LoWPAN applications. Their conclusion is some routing protocols are confirmed that the routing protocols have own advantages depending upon the application where it they are used.

[24] We then analyzed the available routing algorithms in 6LoWPAN like Hi-Low, Extended Hi-Low, LOAD, M-LOAD, DYMO-Low and S-AODV com-pared on the different metric of the home automation applications routing requirement like energy

consumption, mobility, memory uses, scalability, and so forth. From the comparison, we know that not all routing requirements of home automation applications met by the available routing protocol even with modification, although the vast majority can fulfill. Mobility requirement can be met by LOAD, DYMO-low, S-AODV and MLOAD routing protocol whereas Hi-Low and Extended Hi-Low routing protocol can support the high scalability of the home automation network. Hi-Low and S-AODV can support high convergence due to have low delay and no use local repair when route perform. S-AODV provides benefits in terms of constraints node power consumption and memory, for 6LoWPAN home automation devices. Thus, it is a challenge for us to explore more about RPL [9], a new IPv6 routing protocol for low-power and lossy networks (LLNs) standardized by IETF RoLL working group. The RPL implementation in home automation is a challenge because of generally this routing aims to offer a routing protocol for LLNs, it is by definition not restricted to any specific link layer.

2.2.2 Power Management: IPv6-USN home nodes have specific hardware characteristics and limitations. Most of these nodes have limited available energy. In our case, the home gateway is always connected to USB port, no batteries are needed, but as discussed, our IPv6-USN home nodes based on TI CC2530 need batteries as power source. Although AA batteries that provide the power to the 6LoWPAN-based home nodes are rechargeable, but to save long periods of live without the need of periodically replacing its batteries, we need to have the energy robust home nodes with efficient energy consumption and total energy independence.

To solve energy independence issue, at the first we designed the IPv6-USN home automation system with energy harvesting [25]. We put additional components for power management and energy harvesting needed. Thus, our self-powered IPv6-USN home automation nodes presented in the diagram as depicted in Figure 4. The voltage input from the energy harvester is used to charge the AA battery packs by the first stage DC-DC converter. Then battery voltage is supplied at a stable level to the 6LoWPAN home device main circuit. For power management purposes, the node also needs to continuously monitor the voltage and the current drawn from the battery pack, which is achieved by the energy measurement module.

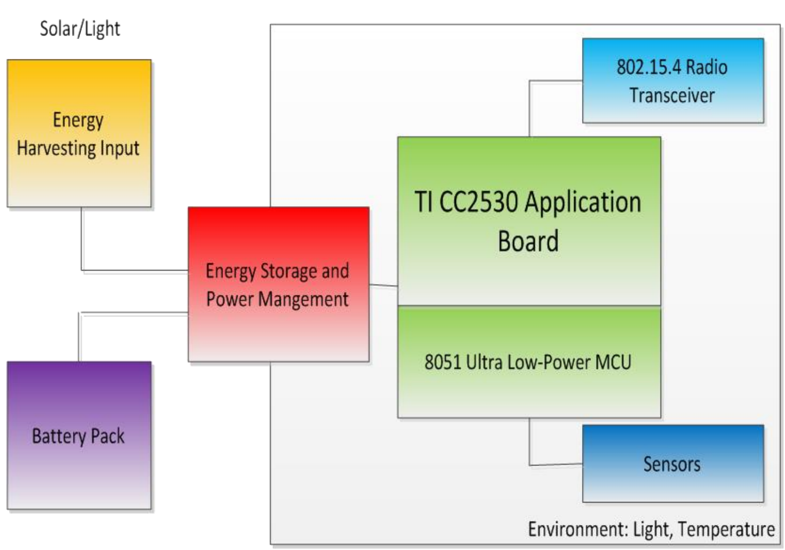


Figure 4. IPv6-USN Home Automation Nodes with Energy Harvesting

Figure 5. Home Automation Network Testbed Environment

3. Setting of Energy Aware Environment

IPv6-USN approach for home automation system is designed for control and monitoring of household devices. We are setting up a home automation scenario test environment to experiment interconnection between home automation devices in ad hoc and simple IPv6-USN network, based on 6LoWPAN over IEEE 802.15.4 protocol, with an existing IPv6 network, based on Ethernet/Wi-Fi. To test interconnection between IPv6-USN node and outside IPv6 network for the first time, we develop LED sensor in our node and IPv6 controller based-on Java application. The remote user's communications transverse the internet until they reach our home gateway. After that, the communications are wirelessly transmitted to the IPv6-USN home nodes. For the desktop application of this testbed implemented by Windows-7 IPv6 stack and for mobile application implemented IPv6 using android API Inet6Address. The captures of our environment are seen in the Figure 5.

3.1. Home Automation Device Interconnection

As described earlier in this paper, TI CC2530 based on Contiki OS wireless sensor networks supporting 6LoWPAN stack is implemented for our IPv6-USN home automation nodes and our border router [14] based on the RapsberryPi (RPi) [27] acting as our home automation gateway. The implementation of these modules is connected to the PC Serial to USB and use hyper terminal to confirm the behavior of each module. In addition, to confirm of the packet, we use 6LoWPAN TI CC2531 module [28] to capture the Air Packet transmission between our home automation nodes. When the IPv6-USN node is up and running in the home automation network, we use packet the packet sniffer to visualize the packet going over the air.

The overall architecture defined as three different kinds of IPv6-USNs: Simple USN, Extended USN, and Ad-hoc USN. A USN is the collection of nodes which share a common IPv6 address prefix (the first 64 bits of an IPv6 address), meaning that regardless of where a node is in a USN its IPv6 address remains the same. An Ad-hoc USN is not connected to the Internet, but instead operates without an infrastructure. A Simple USN is connected network. An Extended USN encompasses the USNs of multiple edge routers along with a backbone link interconnecting them. In this study, we design and implement a system for checking the experiments in two kinds of architecture: ad-hoc and single network. One of the communications within the wireless sensor network, and the other is the wireless sensor network communication with the outside IPv6 network in Internet.

