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ENERGY MANAGEMENT SYSTEM FOR EDUCATIONAL BUILDINGS USING THE PRIME NARROW BAND PLC STANDARD

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ABSTRACT

Energy Management System (EMS) plays a big role in the realization of the Smart Grid. In this research, an EMS for a school building is implemented using the narrowband Power Line Communications (NBPLC) technology based on the PRIME standard. This study demonstrates the utilization of the NBPLC for EMS application. Four C2000 PLC modem from Texas Instrument are used as base node (BN) and service nodes (SN). The base node is connected to the host PC while the service nodes are connected to the appliances in the corresponding rooms of the building. The host PC contains the program that sends a command to a particular service node depending on the class schedule in that room. The program is a graphical user interface developed using Matlab. The commands are the basic turning ON and turning OFF of appliances. The program through the base node sends the ON command to the specific service node of the room where a class is scheduled. A motion detection feature is included to anticipate events where the room with a scheduled class may be empty because of alternative classes, called-off classes, or class suspension. The motion sensor is connected to the service node. The BN requests for the motion sensor status thirty minutes after the start of the class period. If no motion is detected, the program sends an OFF command to the corresponding service node. This positively reduces power consumption and consequently reduces energy wastage. To determine the energy wastage without the system in place, kiloWattmeter was installed in three rooms and the energy consumption was recorded for the whole term comprising 14 weeks. The total consumption read from the meter was 2,736.2 kWhrs. An average consumption per hour was computed based on the first reading of the kWhr meter whereby all the appliances in the rooms are turned on. This is the basis in determining the consumption of three rooms considering only the times where the room has a schedule class. The consumption could have just been 2,089.7 kWhrs. This translates to wastage of 646.5 kWhrs. While this value is relative, if the whole campus with more than a hundred rooms is considered, the impact of such wastage is huge.

Keywords: power line communications, NBPLC, energy management system, PRIME PLC standard, EMS, C2000 PLC modem.

1. INTRODUCTION

Energy Management System (EMS) is a structured approach of monitoring and controlling energy use (Energy management system: Introduction) and is an indispensable tool in the Smart Grid (SG) realization, spectrum power scada and energy management systems. The core goal of EMS is to save energy by automatically switching on and off different electrical devices in the building based on preset conditions which are typically monitored by sensors (Killough). EMS deployment can be either wired or wireless. Each system has its pros and cons. The wired EMS requires the installation of cables which is more cost effective if installed at the onset of the construction of the building. It has a high reliability compared to the wireless system. However, its downside is during retrofitting, renovation and or installation in an already-erected edifice where installation and maintenance cost are relatively high (Evans). The wireless EMS is cheaper and easier to deploy. Wireless technologies for EMS include Zigbee, Bluetooth, and Wifi. Zigbee network is a popular choice among wireless systems because of its low power consumption and it is practically cheaper especially for installation in small buildings (Wireless energy management system). Wi-Fi is now thought because of its ubiquity, however, it is an overkill approach considering that the EMS systems are not data intensive and are normally low data rate. Bluetooth is expensive and has a short range. Other issues of wireless systems include reliability, battery life, security, and interference with other wireless networks (Wang S. , 2010). Aside from this, EMS devices tend to send data at the same time during emergency situations like power outages, thus, channel congestion is very likely to occur (Galli, et al. For the grid and through the grid: The role of power line communications in the smart grid, June 2011). This is not the case in PLC since it uses cooperative coding schemes. It is also considered a cost-effective communications solution for EMS since the wires already exist and it can be easily integrated to the other components of the SG network (Tonello, Aug 2012).

This study demonstrates the utilization of the NBPLC in the implementation of EMS in the educational buildings. Unlike offices and other buildings, occupancy of rooms in school buildings is based on course schedules. While utilization of the rooms is being optimized by assigning courses for the whole day of operation, there are several scenarios that could leave a room unoccupied in between scheduled classes. This may include dissolved courses, called-off classes, alternative classes held in a different room, and differing time period for some courses, that is, some may be a one-hour class, others may be a one-and-a-half-hour class, or a once-a-week class. Since it is not feasible for the assigned personnel to turn ON and OFF unoccupied rooms in between classes covering several floors at the same time and for the entire day, energy is wasted during the unoccupancy period. Hence, automating the turning ON and OFF of the appliances in the classroom through the use of NBPLC could reduce this energy wastage to a relatively significant value.

