Wireless Energy Monitoring Solution Using 2.4 GHz 6LoWPAN

Mitul Vekariya, Mohit Agarwal, Parav Nagarsheth
Electronics and Communications Engineering Branch, Electrical Engineering Department
Institute of Technology, Nirma University
Ahmedabad, India

***Abstract*— Over-use and mismanagement of electrical energy is a prevalent problem in the contemporary world. To overcome this potentially crippling flaw in electricity distribution, an effective monitoring system has to be developed. This paper proposes an integrated hardware and software solution for wireless monitoring of energy consumption of the end-user through a network of metering nodes connected to every device. To achieve scalability in this network, 6LoWPAN is the protocol of choice. It combines IPv6 with an efficient header compression scheme to meet the stringent requirements of 802.15.4 data payload. The steps involved in design and development of the network and the nodes have been elaborated. The feasibility of this design has also been scrutinized.**

***Index Terms* — Energy Monitoring, 6LoWPAN, 802.15.4, Wireless Sensor Networks.**

I. INTRODUCTION

In 2011, the world consumed an unprecedented 18,466 TWh unit of electrical energy [1]. To meet the demands of the developing world, this figure can be expected to increase manifold [2]. Thus, the need to mitigate the pressure on the Earth's natural resources has never been higher. One obvious solution is to switch to non-conventional energy sources like the wind energy and the solar energy. However, such technologies are still under-development, and eventually don't address the perpetual problem of reckless energy wastage. A scalable model needs to be developed that attempts to solve the challenges of energy conversation.

Electrical energy monitoring and analysis systems have been around for decades. However, they have primarily been present at the grid level, to regulate the supply of electric power to large areas like cities, districts or industrial hubs. These systems are unable to check usage at the consumer level, where maximum wastage is likely to occur. This can be effectively solved by deploying nodes which monitor electric power consumption of consumer devices.

Figure 1 illustrates the block diagram of an energy monitoring network. Everyday appliances like lights bulbs and by-extension, sockets become nodes which have the ability to measure line voltage, current and active energy consumed by them. On the other hand, an edge router (coordinator and internet gateway) is responsible for creating a network, acquiring the metered data from the nodes and sending application layer packet information to an HTTP server for display on the user's device.

The following standards have been discussed and implemented in the application:

- IEEE 802.15.4 MAC and Physical layer definition for low power and low data rate communications [3]
- IPv6 over Low-Power Wireless Personal Area Networks (6LoWPAN) [4]
- Neighbor Discovery Optimization for IPv6 over Low-Power Wireless Personal Area Networks (6LoWPAN-ND) [5]

Implementation of the above standards has been discussed in detail in further sections.

The rest of the paper is organized as follows:

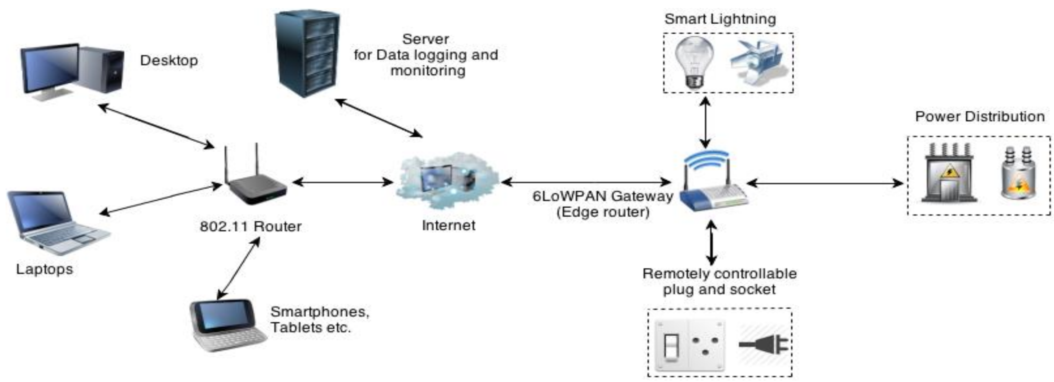

Fig. 1. Block diagram of an energy monitoring network

The application overview along with salient features of IEEE 802.15.4 and 6LoWPAN standards are described in section II. Section III presents design of hardware and software followed by testing and evaluation of the integrated design is given in section IV. Final conclusion and a brief about further work scope are given in Section V.