3.1.1. Adhoc IPv6-USN: As described before, for the first we implement and analyze our IPv6-USN Home automation in Ad-hoc 6LoWPAN architecture which is not connected to the outside world, depicted in Figure 6. This implementation is to check the communications within the wireless sensor network (host, router, and coordinator) inside home automation. This is also to check Neighbor Discovery (ND) which is one of important term used with 6LoWPAN. ND is the basic mechanism in 6LoWPAN and defines how routers and hosts communicate with each other on the same link [29]. The general mechanism depicted in Figure 7.

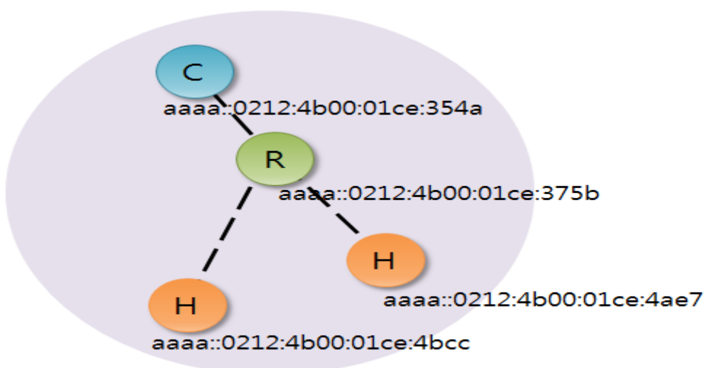


Figure 6. Adhoc IPv6-USN

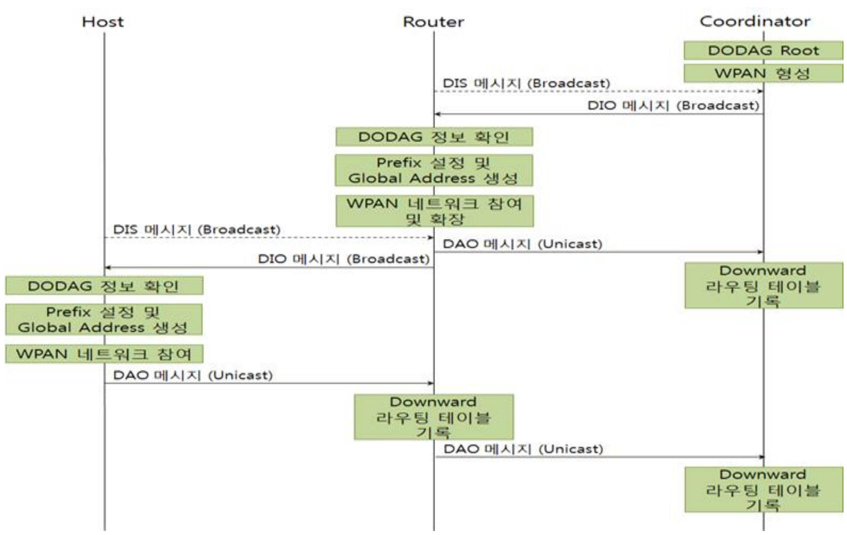


Figure 7. Neighbor Discovery (ND) Mechanism in 6LoWPAN

Our home gateway acting as a coordinator of nodes and set itself as RPL DODAG root for the home automation network. This device has 2 IPv6 addresses, local and global address. Local address of WSN interface is using its MAC address with the address prefix fe80::/64 and for the global address aaaa::/64 prefix is used, only IPv6 global address will be identifiable from the outside IP network. RPL DODAG root will generate and broadcast to inform the DODAG Information object (DIO) message to the home neighboring node through the specific port and wait for a reply. DIO message broadcast home node information to the parent node and transmits a response msessage (ACK) to coordinator, and then the DAG is formed. Connection between coordinator and the home nodes is made after the same procedure as above and be able to communication via UDP uip_udp_packet_send () function.

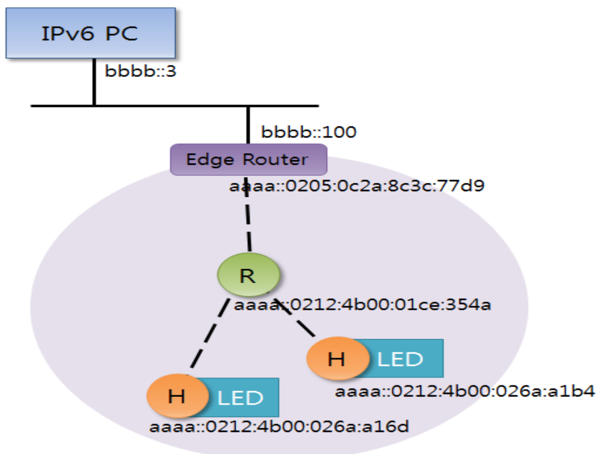


Figure 8. Simple IPv6-USN

3.1.2. Simple IPv6-USN: At this step, to evaluate interconnection between IPv6-USN home automation and outside IPv6 net-work, we created simple network (depicted in Figure 8). For the first, to make sure the network interconnection has been established, we have checked interconnection between home node and outside IPv6 network through ping6 test.

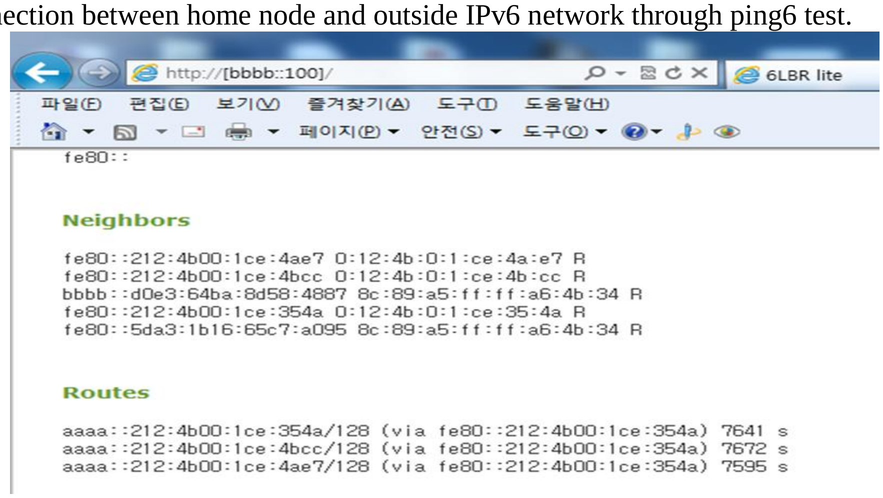


Figure 9. IPv6-USN Routing Table

We then developed a simple webpage to display the status of the current routing tables in our home automation gateway, as we can see in Figure 9. We also developed, LED sensor in our nodes with remote actuator/controller based-on Java application. This application has implemented IPv6 using android API Inet6Address. The captures of our application are seen in the Figure 10. Figure in left shown the first screen of our application and the menu to send command to sensor nodes that will be monitored. The figure in right shown the home node condition resulting on/off commands that sending a message from the remote actuator.