This paper is divided into several sections, Section 2 briefly discusses PLC, Section 3 discusses the EMS components, Section 4 provides the data and results, and Section 5 gives the conclusion.

2. THE PLC CONCEPT

Power line communications (PLC) has been in use since the 1920's for voice communications as well as the control and remote metering of power plants (Ferreira, Lampe, Newbury, & Swart, 2010). There are two types of PLC, narrowband (NBPLC) and broadband (BBPLC).

Narrowband PLC is now increasingly becoming popular especially in low data rate applications such as automatic meter reading (AMR) and EMS deploymen (Stimmel & Kirkpatrick, 2012) (Dostert, 2001). It is operating in the range 3kHz to 500kHz (Oksman & Zhang, 2011). Its popularity lies on the fact that low frequency signals can pass through transformers (Artale, et al., Sept 2013.) (Males, Popa, Lavric, & Finis, Nov. 2012). Several standards have been developed for narrowband PLC that include PRIME, G3-PLC, and IEEE P1901.2. The modem used in this study is programmed to operate using the PRIME standard.

PRIME or PoweRline Intelligent Metering Evolution is a PLC standard for application in the advanced metering, smart grid and asset monitoring (PRIME, 2013). PRIME is a bidirectional communications standard with an effective data rate of 21-128 kbps. PRIME operates at the PHY and MAC layers. PRIME supports a tree topology network with the base node (BN) as the root and service nodes (SN) as the leaf.

3. EMS COMPONENTS AND OPERATIONS

The Energy Management System developed in this project comprises of a host PC that contains the scheduler program, the PLC modems (configured as the Base Node and service nodes), the electrical interface, and the motion sensor (Figure-1). The host PC with the designed graphical user interface (GUI) is connected to the base node via a USB/JTAG cable. The designed EMS can handle up to 120 service nodes. The service node drives three relays, one for the lights, the second for the airconditiong unit (ACU) and the third one for the electric fan. The service node also accepts local signal from the motion sensor that detects the presence or absence of people in the classroom. This enhances the functionality of the system by overriding the scheduler program in the event that the room becomes empty due to other out-of-the-room or off-schedule activities.

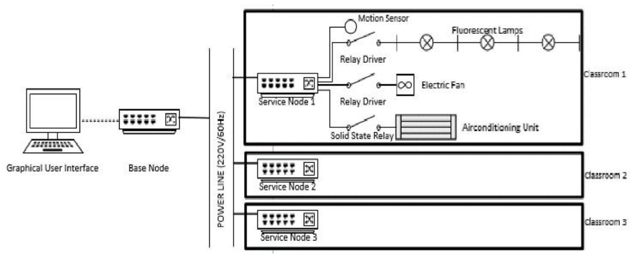

Figure-1. EMS block diagram.

3.1 System flowchart

The system flowchart is shown in Figure-2. Both the base node (BN) and service nodes (SN) are based on C2000 PLC modem developer's kit from Texas Instrument. The base node has two main functions: (1) communicate with the host PC, and (2) communicate with the service nodes. When the host PC sends an addressed command to the base node, the BN broadcasts this packet over the powerline.

Each of the service nodes listens to the line and waits for the packet that contains its address. The service node that is being addressed executes the command that appears in the payload field. It then sends a reply to the base node, with TYPE = ACK, Source (SRC) address = its own address, and the Destination (DEST) address that of the base node.

Upon reception of the ACK, the base node reports to the host PC. If the timeout expires before it receives a packet, the host PC resends the command to the base node for retransmission. This is repeated until the BN receives an acknowledgement packet but stops when the counter maxes out.

3.2 Graphical user interface

The graphical User Interface (GUI) acts as the main controller of the entire system. It is the one that sends the commads to the modem to turn on or off an appliance. It is developed using Matlab and contains the scheduler program and EMS commands. The scheduler program contains all the class schedules for each room and all the rooms in a building. Each room has 12 time-slot periods allocation each day from Monday to Sunday (Figure-3). The GUI is operated by those with admin function who can insert a schedule, enable or disable the room, enable or disable a specific time slot, rename the rooms or building and lock the status of a specific time slot especially those where classes are permanently scheduled for the whole term. For ease in encoding and monitoring, the GUI for the rooms which is implemented using push buttons is color coded. The EMS commands sent by the GUI to the service nodes via the base node are summarized in Table-1.

