

## Research Article

# Battery-Less 6LoWPAN-Based Wireless Home Automation by Use of Energy Harvesting

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Being one of the current main technologies, wireless sensor network (WSN) is absolutely critical and plays an increasingly important role in the development of a wide range of data acquisition, processing, and control applications. One interesting challenge application of the WSNs is Internet-based home automation system. The rapid expansion of IPv6, moreover, after IETF defined 6LoWPAN as a technique to apply IPv6 into WSNs standard, added potential for Internet paradigm communication, control, and monitoring of home automation devices from anywhere on the globe. The use of 6LoWPAN communications technology also helps lower expense of the system and decreases complexity of the home automation architecture. When implementing 6LoWPAN-based home automation system, the important feature is long periods of life to support full automation without the need for periodically replacing its batteries. To have this, 6LoWPAN home devices with total energy independence are needed. By using additional components for power management and the implementation of 3 V, 70 mA small polycrystalline silicon solar cell for solar energy harvesting, we can have home automation node for an indefinite amount of life time.

## 1. Introduction

Wireless sensor networks (WSNs) are employed in a wide range of data acquisition, processing, and control applications. Their advantages over traditional wired sensor networks include mobility, increased reliability, easier installation, and lower deployment cost. One interesting challenge application of the WSNs is home automation system. There are so many definitions of home automation available in the literature. [1] Bromley et al. describe home automation as the introduction of technology within the home to enhance the quality of life of its occupants, through the provision of automation services such as multimedia entertainment, telehealth, and energy conservation. The home environment has seen a rapid introduction of Internet protocol enabled technology. This technology offers new and exciting opportunities to increase the connectivity of devices within the home for the purpose of home monitoring and automation. Recently, home automation systems have been challenged with the two outstanding needs: the need for the high interoperability between home devices and the need for user

interfacing and accessing to the system from different end points.

There has been significant research in the field of home automation. The authors of [2] developed an embedded board that physically connected all the home automation devices through integration with a personal computer based web server and then provided remote access to the system. However, the system requires an intrusive and expensive wired installation and the use of a high end computer. The authors of [3] introduced a Bluetooth based home automation system, by connecting each home device to a local Bluetooth subcontroller. 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. The authors of [4] defined a ZigBee-based home automation networks, a flexible home automation architecture, and through adoption and evaluated the potential of ZigBee. However, this system still has problem with evolvability, scalability, and internet integration. End-to-end paradigm where only

the end-to-end points participate in the application protocol exchanges which cannot be implemented with this solution. ZigBee needs intermediate local proxy server to enable communication between embedded home devices and Internet.

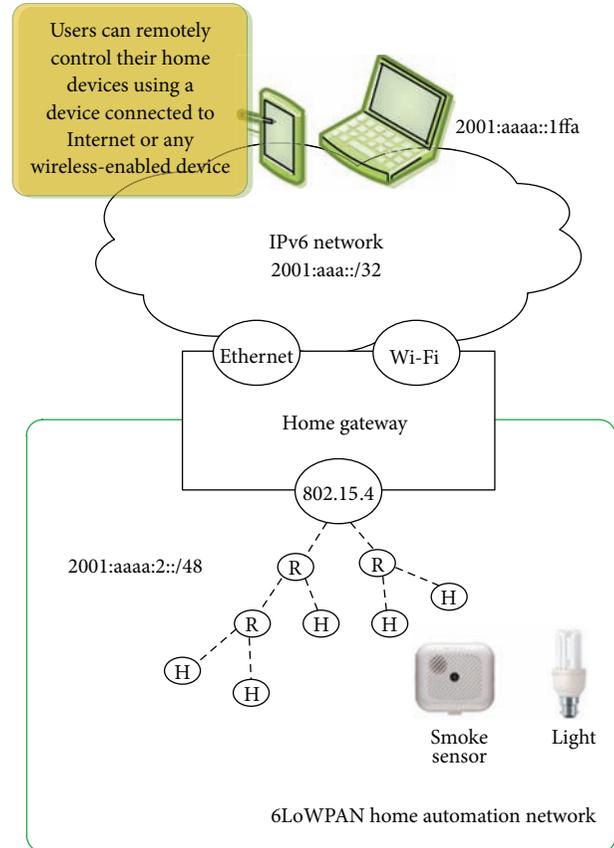
A possible strategy to solve the problem listed above could be adopting 6LoWPAN. The introduction of 6LoWPAN protocol enables home automation device based on 802.15.4 wireless sensor network standard to be compatible with IPv6 while maintaining low-power consumption and taking the nature of wireless networks into account [5]. The 6LoWPAN standard also promises the fulfillment of the emerging trend of embedded Internet technology in all aspects of everyday life [6], mainly because of its low costs, low-power, scalability, possibility to adapt to existing technologies. The authors of [7, 8] tried to implement 6LoWPAN for home automation network, but between the features of any 6LoWPAN-based home automation system are long periods of life without the need for periodically replacing its batteries. To have this, we need to design the 6LoWPAN home device with total energy independence. In this case, additional components for energy harvesting are needed, and the power management of the 6LoWPAN home devices is an important topic.