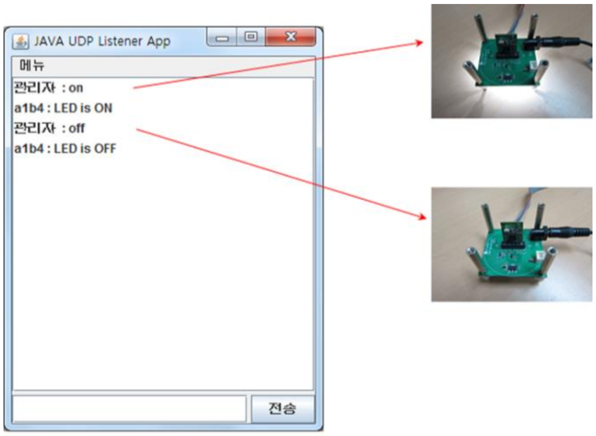


Figure 10. LED Sensor Control Program and The Results

3.2. RPL Routing Approach for Home Automation

RPL allows individual RPL networks to choose different objective functions. A power-constrained network can choose an objective function that optimizes network power consumption and a latency-bound network can choose an objective function that optimizes latency. DIO messages include a list of objective functions that the sending node supports. To provide a baseline for interoperability, RPL includes a default objective function called Objective Function 0 (OF0) that only seeks to optimize hop count. A rank number is assigned to each node which can be used to determine its relative position and distance to the root in the DODAG. For instance, the formula of rank is following [11]:

R(N) = R(P) + rank_increase where:

Rank_increase = (Rf x Sp + Sr) x MinHopRankIncrease

Where:

R(N) : the current node's rank

R(P) : the parent rank value

Sp : step of rank value

Rf :rank factor

Sr : less than or equal to the configured stretch of rank

MinHopRankIncrease : minimum increase in Rank between a node and any of its DODAG parents.

RPL provides dog-legged paths for point to point (P2P) communication between arbitrary sensors in the network, as described in previous section. Since P2P communication is a fundamental requirement for several applications, including some in home automation, extension of the protocol, called RPL-P2P [30] has been considered in order to provide shorter P2P paths between sensors, when available. This mechanism allows routers to discover and establish path(s) to another router, based on a simple reactive mechanism.

RPL-P2P allows a IPv6-USN router to discover on demand routes to one or more IPv6-USN routers in the LLN such that the discovered routes meet specified metrics constraints, without necessary going along the links in an existing RPL DAG. Essentially, when a router needs to discover a path to another router B, router A originates a message similar in functionality to an AODV Route-Request indicating it seeks a path to A [31]. This message is piggy-backed on DIO messages, and disseminated throughout the network using Trickle [32], effectively creating a temporary DODAG rooted in router A. While traveling across the network, the message installs temporary next-hop information towards A on the traversed routers, and may accumulate information about the path travelled so far. Upon receiving such a message, router B sends a message back to A, similar in functionality to an AODV Route-Reply, along the recorded path, thus establishing a path between A and B, and the temporary DODAG eventually expires.

RPL-P2P introduces a new DIO option that specifies the address that should be discovered and records the traversed path. This mechanism defines two new RPL Control Message type, the Discovery Reply Object (DRO) and the Secure DRO. A DRO serves some functionally such as to carry a discovered Source Route from a target to the Origin and to establish a Hop-by-hop Route as it travels from Tar-get to the Origin. The lifetime of the DODAG is restricted to the time of the route request. RPL-P2P allows us to use source routes as well as hop-by-hop routes and it is possible to specify metric constraints for the discovered routes.

Table 2. Features Required for RPL Implementation in Home Automation

Feature	Information
Network Diameter	5 – 10 hops, typical diameter of the most common case in home automation
Network Topologies	LoWPAN network configured according to any of the following topologies - A stand-alone network of 5-10 nodes without home automation gateway - A connected network with one home automation gateway
Network Purposes	- direct control - monitoring
Home Automation Devices Memory	Majority with very low memory capacity
Traffic Characteristic	The majority of traffic is light-weight point-to-point control style; e.g Put-Ack or Get-Response Exceptions: bulk data transfer for firmware update and logging
Communication Paradigm	- Source-sink (SS) communication paradigm - Publish-subscribe (PS, or pub/sub) communication paradigm - Peer-to-peer (P2P) communication paradigm - Per-to-multi peer (P2MP) communication paradigm - N-cast communication paradigm

3.2.1. RPL-P2P Implementation: Until now the IETF working group still discussing issue to provide guidance for selection and the use of RPL protocol set in home automation control [33]. Some of feature required that we need to consider when implement RPL protocol in IPv6-USN home automation network depicted in Table 2.

In the case of SS/PS paradigm over an IPv6-USN network to a server reachable via a home automation gateway, the use of default RPL is recommended. Given the low resources of the devices, source routing will be used for the message from the outside IPv6 Network to the destination in the IPv6-USN network. No specific timing constraints are associated with the SS/PS type messages so network repair does not violate the operational constraints. When no

SS/PS paradigm traffic takes place, it is recommended to load RPL-P2P code into the network stack to satisfy memory requirement by reducing code.