II. Application Overview

A. Energy Metering

Figure 2 illustrates the sampling block of the energy metering IC. The IC has two fully differential voltage input channels, which sample the buck converted voltage and current waveforms. The maximum input voltage to the differential Programmable Gain Amplifiers (PGA) in the channels is limited to ±500mV. Hence, external current and voltage transducers are required to sample load current and line voltage. An external analog low-pass filter (RC) at each channel prevents aliasing, an artifact of all sampled systems [6].

The analog-to-digital conversion (ADC) is performed using two oversampling sigma-delta modulators. A 24-bit register for each channel stores the instantaneous value of voltage and current. The corresponding root mean square values are calculated by squaring the instantaneous values, averaging and then obtaining the square root. These are stored in a separate register. The waveform and the rms registers have corresponding offset registers to compensate for possible errors during conversion and sampling.

To obtain the real active power, the current and voltage waveforms are multiplied. The dc value of the instantaneous power signal is extracted using a low pass filter to obtain the active power information. The active energy is obtained by further accumulating the value of active power in the active energy register.

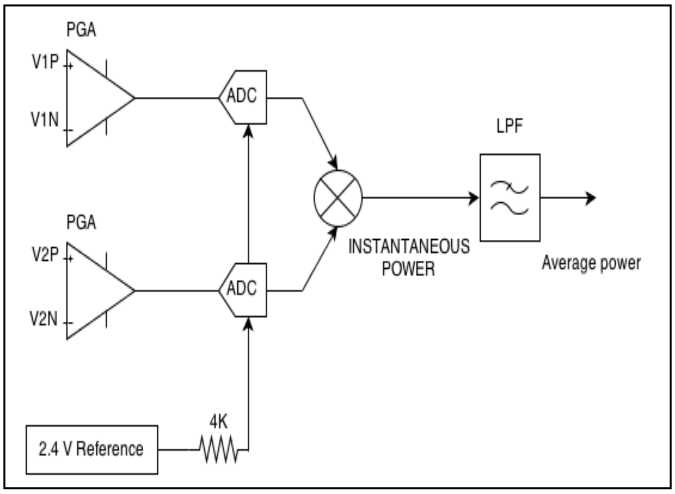

Fig. 2. Active power calculation

B. IEEE 802.15.4

IEEE 802.15.4 standard specifies the physical (PHY) and Media Access Control (MAC) layer for Low Power Wireless Personal Area Networks (LoWPANs). IEEE 802.15.4 over 2400 MHz defines the PHY layer for this application [3]. This standard has been designed keeping in mind the constraints of low-cost, low-power devices, with less emphasis on overall throughput.

The complete PHY layer and a partial MAC layer have been implemented on a single System-on-Chip (SoC). The PHY layer of the 802.15.4 identifies the use of several modulation schemes in several frequency bands. The 2450 MHz (2.4 GHz) frequency band is license-free worldwide, and hence is the ideal band for this application. The modulation scheme specified for the 2.4 GHz band is Orthogonal-Phase Shift Keying (O-QPSK) with 16-ary orthogonal signals. The PHY layer is also responsible for energy management, channel selection, data transmission and reception and link quality indication (LQI) for received packets. It also facilitates low power operation wherein a node may remain inactive for longer periods compared to the duration for which it is actually communicating, thereby saving power and reducing channel traffic. It only consumes up to 1% power compared to IEEE 802.11 (Wi-Fi) and is significantly simpler to integrate with embedded systems.

The MAC layer of the IEEE 802.15.4 standard provides an interface between the higher level layers and the PHY layer. It also manages several critical tasks like generating network beacons, synchronizing the beacons, PAN association and disassociation, frame validation and checksum validation as well as collision detection schemes like Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA).