In this paper, we presented and analyzed implementation of energy harvesting in the 6LoWPAN-based home automation infrastructure. The rest of this paper is divided into five sections. Section 2 presents our 6LoWPAN-based home automation system. Section 3 discusses setting environment of our system design for 6LoWPAN-based home automation energy harvesting. Finally, Section 4 will evaluate and Section 5 will conclude our research in this system.

## 2. Overview of Our 6LoWPAN-Based Home Automation System

This section describes our conceptual design of a flexible home automation network using 6LoWPAN (see Figure 1). Our goal is to develop a home automation system that is robust, flexible, easy to use and has a wide range of capabilities. The 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 6LoWPAN and ordinary IPv6 network based on Ethernet and Wi-Fi. It also facilitates local and remote control and monitoring of the home devices and provides 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.

**2.1. 6LoWPAN Home Automation Network.** As discussed, the proposed system architecture implements 6LoWPAN home automation network. The use of 6LoWPAN offers certain advantages and provides a comprehensive home automation solution. This technology is designed to be used on applications that required low data rate, low cost, low-power consumptions, and two-way wireless communications [9].



R: 6LoWPAN home coordinator  
H: 6LoWPAN home device

FIGURE 1: 6LoWPAN home automation system architecture.

The wireless nature of 6LoWPAN helps overcome the intrusive installation problem with the existing home automation systems identified earlier. The 6LoWPAN devices based on IEEE 802.15.4 standard theoretically provides 250 kbps data rate and 127 bytes frame size; this would need a considerable amount of compression for controlling most home automation devices using IPv6. The automatic installation and IPv6 addressing of 6LoWPAN provide novel solution to end-to-end connectivity and ubiquitous Internet-based home automation system and help tackle the expensive and complex architecture problems with existing home automation systems, as identified earlier.

**2.2. Home Gateway.** Home gateway, as depicted in Figure 2, is our edge route [10], and it is charged by providing interoperability between different connecting networks. The home gateway provides data translation services between Internet based on Ethernet/Wi-Fi and 6LoWPAN networks based on 802.15.4. One way to integrate 6LoWPAN into home gateway is to provide basic layer 1–3 functionality using a 6LoWPAN network processor, which used 802.15.4 as low-power wireless interface. In order to use 6LoWPAN wireless interface with a standard IPv6 protocol stack, our home gateway functionality



FIGURE 2: Home gateway.



FIGURE 3: 6LoWPAN home nodes based on TI CC2530.

implemented 6LoWPAN adaption layer, 6LoWPAN-ND, and IPv6 RPL routing, IPv6 interconnection.

In order to interconnect 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 6LoWPAN mesh into its own subnet, therefore clearly identifying the home automation nodes. In bridge mode, this home gateway provides switching capabilities, allowing to interconnect a standard IPv6 based network with an 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 interface are forwarded to the Ethernet segment. Home gateway is acting as an NDP proxy on the Ethernet side and is using NDP parameters to configure the 6LoWPAN mesh. Source and destination MAC addresses 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.

**2.3. 6LoWPAN-Based Home Node.** The 6LoWPAN node for this test bed is based on TI CC2530 application board [11]. 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, 8 KB RAM, batteries, and ambient/environment power source. In this environment, the application boards run Contiki, 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 digital ambient light sensors ISL 29023, an integrated ambient and infrared light-to-digital converter I<sup>2</sup>C interface. In normal operation, typical current consumption of this sensor is 70  $\mu$ A, and the power consumption can be reduced to less than 0.3  $\mu$ A when powered down.