Due to considering limited memory of a majority of the home devices, we need to design RPL-P2P with source routing in non-storing mode and a network diameter limited to 10 hops, which consider the most common cases in home automation control networks. We also need to design our home gateway to be aware of sleeping nodes in order to support the distribution of updated global prefixes to such sleeping nodes. Furthermore, when operating RPL-P2P on a stand-alone basis, there is no authoritative root node maintaining a permanent RPL DODAG. For the path metrics Objective Function Zero (OF0) is preferred to use as objective function (OF) even though [10] provides ETX as another option, because OF0 select the path to the root with minimum hops. Then, since RPL-P2P only creates DODAGs on a temporary basis during route repair, there is no need to repair DODAGs. In order to support low-cost devices, we set RPL security not to use timestamp (T='0'), use CCM with AES-128 (algorithm ='0'), use group key (KIM='10'), and use MAC-32 (LVL='0'). Finally, due to deployment based on IEEE 802.15.4, we need to apply security at layer 2 using the mechanisms provided by the standard [34] and our home gateway enforces access policies to limit access to the trusted LLN domain from the home network.

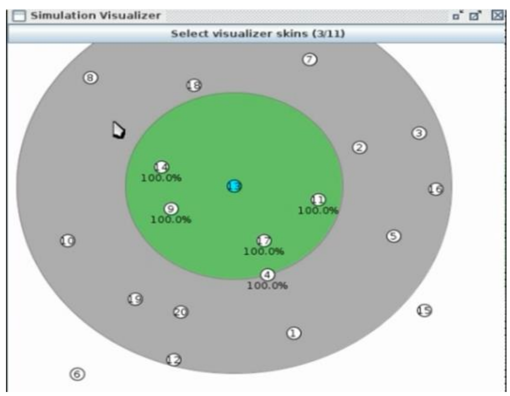


Figure 11. Cooja Simulator for Contiki

In order to study more about the behavior of RPL and RPL-P2P, as depicted in Figure 11, we use Cooja Simulator [35] which provides a set of visualizer module for Contiki OS. As described in previous section, Contiki was initially chosen because it includes an IPv6 stack with 6LoWPAN support, as well as ContikiRPL [36], an implementation of default RPL, which was used as basic for our RPL-P2P implementation.

3.2.2. Routing Performance Metrics: The IPv6-USN home nodes are small and operate with very small batteries that provide power for only a very limited time. However, by set of duty cycling in proper way, we can significantly reduce energy consumption of home node. There are two techniques of duty cycling, sampled listening [37] and scheduling [18]. For instance Contiki uses sampled listening duty cycling. There are two (2) crucial duty cycling parameters that we need to evaluate in term of energy consumption of IPv6-USN nodes: DIO Interval Minimum and Frequency of Application messages.

The more quickly the DIOs are transmitted the more quickly the network gets converged but the more energy consumption needed. A careful tweaking of this parameter is necessary for improved performance keeping in home automation area. In Contiki this parameter is controlled by Trickle timer RPL_DIO_INTERVAL_MIN. The value of Trickle timer starts from the lowest possible value Imin and is doubled each time it is transmitted until it reaches its maximum possible value of Imax. The value of Imin is determined by the RPL DIO interval Mini-mum and computed as:

Imin = 2 ^ RPL_DIO_INTERVAL_MIN
So, if we set RPL_DIO_INTERVAL_MIN = 12
Then, Imin = 2 ^ 12 = 4096 ms = 4 s
This is the smallest interval between two DIOs provided RPL_DIO_INTERVAL_MIN equal 4.

The frequency of application messages is the rate at which a node sends application level messages to the router. The more often the application sends messages the more likely for it to drain the network resources because application packet transmissions takes considerable amount of energy, bandwidth for IPv6-USN home automation. We tune this parameter by setting SEND_TIME in our sample Contiki application.

We design a sample network in the Cooja Simulator, thanks to [31] for sharing the RPL-P2P implementation source code. We use a Cooja plugin called Contiki Test Editor to measure the simulation time and stop the simulation after specified time. This plugin also creates a log file (COOJA.testlog) for all the outputs from the simulation which we will analyze at the end of simulation. In order to give lossyness condition as well as in real implementation, we use the Cooja Unit Disk Graph Medium which introduces lossyness to respect relative distances of home nodes. The parameters for simulation and its environment are shown in Table 3. Finally, we then evaluate the performance of OF0 in terms of three metrics: Energy Consumption, Network Latency, and Packet Delivery Ratio to propose energy efficient oriented routing.

Table 3. Simulation Parameters

Parameters	Value
Delay Threshold	2 s
PDR Threshold	85%
RPL MOP	UPWARD_ROUTE, DOWNWARD_ROUTE
DIO Min	4-16
RX Ratio	30-100%
TX Ratio	100%
TX Range	50m
Interference Range	55m
Simulation Time	1 Hr
Client Nodes	10

The first metric performance metric is Energy Consumption. To make good energy estimation we use percent radio on time of the radio which dominates the power usage in sensor nodes. Furthermore we take the average percent radio on time for all the nodes in the whole network setup. To compute the power consumption we use the mechanism of Power-trace system available in Contiki [18, 19]. Powertrace is a system for network-level power profiling for low-power wireless networks which estimates the energy consumption for CPU processing, packet transmission and listening. This mechanism maintains a table for the time duration a component like CPU, radio transmitter was on. Based on this computation we calculate the percentage of radio on time duration. We then compute average current consumption for radio transmission and listening as these are the most energy consuming component.