The IEEE 802.15.4 MAC layer offers a substantial flexibility with respect to its implementation, while allowing many of its features to be reused in the upper layers. For e.g., in this application, the use of beacon frame format has been purposefully avoided, leaving association and disassociation events to the upper layers. At the same time, the various addressing schemes of the MAC layer have been thoroughly used to assign addresses by the upper layers. It is not uncommon to find instances of both 16-bit and 64-bit addressing schemes in the MAC layer of this application. The general frame format of the MAC layer is shown in Fig. 3 [3].

Despite the obvious advantages of IEEE 802.15.4 with respect to power consumption and ease-of-implementation, it is not suitable for applications which require high data throughput like browsing, streaming, file transfer etc. Hence, it is mainly deployed in sensor networks or low data-rate networks.

Octets:2	1	0/2	0/2/8	0/2	0/2/8	variable	2
Frame control	Sequence number	Destination PAN identifier	Destination address	Source PAN identifier	Source address	Frame payload	Frame check sequence
		Addressing fields					
MAC header						**MAC payload**	**MAC footer**

Fig. 3. General MAC frame format

C. 6LoWPAN

With the advent of Internet Protocol, Version 6 (IPv6), the possibility of making the internet home to a large sphere of embedded devices has become a reality [7]. IPv6 can assign 3 x 10^{38} unique addresses, a huge number considering that the small address space of IPv4 (only 4.3x10^{9} unique addresses) is about to exhaust only now [8]. Thus a large amount of spare addresses can be used to identify the aforementioned embedded devices, on the internet.

6LoWPAN is a protocol definition to enable IPv6 packets to be carried on top of low power wireless networks, specifically IEEE 802.15.4[4]. However, directly transporting IPv6 packets in the 802.15.4 payload is not possible, chiefly due to the following reasons:

- 802.15.4 addressing modes have no support for a 128-bit address space [3]
- The Maximum Transmission Unit (MTU) of IEEE 802.15.4 is 127 bytes, compared to the MTU of IPv6, viz. 1280 bytes [9]

The above constraints can be met by efficient header compression and upper layer optimization schemes [9]. The OSI model of 6LoWPAN in Fig. 4 illustrates the presence of an additional 6LoWPAN adaptation layer between the data link layer and the network layer [10].

Aside from a large address space, 6LoWPAN introduces several desirable features like auto-configuration and statelessness, These features can be exploited for coordination of hundreds of devices in a LoWPAN It also ensures interoperability in other IP network links like Wi-Fi, Ethernet, Serial lines etc., with the option of a simple tunnelling mechanism to translate IPv6 to IPv4 [4]. In comparison with other upper-layer 802.15.4 protocols like Zigbee, following are some of the features that make 6LoWPAN to perfectly use with Internet Protocol (IP).

1) *Header Compression:* The internet protocol header compression (IPHC) is implemented in the adaptation layer. The header compression scheme defined in the initial standard definition (RFC4944) has now been obsolete by RFC6282. The dispatch field distinguishes 6LoWPAN packet from other IEEE 802.15.4 packets [11]. The following fields are either compressed wholly or partially:

a) Source IP: The 64-bit prefix can be assumed either link-local or specified inline. The 64-bit interface identifier (IID) form the 64-bit or 16-bit short address specified in the 802.15.4 header. It is normally derived from the Extended Unique Identifier (EUI-64), i.e. the physical address; or can be an address specified by a router.

b) Destination IP: Same as source IP compression.

c) Hop Limit: Useful in compression of ICMPv6 messages.

d) Next Header: Can be compressed for pre-determined headers or carried inline like UDP [11].

e) UDP Ports: Compressed to a 4-bit field to specify ports from 61616 to 61631.

Application layer
Transport layer (UDP)
Network layer (IPv6)
6LoWPAN adaption layer
Data link layer (IEEE 802.15.4)
Physical layer (IEEE 802.15.4)