6LoWPAN-based home nodes have specific hardware characteristics and limitations. Most of these nodes have limited available energy. In our case, although AA batteries that provide the power to the 6LoWPAN-based home nodes are rechargeable, but, to save long periods of life without the need for periodically replacing its batteries, we need to design the 6LoWPAN home device with total energy independence. To solve this, additional components for power management and energy harvesting are needed. Thus, our 6LoWPAN-based home automation devices are 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.

### 3. Setting of Test Environment

6LoWPAN 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, based on 6LoWPAN over IEEE 802.15.4, with an existing IPv6 network, based on Ethernet/Wi-Fi. To test interconnection between 6LoWPAN node and outside IPv6 network, we develop a light sensor remote and mobile control based on Android application. The remote user's communications transverse the internet until they reach our home gateway. After that, the communications are wirelessly transmitted to the 6LoWPAN-based home nodes. The application of this test bed has implemented IPv6 using Android API Inet6Address. The captures of our application are seen in Figure 5. The figure on the left showed the first screen of our application and the menu to select sensor nodes that will be monitored. The figure on the right showed



TABLE 1: Battery characteristics.

Max. charge voltage	1.5 V
Nominal voltage	1.2 V
Nominal capacity	2850 mAh
Standard charge	270 mA/16 h
Fast charge	2700 mA/1.1 h

TABLE 2: The most common energy harvesting sources.

Harvesting technology	Power density	Source of information
Photovoltaic cells	40 mW/cm <sup>3</sup>	Borgoine, 2011 [16]
Piezoelectric	10–100 uW/cm <sup>3</sup>	Chandrakasan et al., 2008 [17]
Thermoelectric ( $\Delta t = 15$ deg K)	9.4 uW/cm <sup>3</sup>	Yang et al., 2013 [18]
Acoustic noise (149 dB)	252 uW/cm <sup>3</sup>	Kralov et al., 2011 [19]

power, thermal energy, and wind energy. In recent years this term has been applied mainly to sensor networks, where wireless sensor devices employ this process to replenish their energy resources [13, 14]. The implementation of energy harvesting in 6LoWPAN home automation has been introduced by [8, 13]. When they applied this technology to their 6LoWPAN-based temperature monitoring node, it makes their system became energy independent. However they did not give enough examination and detail energy consumption needed by 6LoWPAN-based home node while transmitting data application. We believe that this is very important due to the optimized system while, using the harvested energy, the power management design should achieve two fundamental requirements: energy-independent operation and node operation performance level [15].

We can approximate the sensor network with a closed energy system where each node has a total power output from the energy source  $P_s(t)$  at time  $t$ , and a total energy being consumed at that time is  $P_c(t)$ . There are three cases which can be separated to model the energy behavior of a load and write the physical condition on energy conservation: harvesting system with no energy storage, harvesting system with ideal energy buffer, and harvesting system with nonideal energy buffer [15]. These conditions help us to derive requirements on  $P_s(t)$  and  $P_c(t)$  which allow energy-independent operation to be guaranteed.

The remaining energy  $E$  by the home automation node at any time  $t$  is given by sum of its total power output  $P_s(t)$  minus its total energy being consumed  $P_c(t)$  and can be estimated by the following formula:

$$E(t) = \int_0^t (P_s(t) - P_c(t)) dt, \quad (5)$$

where  $E(t)$  is remaining energy of the home automation node,  $P_s(t)$  is total power output from energy harvesting source, and  $P_c(t)$  is total energy consumption of the automation node.

A node is deemed energy independent if its remaining energy satisfies the following formula:

$$E(t) > 0, \quad \forall t > 0. \quad (6)$$

Depending on the application and location, a variety of sources for energy harvesting have been researched [13, 14, 20, 21] such as a solar power and thermal, vibration, and kinetic energy. Photovoltaic (solar) cell has the capability of converting light energy into electrical energy. Several research efforts have been conducted and so far have demonstrated that photovoltaic cells can produce sufficient power to maintain a microsystem. The vibrational harvesters use one of three methods: electromagnetic, electrostatic, or piezoelectric. Piezoelectric energy harvesting sources alter mechanical energy into electrical energy by straining a piezoelectric material to complete energy harvesting solution optimized for high-output impedance energy. This is well suited for low-power WSN nodes, since it accumulates energy over a long period of time to enable efficient use of short power bursts. Summary of the most common energy harvesting sources is depicted in Table 2.