The second performance metrics of interest in this research is Network Latency. The latency is defined as the amount of time taken by a packet from node to reach the router and is the average of the latencies of all the packets in the network from all the nodes. The Network Latency can be computed using the following equation

$$\text{(Eq.1) } Total\ Latency = \sum_{k=1}^{n} (\text{Recv Time (k)} - Sent\ Time\ (k))$$

Where:
n : total number of packets received successfully
the timing information is provided by Cooja Simulator

And then to compute the average Latency we divide the Total Latency from Eq.1 by number of total received packets. The total number of received packets is counted at the router.

$$\text{(Eq.2) } Average\ Latency = Total\ Latency / Total\ Packets\ Received$$

The last metric is Packet Delivery Ratio (PDR) and is defined as the number of received packets at the node to the number of sent packet to node. We take average PDR of all the packets received successfully at the node. To compute the average PDR we measure the number of sent packets from all the nodes to the router and divide it by the number of successfully received packets at the router.

$$\text{(Eq.3) } Average\ PDR = (Total\ Packets\ Received / Total\ Packets\ Sent)\ x\ 100$$

For our note, the probability of success of packet reception at a node increases as node's distance (D) decreases towards the other node in its transmitting range (R). Thus the minimum probability of success would be at the edge of transmitting range R and equal to RX ratio. Whereas the probability of success of packet reception at a node at a distance D can be computed as:

$$\text{(Eq.4) } Probability\ of\ success = 1 - (D^2 / R^2)\ x\ (1 - RX)$$

Where:
D : the distance between the two nodes and D is less than or equal to R.
R : the reception range and greater than 0
RX : the success ratio

4. Evaluation and Analysis

In this section we first evaluate the routing performance in terms of performance metrics of interest: energy consumption, network delay, and packet delivery rate. This evaluation based on our configuration of routing parameters to observe this cause and effect on performance metrics of interest.

4.1. Energy Consumption Measurement

As we know, to have home automation systems which have long periods of live, the power management is important. In our implementation, the home gateway is always connected to USB port, no batteries are needed, but as discussed, our IPv6-USN home node based on TI CC2530 need batteries as power source. As we describe in previous section, to compute the power consumption we use the mechanism of Powertrace system available in Contiki.

To measure the current consumption of our node, we then measure the voltage of a resistor 10 Ω placed in series with the node. It is determined as long as I below than 30 mA. However, the current consumption of our IPv6-USN home node is almost independent of the input voltage. Once the current is determined, the average current consumption can be found using the general formula (Eq.6).

$$\text{(Eq.5)}\ I_{avg} = \sum_{i=0}^{n}\left(\frac{T_i}{P_i} * I_i\right) + \left(1 - \sum_{i=0}^{n}\left(\frac{T_i}{P_i}\right)\right) * I_{sleep}$$

Where,
Ti = Time for which device consumes average cur-rent Ii
Pi = Total Time period for which average consump-tion is measured
Isleep = Current consumption while in sleep mode
Iavg = Average current consumption over periode Pi

Knowing Ii, Isleep, Ti we can find Iavg based on the period of active sequences. As final step, calculate the total life time of the our IPv6-USN home node, know that,

$$\text{(Eq.6)}\ \frac{Battery\ Capacity\ [mAh]}{Average\ Current\ [mA]} = Lifetime\ [h]$$

The battery capacity will differ from one battery type to another. In our system, two AA sizes Duracell Deluxe batteries are used, the characteristics of this battery are shown in Table 4. The energy consumption and the power input of IPv6-USN home automation node depend largely on the application and the sensor used. When the nodes are up and running in the small home automation network, the average current consumption during the 292.5 ms is 34.6 mA and the sleep current of the system was measured to be 4.8 uA. The detail estimates of the energy consumption for CPU processing, packet transmission and listening for our node shown in Table 5.

Table 4. Battery Characteristics

Max Charge Voltage	1.5 V
Nominal Voltage	1.2 V
Nominal Capacity	2850 mAh
Standard Charge	270mA/16 h
Fast Charge	2700mA/ 1.1 h

Now proceed to find the total average current consumption, based on (Eq.5) for the ~5000 ms (5s) packet interval SEND_TIME, as we set for Imin value in previous section. Substituting in the formula values from Table 4 provides:

$$\left(\frac{292.5}{5000} * 34.6\right) + \left(1 - \frac{292.5}{5000}\right) * 0.0048\ mA = 2.212\ mA$$

Based on (Eq.6) we can now be used to calculate the expected lifetime of the system:

$$\frac{2850\ mAh}{2.212\ mA} = 1288\ hrs = 53\ days$$

Hence, if the home node is configured to transmit one packet every 5 seconds, with small application acknowledgment and no data polling, the board can operate for maximum 53 days with two AA Duracell Deluxe batteries. In our system, to reduce energy consumption of an IPv6-USN home node, we propose the use of RPL routing protocol with energy efficient oriented algorithm. We compare the next path by calculation of weighting value (@) with link performance metrics expect (ETX) and the node remaining energy respectively and then select the best path.

path=@ x ETX+(1-@)/(Remaining Energy) …………………………………… (Eq.7)

To Find @, we need to have duty cycle that consider link performance metrics by setting number of DIO Interval Minimum in proper way. Because it will seriously affect to network connectivity, to avoid undesirable routing instabilities resulting in increased latencies and packet loss.

Table 5. Current Consumption Detail

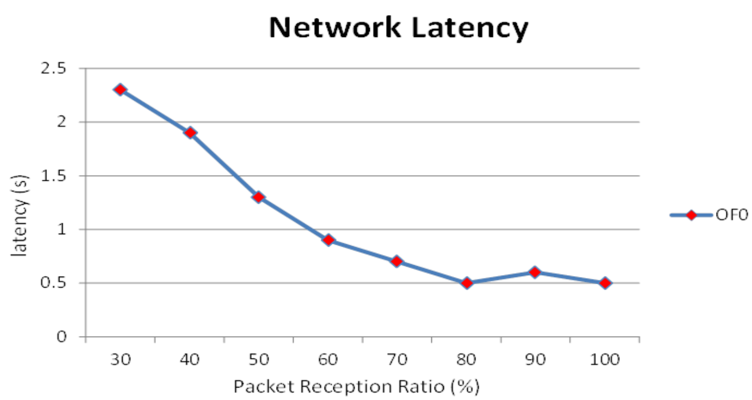
Event	Description	Duration [ms]	Current [mA]
1.	Waking Up	45	0.68
2.	Processing data packet	25.6	30.2
3.	Transmit packet and receive ACK	16.6	78.6
4.	Request and receive ACK	21	98.6
5.	Post processing packet	18	29.4
6.	Request Data (Single Poll)	29	94.3
7.	Prepare to Sleep	6	26.4
8.	Set up radio	4.5	24.2
9.	Start CSMA-CA	5.2	90.8
10.	Switch from RX to TX	3	64.4
11.	Switch from TX to RX	2.9	62.3
12.	Prepare for deep Sleep	21	24.2