Fig. 4. 6LoWPAN Model

2) *Neighbor Discovery Optimization (ND):* It is one of the unique features of IPv6. 6LoWPAN-ND defines several optimization schemes for low data rate systems. Figure 5 show the steps required to configure a 6LoWPAN node (6LN), 6LoWPAN router (6LR) and a 6LoWPAN border router (6LBR). A 6LN on power-up assigns itself a link-local address, derived from its EUI-64, which is assumed to be globally unique. For configuration, it periodically transmits a router solicitation (RS) message to all the router multicast address FE80::2 until it receives a router advertisement (RA). The RS packets are transported as link-layer broadcast packets in 802.15.4, since there is no multicast support [5]. The RA contains a source link address option (SLLAO) which contains the link-layer address of the 6LR. To save power, the 6LR transmits RA messages only on receiving RS. After reception of the RA, the 6LN transmits a neighbor solicitation (NS) message to register a 16-bit short address it assigned to itself. The 6LR forwards this message to the 6LBR to perform duplicate address detection (DAD). So, node doesn't require to join solicited node multicast address [5].The 6LBR returns a duplicate address confirmation (DAC) message which either approves or rejects the requested address. On receiving the neighbor advertisement (NA), the 6LN is officially registered with the network.

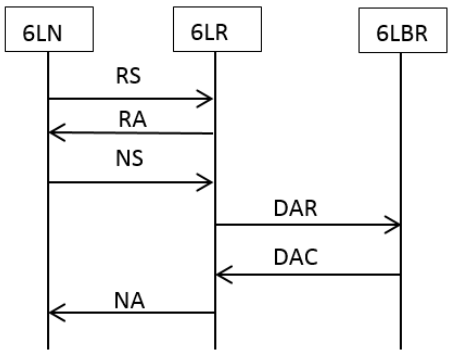

Fig. 5. 6LoWPAN Neighbor Discovery

III. DESIGN AND IMPLEMENTATION

The design of the hardware and software can be decomposed into several blocks. This section provides a detailed outlook of the steps involved in designing, debugging and finally integrating several blocks of the application.

A. Node Hardware Design

The node hardware design involves designing the schematic, selecting the components, designing the layout, fabricating the PCB, soldering and testing. Figure 6 shows a simplified block diagram of the actual node.

1) Power Supply: A large number of components on the PCB require low-voltage DC supply. The input AC (110-230V) is converted to 12V DC using an isolated Switched Mode Power Supply (SMPS). Two low-dropout linear regulators in cascade provide 5V and 3.3V to low-power circuitry. A wide range of decoupling capacitors are used to remove the effects of supply ripple in sensitive parts of the hardware. On the supply side, a 5A slow-blow fuse protects against short-circuits. Similarly, a metal oxide varistor (MOV) protects against high voltage transients.

2) Energy Metering IC: The ADE7753 is a single phase multifunction energy metering IC from Analog Devices. As discussed before, it incorporates all the signal processing required to perform line voltage measurements, active energy measurements and rms calculations on voltage and current [6]. A 1:500 turn current transformer with a 10 ohm load converts the load current into a voltage signal for sampling. A 1 mega ohm resistor divider network across the line voltage delivers input to the voltage channel of the IC, as shown in Fig. 6. In a mixed-signal design, interference of analog and digital signals have a detrimental effect on signal conversion. Hence, to minimize the return paths, the PCB has separate analog and digital ground planes, tied together at a single point. The analog ground plane is used as the reference for the anti-aliasing filters, voltage and current transducers, and the analog-to-digital converters. The digital ground plane is used as reference for the rest of the components, which use digital signals. The ADE7753 is equipped with a 3-wire serial peripheral interface (SPI) for communication with an external microcontroller. This interface is used to read from and write to the internal registers on the ADE7753.

3) Application Processor: The application processor is an ATMEGA328P microcontroller from Atmel. It runs a program which is responsible for critical functions of the node, whilst acting as an intermediary to the network processor. The primary function of the processor is to read the values of active energy, rms voltage and current from the energy metering IC. These raw values are converted into readable SI units using an equation involving several constants: the equivalent value of the register for full-scale analog input and the respective transducer constants. The application processor can be used to debug and calibrate the energy meter from these values. The ADE7753 registers are read periodically every 500 milliseconds, conforming to the update rate of the IC. These values are displayed on a 16x2 LCD interfaced with the ATMEGA328P. The application processor also controls a relay, capable of switching power to the AC load. Hence, providing a method to monitor and control the load. All functions and features of the application processor are available to the network processor over a 2-wire Universal Asynchronous Receiver Transmitter (UART), using a simple protocol. If required, the ATMEGA328P can store the metered values on an on-chip EEPROM for data retention in case of a power failure.