All of the energy sources stated in the beginning have small energy density values compared to more classic energy sources, such as batteries. In the past, the use of radio transceivers often implied large amounts of power consumption. This is no longer the case today, as recent advances in the design of low-power electronics and energy storage have made wireless sensor networks a prime candidate for the successful integration of energy harvesting techniques. By analyzing the data from Table 2 we can see that solar cells offer the best efficiency while at the same time being an environmentally-friendly power source. In overall, photovoltaic energy conversion is a well-known integrated circuit compatible technology that offers the highest power output levels, when we compare it with the other energy harvesting mechanisms. However, its power output is strongly dependent on environmental conditions, that is, varying light intensity due to the placement (indoor/outdoor). This can be a suitable energy source for locations in which the availability of light to network nodes can be guaranteed to a sufficient degree and for which battery supply is impractical. For indoor lighting, the main source of energy is the lighting system itself. This may seem strange, but a solar energy harvesting system can collect the light and store the energy in a battery for use when it is dark, keeping a system running for year without available.

A 6LoWPAN home node that has energy harvesting as a supplement to the battery energy can maximize the life time and virtually run for an infinite amount of time without the need for periodically replacing its batteries. However, total power output needed from energy harvesting depends largely on energy consumption of the 6LoWPAN home node application and the sensor used. In order to maximize home node performance and satisfy energy independence, we used 3 V, 70 mA small polycrystalline silicon solar cell.

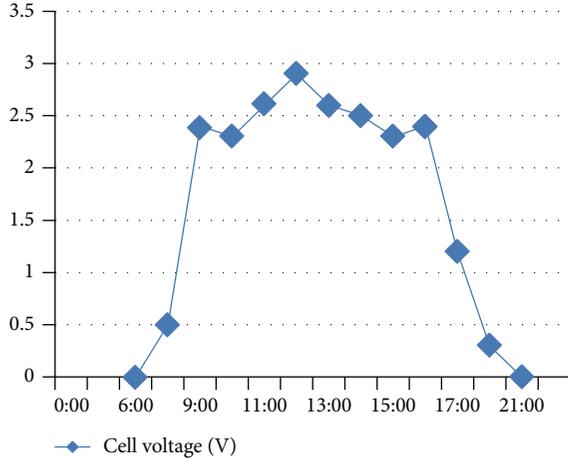


FIGURE 6: Photovoltaic cell voltage measurement.



FIGURE 7: Air packet capture view.

#### 4. Evaluation

We established energy harvesting system that can harvest sufficient energy for the 6LoWPAN home device needs. To successfully power our nodes we did the following experiment: we measured the average output power on a fixed 1 k $\Omega$  load when the cell was in full sunlight. The result of our measurement is depicted in Figure 6. At noon, about 10 hour, the voltage condition reaches stable energy level at 2-3 V, so can generate electricity to give enough storage capacity for our energy harvesting system.

With an average power 87 mW, we can calculate the total energy harvested  $E_s$  in one day by the solar cell:

$$E_s = P_s \times t_s = 87 \text{ mW} \times 10 \text{ h} = 3132 \text{ Joule}, \quad (7)$$

where  $E_s$  is total energy harvested from source,  $P_s$  is total power output from harvesting source, and  $t_s$  is total duration of energy harvested.