4.2. Packet Delivery Rate and Latency Measurement

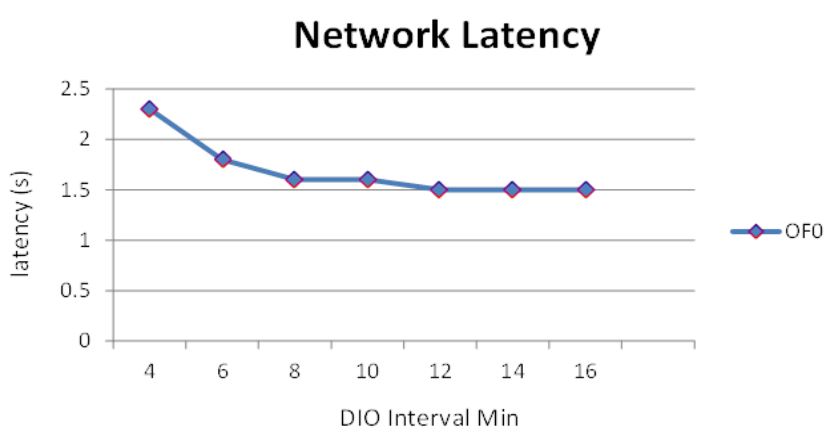
As we described in previous section, because we proposed to implement smart and energy efficient orienter RPL protocol to our IPv6-USN home automation network, we used OF0 as our objective function. OF0 select the path to the root with minimum hops. This can be achieved by comparing the rank of parents. By default, Contiki uses 16 bit rank in units of 256 (min_hoprankinc) which allows a maximum of 255 hops.

The objective of our experiment is to evaluate the objection function OF0 in terms of Energy Consumption, Packet Delivery Ratio of the network for the upward traffic with respect to different levels of lossyness. We repeat the simulation for different RX values ranging 30 to 100%. We set Send Packet Interval to 4s and Start Delay to 60s. The average values of Network Latency and PDR are computed using equation Eq.2, Eq.3 and Eq.4 respectively, while Energy Consumption is computed using Powertrace mechanism. The result is shown in Figure 12 and 13.

Figure 12(a) is shown the Network Latency performance from Packet Reception Ratio 30% to 100%, the Latency is going decrease because the more lossy links decrease (RX Ratio increase). The average Network Latency of our Objection Function is 1.0875s. This is considerable different because the network size and the longest route possible is 10 hop while in the real home automation scenario it can be smaller. The average Network Latency decreases from 2.4s to 1.6s for DIO Interval Minimum between 8 and 16 respectively, as depicted in Figure 12(b). The decreasing of Network Latency because of the packet buffering decreases and radio collision also decrease and as a result the packet reaches the destination relatively quickly than before.



(a) Latency Performance to Packet Reception Ratio

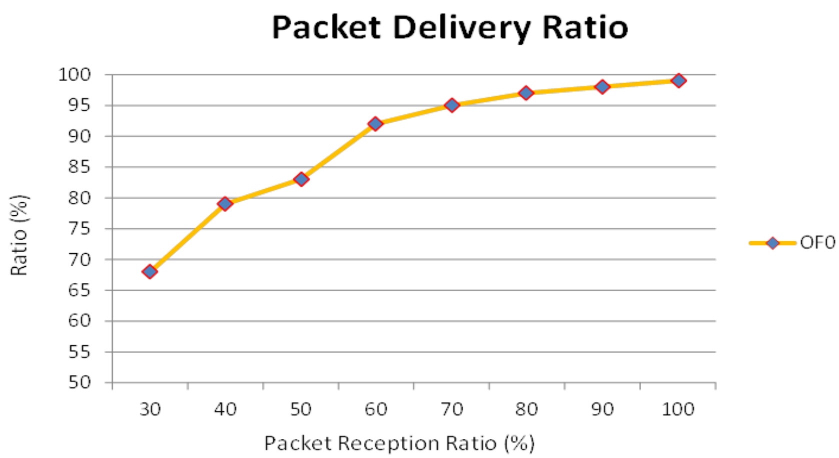


(b) Latency Performance to Number of DIO Interval Minimum

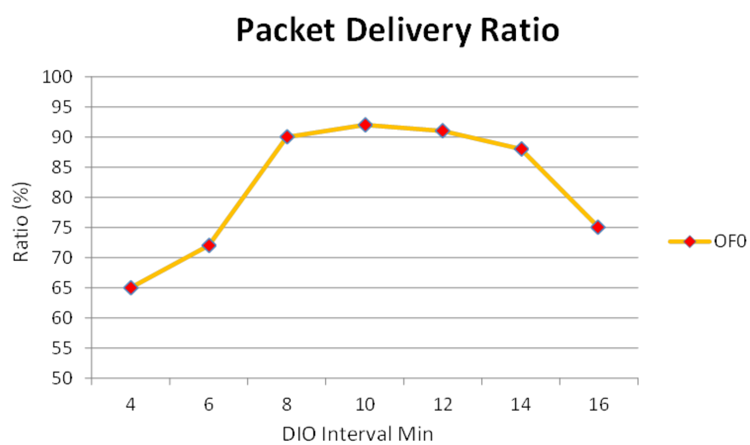
Figure 12. Latency of Objective Function

Packet Delivery Ratio is very important metric because is used by sensor node to compute the best route, optimum transmission rate and power consumption [20]. From Figure 13(a) above, we can know that the PDR of our Objection Function is 88.875%. We need to note that the different in PDR for Objective Function becomes less as the lossyness in the radio medium decreases. In Figure 13(b) the PDR is below 85% at beginning, for DIO Minimum Interval 4-6 which mean due the RPL-P2P network suffer collisions and therefore the PDR is poor. How-ever as we increase the DIO interval 8-14 RPL-P2P provides a good PDR of more than 90%. We can also observe that PDR falls for DIO Interval Minimum of 16 and greater. The reason is that the value of DIO

Interval Minimum higher than 16 does not provide a quick network convergence. Consequently the network is not converged fully and as a result incurring packet loss to some of destinations in the network. We conclude that to achieve a high PDR for RPL-P2P in home automation the recommended DIO Interval Minimum is between 8 and 14.