4) Network Processor: The function of the network processor is performed by STM32W108, a fully integrated SoC which integrates a 2.4 GHz, IEEE 802.15.4-compliant transceiver and a 32-bit ARM Cortex-M3 microcontroller, from STMicroelcetronics. It runs off an external 3.3V supply for powering the controller and uses an in-built 1.8V regulator for the radio. It claims to be extremely power efficient with a 1uA power consumption during deep sleep modes, required to retain the RAM contents. Many transceiver components like the VCO, loop filter and power amplifier are integrated within the SoC. However several external components like the balun, filter and antenna are connected to the SoC externally via PCB traces [12]. To keep electromagnetic interference (EMI) to a minimum, care was taken to choose the smallest possible footprint for each external component (including capacitors and resistors). As a result, soldering the surface mounted (SMD) components and the SoC itself was a significant challenge, requiring several days of trial-and-error to achieve acceptable performance. The authors recommend the use of professional soldering equipment in case of unavailability of suitable ready-made modules for a similar application [13]. The network processor accepts metering data from the application processor over the UART interface and parses external requests to the application processor, to switch the load. It also runs a 6LoWPAN stack with implementations like neighbor discovery in the network layer and universal datagram protocol (UDP) in the application layer.

B. Application Software

The application software was developed on the Arduino IDE, using the Arduino libraries. For atomicity and extensibility, the code is logically divided into:

- **ADE7753 libraries**, to provide a low-level API to set various parameters of the IC and read metered values.
- **Conversion functions**, to convert raw sampled and/or processed values into SI units.
- **Application Loop**, to poll the UART interface and to send parsed data to the network processor.

C. Edge Router

The edge router is

- A PAN Coordinator in the 802.15.4 network.
- An internet gateway for connectivity to global networks.

It runs on a small open source computing platform, the

Beaglebone. To provide 802.15.4 PHY and MAC support, the Beaglebone is interfaced with a MRF24J40MC 802.15.4 module from Microchip, via SPI. The edge router is connected to the internet via Ethernet. The code for the edge router is written with a set of non-OS abstraction libraries for the Texas Instruments AM335x microprocessor, termed as Starterware. The TCP/IP functionality is provided by a slightly modified port of the lwIP stack. The 6LoWPAN stack runs side-by-side the lwIP stack. Dual stack model is implemented in edge router [15]. To handle concurrent requests, most of the code is interrupt driven.

The edge router keeps a cache of the addresses of all nodes registered with it. It also runs a web server to display the status of the nodes to the end-user, as shown in Fig. 9. To switch the load, the user can press a button on the web server and the relay on the corresponding node will be toggled.

D. 6LoWPAN Stack

The code for the 6LoWPAN stack is written in the C programming language. An interrupt-driven model is used to transmit and receive the packets. The packets to be transmitted and received are stored in separate buffers, space for which is statically allocated in memory. A static allocation is necessary in embedded systems with limited RAM, to optimize memory use at compile-time.

The primary functions of the stack are as follows:

1) Node Auto-configuration: An uninitialized node tries to solicit with a nearby router by broadcasting RS messages on the all router multicast address [5]. This activity is repeated until it receives an advertisement from the router. If no RA is received after a predefined number of times, the node gives up and goes to sleep. This is the only explicitly called function in the entire stack. The entire procedure is shown in Fig. 7.

2) Packet Reception: If a valid 802.15.4 packet is received, the MAC layer copies the packet into a buffer and generates an interrupt. The interrupt handler checks the packet for a 6LoWPAN dispatch field and if found, forwards it to the upper layer functions. These functions extract data from the packet and call the corresponding event handlers, if a response is required. For e.g. on reception of the RA, the 6LoWPAN stack calls eventhandler_NS().

3) Packet Transmission: A packet transmission is normally required by one of the event handlers. The data of each packet is assembled byte-by-byte in the event handler by calling various functions for generating the IEEE header, the IPHC header and the ICMPv6 or UDP headers. Finally the total length of the packet is calculated and the packet is transmitted via CSMA-CA.