In addition to taking into account light sensors with an additional 1 mA at most and implying that no application acknowledgment is implemented, our 6LoWPAN home device consumed a maximum of 3 mA at 3 V from the power source. The total energy consumption  $E_c$  for the 6LoWPAN home node to run without pause for the duration of a single day will be

$$E_c = V_s \times I_c \times t_c = 3 \text{ V} \times 4 \text{ mA} \times 24 \text{ h} = 1037 \text{ Joule}, \quad (8)$$

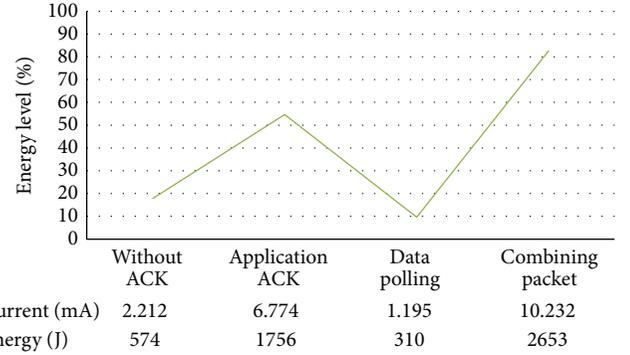


FIGURE 8: Energy consumption measurement.

where  $E_c$  is total energy consumed by 6LoWPAN home node,  $V_s$  is power source voltage,  $I_c$  is total average current consumption by 6LoWPAN node, and  $t_c$  is total duration of energy energy consumed.

When the 6LoWPAN node is up and running in the home automation network, we use the packet sniffer to visualize the packet going over the air. Figure 7 shows air packet capture view of our 6LoWPAN home automation node transmission. The detail of various results and explanation of what is happening in the home automation device during a data transmission is depicted in Table 3.

At the same time, we also measure total average current consumption measurements of our 6LoWPAN home automation system during transmission of packets by using the oscilloscope. Summary results of total energy consumption for the data transmission without ACK, with application ACK, data polling, and combining data packets are shown in Figure 8. Our result proves that, given enough storage capacity and enough incident radiation, solar energy harvesting can power a 6LoWPAN home node for an indefinite amount of life time. Taking into account the fact that nodes employ power management in the software stack, alternating between long periods of sleep, and only short intervals when they are active, there is actually energy independence with excess energy produced. This additional energy is stored in the battery pack to be consumed during the night or on clouded days.

In Table 4, the detail comparison of our proposed solution with relevant works in wireless home automation system is shown. Our proposed system enables home users to check the home automation device status and control them remotely from the globe. In addition, the use of 6LoWPAN communications technology also helps lower expense of the system and decreases complexity of the home automation architecture. And then, by implementing solar energy harvesting we have 6LoWPAN-based home automation systems which have long periods of life without the need for periodically replacing their batteries.

#### 5. Conclusion

We have presented in this paper our work to answer the issues mentioned at the beginning of this paper. We proposed the simple but reliable system that can control home

TABLE 3: 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)	Postprocessing 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

TABLE 4: Feature in existing and proposed systems.

No.	System	Access		Complexity	Power management
		Direct control at home	Internet		
1	Bluetooth, Sriskanthan et al. 2002 [3]	√		Low	Home power
2	ZigBee, Gill et al. 2009 [4]	√		Low	Battery
3	6LoWPAN, Dörge and Scheffler 2011 [7]	√	√	Low	Battery
4	Our proposed system	√	√	Low	Energy harvesting

automation devices over 6LoWPAN. The usage of 6LoWPAN decreases complexity of architecture and low fiscal expense. Transparent Internet-based home device controlling also can be implemented. In our system, we proposed the use of TI CC2530, low energy consumption SoC solution for 802.15.4 application combined with Contiki, an open source OS for memory embedded systems which has connections with digital ambient light sensors ISL 29023. The use of 6LoWPAN home gateway provides smart platform while interconnecting the home automation network, based on IEEE 802.15.4 and 6LoWPAN, with existing IPv6 network, based on Ethernet.

The important features of our 6LoWPAN-based home automation system are long periods of life and energy efficient, without the need for periodically/every 53 days replacing its batteries. We designed the 6LoWPAN home automation device with total energy independence by using 3 V, 70 mA small polycrystalline silicon solar cell for energy harvesting. Given enough storage capacity and enough incident radiation, solar energy harvesting can power a 6LoWPAN home automation node for an indefinite amount of life time.

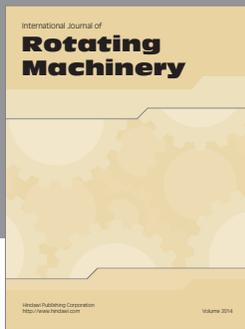
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