(a) PDR to Packet Reception Ratio



(b) PDR to Number of DIO Interval Minimum

Figure 13. Packet Delivery Ratio (PDR) of Objective Function

The tweaking of trickle time [18] parameter causes a tradeoff between our proposed performance metrics. We summarize the observations made in Table 4-2.

Table 0-1. Recommended Values for DIO Interval Minimum

Performance Metric	DIO Interval Min	Energy Consumption
Network Latency	8-16	decrease 15-20%
PDR	8-14	decrease 15-20%

5. Conclusion and Future Works

We have presented in this paper our work to constructing energy aware home automation within IPv6-USN architecture. Our proposed system enables home users to check status of the home automation devices based-on IEEE 802.15.4 low-power wireless network standard and control them remotely using Home Wi-Fi and Internet. In Table 6, the detail comparison of our proposed solution with relevant works in wireless home automation system is shown.

Table 6. Feature in Existing and Proposed System

No	System	Access		Routing	Energy
		Direct control at home	Internet		
1	ZigBee, Khusvinder, et al. 2009 [2]	√	-	-	-
2	6lowpan. Dorge et al. 2011 [5]	√	√	-	-
3	6lowpan. D. S. Tudose et al. 2011 [6]	√	√	-	-
4	Our Previous Proposed System [25]	√	√	RPL Routing	Energy harvesting
5	Our Proposed System	√	√	Energy-efficient oriented RPL Routing	Energy harvesting

We also have presented our strategy to implement smart and energy-efficient oriented routing in our IPv6-USN home automation network. By having efficient control transmission and optimal objective function, we can maintain operation performance level of our IPv6-USN home automation with energy consumption reduction around 20%, average latency about 1.0875s, and packet delivery rate above 88.875%.

This paper is just one part of our energy robust IPv6-USN home automation. In our future work, we have plan to considering the web-based constrained application protocol and explore more about the possibility to implement software defined networking concept to increase the robustness of our system.

Acknowledgements

This research was supported by the Basic Science Research Program through the National Research Fund of Korea (NRF) funded by the Ministry of Education, Republic of Korea (2012R1A1A2007014).

References

[1] N. Sriskanthan, F. Tan and A. Karande, “Bluetooth based home automation system”, Microprocessors and Microsystems, vol. 26, no.6, **(2002)**, pp. 281-289.

[2] K. Gill, S.-H. Yang, F. Yao and X. Lu, “A ZigBee-based home automation system”, IEEE Transactions on Consumer Electronics, vol. 55, no. 2, **(2009)**, pp. 422–430.

[3] N. Kushalnagar, G. Montenegro and C. Schumacher, “IPv6 over low-power wireless personal area networks (LoWPANs): overview, assumptions, problem statement, and goals”, RFC 4919, **(2007)**.

[4] M. Kovatsch, M. Weiss and D. Guinard, “Embedding internet technology for home automation”, In Proceedings of the 15th IEEE International Conference on Emerging Technologies and Factory Automation (ETFA ’10), **(2010)** September.

[5] B. M. Dorge and T. Scheffler, “Using IPv6 and 6LoWPAN for home automation networks,” In Proceedings of the 1st IEEE International Conference on Consumer Electronics (ICCE ’11), **(2011)** September, pp. 44–47.

[6] D. S. Tudose, A. Voinescu and M.-T. Petrareanu, “Home automation design using 6LoWPAN wireless sensor networks”, Proceedings of the 7th IEEE International Conference on Distributed Computing in Sensor Systems (DCOSS ’11), **(2011)** June, pp. 1–6.

[7] The New Zigbee IP Spesification, IPv6 Control for Low-Power Devices”, ZigBee Alliance, March (**2013**), http://www.zigbee.org/Specifications/ZigBeeIP/Overview.aspx.

[8] A. Musa, A. F. P. Negara, S. Oh and D. Choi, “A design of 6LoWPAN RPL border router with multi-uplink interface: ethernet and Wi-Fi”, Proceedings of International Conference on Internet Services Technology and Information Engineering (ISTIE '13), **(2013)**.

[9] T. Winter, P. Thubert and RPL Author Team, “RPL: IPv6 Routing Protocol for Low power and Lossy Networks”, RFC 6550, **(2012)**.

[10] J. Vasseur, M. Kim and K. Pister, “Routing Metrics Used for Path Calculation in Low- Power and Lossy Networks”, RFC 6551, **(2012)**.

[11] P. Thubert, “Objective Function Zero for the Routing Protocol for Low-Power and Lossy Network (RPL)”, RFC 6552, **(2012)**.

[12] A. Musa, S. Oh and D. Choi, “6LoWPAN-based Wireless Home Automation: From Secure System Development to Building Energy Management”, The Smart Computing Re-view, vol. 3, no. 2, **(2013)** April, pp. 123-138.

[13] A. Dunkels, “Contiki-a Lightweight and Flexible Operating System for Tiny Networked Sensors”, **(2004)**.

[14] A. Musa, A. Fahmi P. N, S. Oh and D. Choi, “A Design of 6LoWPAN RPL Border Router with Multi-Uplink Interface:Ethernet and Wi-Fi”, Advanced Science Letter, vol. 20, no. 1, **(2014)** January, pp. 55-60.

[15] “A True System-on-Chip Solution for 2.4-Ghz IEEE 802.15.4 and ZigBee Applications”, TI CC2530.

[16] G. Montenegro, N. Kushalnagar, J. Hui and D. Culler, “Transmission of IPv6 Packets over IEEE 802.15.4’, RFC 4944, **(2007)**.

[17] J. Hui and P. Thubert, “Compression Format for IPv6 Datagrams over IEEE 802.15.4-Based Networks, RFC 6282, **(2011)**.

[18] A. Dunkels, J. Eriksson, N. Finne and N. Tsiftes, “Powertrace: Network-level Power Profiling for Low-power Wireless Networks”, Maret **(2011)**.