The 6LoWPAN stack has several data structures which contain elements of packet frames specified in the RFCs and IEEE 802.15.4. The data in each packet can be read/write by pointers to these structures. The packet buffers are ordered in the format given by the IEEE 802.15.4 and 6LoWPAN standards. This facilitates a simple but intuitive method to control various parameters of different packet frame formats, e.g., the ICMP_struct and the UDP_struct may be pointing to the same address in memory. However, they are used to make completely different packets. The memory location they are pointing to can be changed by a simple offset variable.

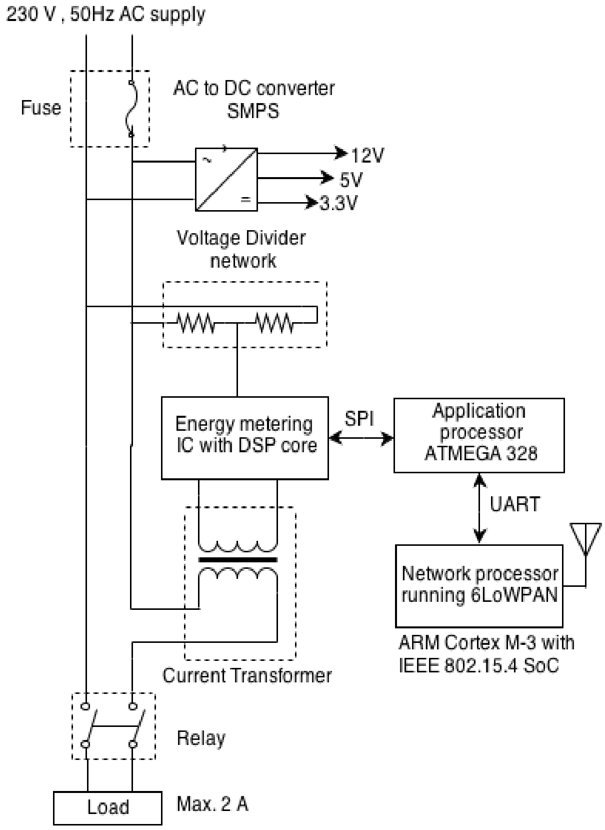

Fig. 6. Block diagram of energy metering node

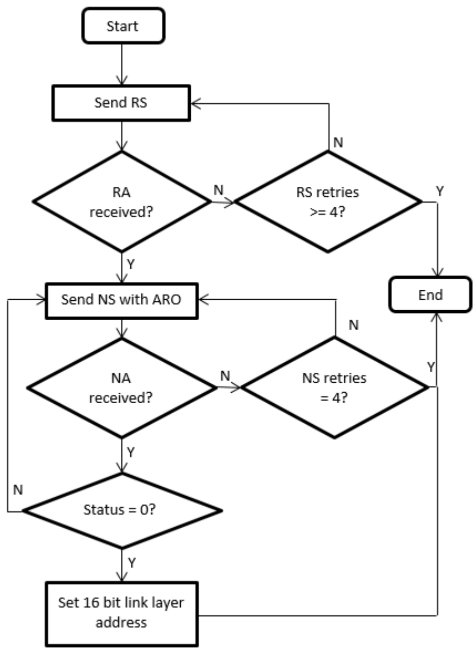

Fig. 7. 6LoWPAN Node Auto-configuration

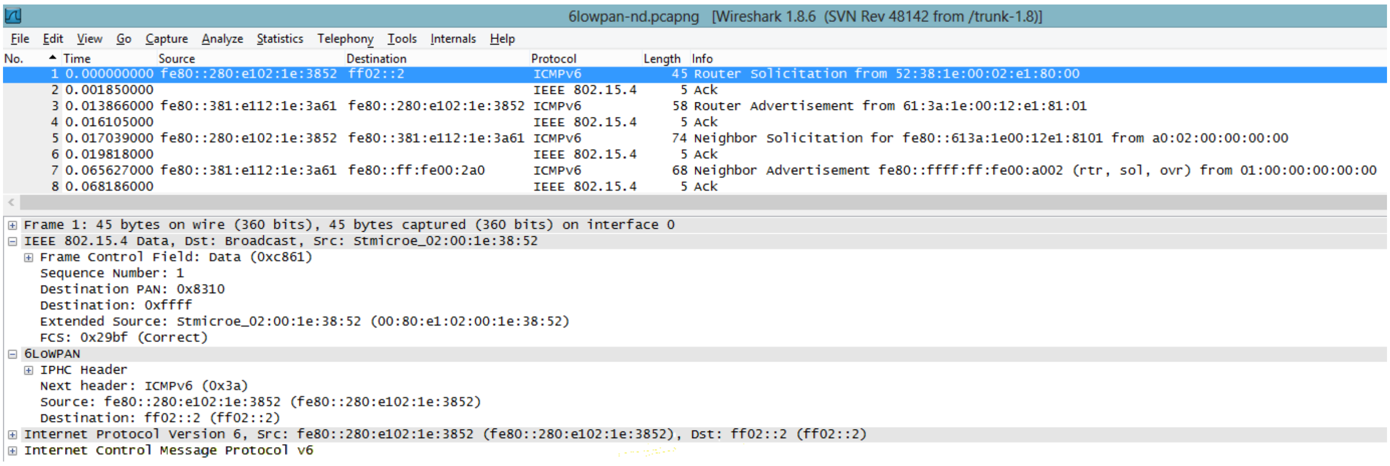

Fig. 8. Wireshark packet tracer screen capture

IV. Testing and Results

A. PCB Testing

The final assembled PCB is shown in Fig. 9. The testing of the PCB was done in batches. Initially, the RF circuit was completely tested by transmitting and receiving packets to and from a reference transceiver. The range of the node could be ascertained to 20 m in closed space and 50 m in open space. After satisfactory RF performance, the circuit pertaining to application processor (ATMEGA328p) was tested. The LCD interface and the serial communication peripherals (UART) between ATMEGA328p and STM32W108 were verified. Further, the AC power supply block and the metering circuit with an external load were tested. The external load was a lamp bank with variable current consumption. Some raw energy metering data was observed before calibration, which is detailed in the next section.

B. Meter Calibration