[19] A. Dunkels, F. Osterlind, N. Tsiftes and Z. He, “Software-based on-line energy estimation for sensor nodes”, In Proceedings of the 4th workshop on Embedded networked sensors, New York, NY, USA, **(2007)**.

[20] R. Draves, J. Padhye and B. Zill, “Routing in multi-radio, multi-hop wireless mesh networks”, Proceedings of the 10th Annual International Conference on Mobile Computing and Networking, New York, NY, USA, **(2004)**, pp. 114–128.

[21] A. Brandt, J. Buron and G. Porcu, “Home Automation Routing Requirements in Low-Power and Lossy Networks”, RFC 5826, **(2010)**.

[22] P. Levis, A. Tavakoli and S. Dawson-Haggerty, “Overview of Existing Routing Protocols for Low Power and Lossy Networks”, Internet Draft, IETF, April 2009. http://tools.ietf.org/html/draft-ietf-roll-protocols-survey-07.

[23] K. Vinai and T. Sudarshan, “Routing in IPv6 over Low-Power Wireless Personal Area Net-work (6LoWPAN): A Survey”, Journal of Computer Networks and Communications, vol. 2012, article ID 316839, doi:10.1155/2012/316839, **(2012)**.

[24] A. Musa, S. Oh, A. Fahmi P. N. and D. Choi, “Routing Approach in IPv6 Ubiquitous Internet-Based Home Automation Network”, Proceedings of Future Information Communication Technology and Applications, Lecture Notes in Elec-trical Engineering, vol. 235, **(2013)**, pp.189-197.

[25] A. Musa, S. K. Oh, A. Fahmi and D. Choi, ”Battery-less 6LoWPAN-based Home Automation by use of Energy Harvesting”, International Journal of Distributed Sensor Networks, vol. 2013, Article ID 924576, 8 pages, **(2013)**.

[26] S. Oh, A. Musa and D. Choi, "6LoWPAN Based IP-USN System Implementation for Improving Scalability", The Journal of Korea Information and Communications Society, vol. 38B, no. 9, **(2013)**, pp. 687-699.
[27] "RaspberryPI, a Credit-card Sized Linux Computer". http://elinux.org/RPi_Hub.
[28] "A USB enabled true system-on-chip (SoC) solution for IEEE 802.15.4, ZigBee and RF4CE applications", TI CC2531.
[29] Z. Shelby, S. Chakrabarti, E. Nordmark and C. Bormann, "Neighbor Discovery Optimization for IPv6 over Low-Power Wireless Personal Area Net-works (6LoWPANs), RFC 6775, **(2012)**.
[30] M. Goyal, E. Baccelli, M. Philipp, A. Brandt and J. Martocci, "Reactive Discovery of Point to Point Routes in Low-Power and Lossy Networks, RFC 6997, **(2013)**.
[31] E. Baccelli, M. Philipp and M. Goyal, "The P2P-RPL Routing Protocol for IPv6 Sensor Networks: Testbed Experiments", Proceedings of International Conference on Software, Telecommunications, and Computer Networks, **(2011)**, pp. 172-177.
[32] P. Levis, T. Clausen, J. Hui, O. Gnawali and J. Ko, "The Trickle Algorithm", RFC 6206, **(2011)**.
[33] A. Brandt, E. Baccelli, R. Cragie and P. van der Stok, "Applicability Statement: The use of the RPL protocol set in Home Automation and Building Control", Active Internet Draft, February 2014, http://www.ietf.org/id/draft-ietf-roll-applicability-home-building-02.txt.
[34] D. Whiting, R. Housley and N. Ferguson, "Counter with CBC-MAC (CCM)", RFC 3610, **(2003)**.
[35] "Cooja Simulator", https://github.com/contiki-os/contiki/wiki/An-Introduction-to-Cooja.
[36] N. Tsiftes, J. Eriksson and A. Dunkels, "Low-power wireless IPv6 routing with ContikiRPL", In Proceedings of International Conference on Information Proceeding in Sensor Networks, ACM/IEEE, **(2010)**.
[37] J. W. Hui and D. E. Culler, "IP is dead, long live IP for wireless sensor networks", In Proceedings of the 6th ACM conference on Embedded network sensor systems, New York, NY, USA, **(2008)**, pp. 15–28.

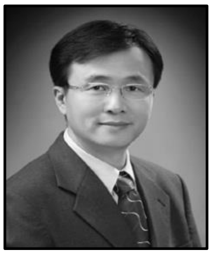
Authors

Ardiansyah Musa, he received the B.Eng in Computer Engineering from University of Indonesia in 2010 and after that he work as an Instructor in same university. Since 2012, he has been with the Advanced Network Systems Lab, Chonnam National University, Gwangju, Korea, pursuing a Master degree in Electronics & Computer Engineering. His main research interests include internet of things for future internet.

Dokyeong Lee, he received the B.Eng in Information & Communication Engineering from Honam University in early 2013. Since 2013, he has been with the Network Systems Lab, Chonnam National University, Gwangju, Korea, pursuing a Master degree in Electronics & Computer Engineering. His main research interests include sensor network development and internet of things.

Isyana Paramitha, she is student in Computer Engineering, University of Indonesia. Since beginning of 2014, she has been with the Network Systems Lab, Chonnam National University, Gwangju, Korea, coming as a guest researcher. Her main research interests include network design and management.

Kalamullah Ramli, nicknamed- Muli, he is a Professor on Computer Engineering, University of Indonesia. He finished his Master in Telecommunication Engineering at University of Wollongong, NSW, Australia in 1997. He then continued his Doktorarbeit on Computer Networks at Universitaet Duisburg-Essen, NRW, Germany, and obtained his Dr.-Ing. in year 2003. His main research interests include embedded system and computer communications.



Deokjai Choi, he received the B.S., M.S in Computer Science from Seoul National University, Korea in 1982 and from KAIST 1984 respectively and also received Ph.D. in Computer Science and telecommunication from University of Missouri-Kansas City, USA in 1995. Since 1996 until now, he has been serving as Professor in School of Electronics and Computer Engineering, Chonnam National University, Korea. His main research interests include topics on context-awareness, pervasive computing, sensor network, future internet, and IPv6.