Meter calibration is an important phase in development of any energy meter. It is desired by both, the grid company and the end-user to ensure correct billing for the energy consumed. For rms calibration, precision AC voltmeter and ammeter were used with a steady load. Slight offsets were adjusted with the help of internal offset registers in ADE7753. Both errors were minimized to be within 1% of the actual values. Table 1 illustrates the measured and reference readings obtained by connecting a lamp bank as load.

Table 1. Reference readings and Measured readings for Vrms and Irms

Reference Voltmeter Reading (V)	Node Reading (V)	Reference Ammeter Reading (A)	Node Reading (A)
220-233	218-230	0.20	0.20
220-233	218-230	0.67	0.66
220-233	218-230	1.01	1.00

The ADE7753 also has an energy-to-frequency converter, which can be used to verify the energy calibration. Here, the output frequency is proportional to the active power or energy consumed by a steady state load. A meter constant is subsequently defined, in terms of number of ticks (frequency) per kilowatt hour (kWh). Henceforth, ATMEGA328p counts the number of ticks and increments kWh where the number of ticks equals the meter constant. The meter constant was derived by calibrating the node against an accurate energy meter.

C. Standard Validation

Validity of any standard implementation is paramount to ensure interoperability with other devices running the same standard. Figure 8 shows the screen grab of Wireshark, an open source packet tracer and identifier [14]. To capture the transmitted packets from the node, an 802.15.4 module (RFC-KIT) from STMicroelectronics, was configured as a packet sniffer. It can be seen that the first message is an RS, transmitted by the node with a destination ff02::2 (all-router-multicast). The router sends an automatic acknowledgement in about 1.8 ms and a following RA message within 14 ms. The entire node configuration (duplicate address detection and assignment of IP address) is completed within a mere 68 ms of the initial power-on.

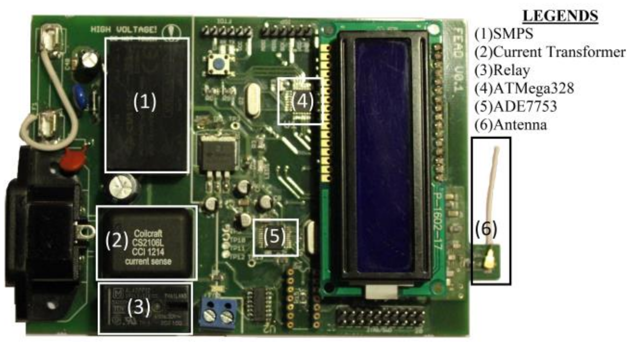

Fig. 9. Energy Metering Node

V. Conclusion and Future Scope

Energy monitoring through wireless meters represents a cost effective and feasible solution to the prevalent problem of energy misuse. The energy metering node is calibrated to measure energy in kWh and transmits the same to an edge router using 6loWPAN protocol. 6loWPAN advocates its superiority in low data rate and low power networks over other existing protocols owing to its compatibility with IPv6 that allows for large number of hosts. It has a significant advantage over Zigbee in these aspects; however it is still not in very wide use. The hardware for the node fulfilled most of the requirements of a typical energy meter. However, improvements could be made to improve noise resilience and to include a tamper-proof seal to prevent data manipulation.

This node has huge potential for filling the existing gaps in energy management. It can be made much user friendly such that any device can be integrated with the node and the corresponding energy consumption measured. In fact, it can be envisioned as a stepping stone towards Home Automation. Additional features can be added to the node like allowing the user to control his devices using external factors like daylight, temperature, and peak demand periods etc. before deploying it in the consumer market. The 6LoWPAN standard can also be extended to include routing protocols, allowing a more global reach for these nodes.

Acknowledgment

The authors thank Dr. D.K. Kothari (Professor, Nirma University) for his incessant assistance and generosity towards the development of this project. A special thanks for Prof Mehul Naik for his invaluable help in developing the RF circuit. The authors are also deeply grateful to IEEE Student Application Grant for sponsoring their project which helped them in completing their project in time.

References

[1] US Energy Information Administration, International Energy Statistics.

[2] R. Hudson, Energy Projections 2006-2030: Price and Policy Considerations.

[3] IEEE Standard for Information Technology – Telecommunications and Information Exchange Between Systems – Local and Metropolitan Area Networks Specific Requirements Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Network (LR-WPANs), 2003.

[4] RFC 4919 "Ipv6 over Low-Power Wireless Personal Area Network (6LoWPANs): Overview, Assumptions, Problem Statement and Goals", August 2007.

[5] RFC 6775 "Neighbor Discovery Optimization for IPv6 over Low-Power Wireless Personal Area Networks (6LoWPANs)", November 2012.

[6] AN-564 Application note "A Power Meter Reference Design Based on the ADE7756", Analog devices.

[7] Zach Shelby, Carsten Bormann "6LoWPAN: The Wireless Embedded Internet", 2009, John Wiley & Sons Ltd, p. 3-5.

[8] Andrew S. Tanenbaum, "Computer Networks", Fourth ed., 2008, Pearson Educations Inc, p. 468,425-427.

[9] RFC 4944 "Transmission of IPv6 Packets over IEEE 802.15.4 Networks", September 2007.

[10] RFC 6606 "Problem Statement and Requirement for IPv6 over Low-Power Wireless Personal Area Network (6LoWPAN) Routing", May 2012

[11] RFC 6282 "Compression Format for IPv6 Datagrams over IEEE 802.15.4-Based Networks", September 2011.

[12] AN3206 Application note "PCB design guidelines for the STM32W108 platform", March 2011, STMicroelectonics.

[13] AN2639 Application note "Soldering recommendations and package information for Lead-free ECOPACK microcontrollers", May 2009, STMicroelectonics.

[14] AN3406 Application note "Using STM32W108-based board and Wireshark for IEEE 802.15.4 packet analysis", 26-May-2011, STMicroelectronics.

[15] Yuanyuan Zhou, Zhiping Jia, Xianli Sun, Xin Li, Lei Ju "Design of Embedded Secure Gateway Based on 6LoWPAN", 13th IEEE International Conference on Communication Technology (ICCT), pp 732 – 736, Sept 2011