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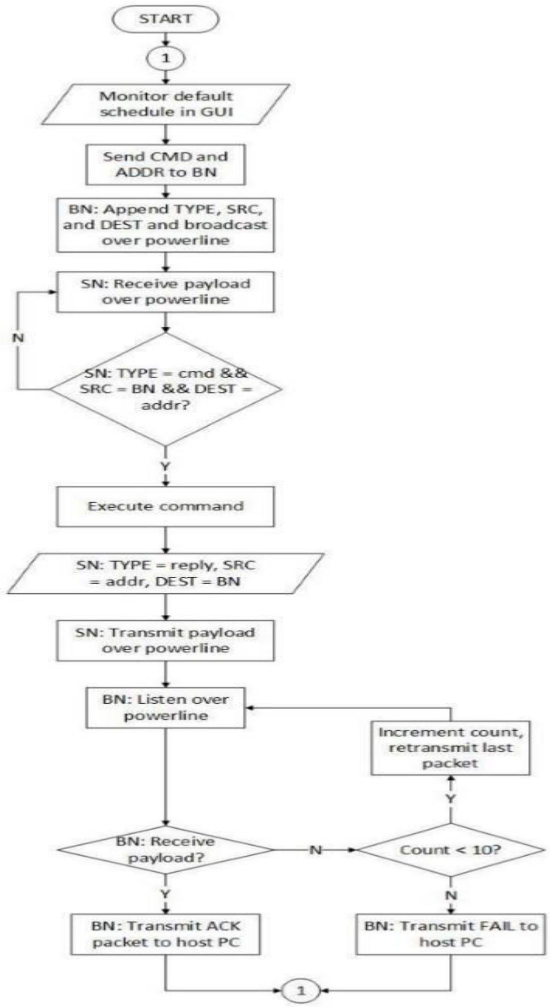

Figure-2. System flowchart.

Table-1. GUI activity.

If there is a class scheduled in the room	
Activity	**Time**
GUI sends an ON command to turn ON the ACU	15 minutes before the class period
GUI sends an ON command to turn ON the lights and fan	start of class period
GUI requests status from the motion sensor, when No Motion, the OFF command is sent	30 minutes after the class period
If there is no class in the room	
GUI sends an OFF command to turn OFF all appliances	1 minute after the end of the class period
If the next class schedule is only 30 minutes apart from the previous class	
GUI sends OFF command to turn OFF lights and fans only	one minute after the end of the class period

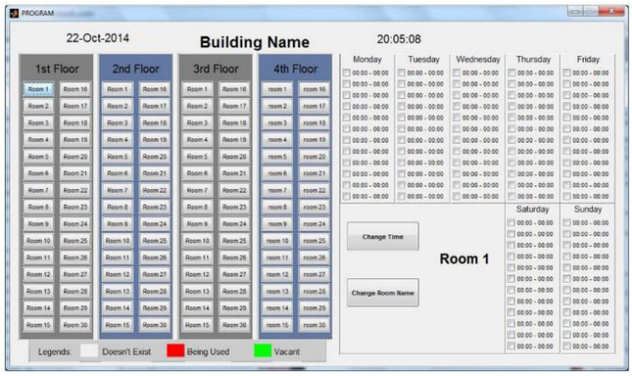

Figure-3. Graphical user interface.

In the GUI, the user can set the COM port number where the modem is connected to. The GUI is invoked with a password and uses handshaking as a method of communications.

3.3 PLC modem

The PLC modem used in this study is TMDSPLCKIT-V3 C2000 Power Line modem developer's kit which can be programmed to work on either of the NBPLC standards mentioned inSec. 2. It operates on various modulation schemes that include D8PSK, DQPSK, DBPSK with or without Forward error correction (FEC). The modulation scheme used in this study is DBPSK+FEC with a data rate of 21.4 kbps as specified in its data sheet. Specifically, PRIME operates from 42 kHz to 89 kHz using orthogonal frequency division multiplexing (OFDM). The signal is transmitted using 97 subcarriers whereby 96 are for data and one is for the pilot signal.

3.3.1 Base node configuration

The base node program is derived from three sample projects of Texas Instruments: TI_Prime_phy_example, sci_echobak, and scia_loopback_interrupts. The first project is a basic implementation of powerline communications using two TMDSPLCKIT-V3 modems using a TMSF28069 DSP chip. This project simply initializes the two modems. The first modem transmits a fixed test payload to the second modem and the second modem sends it back upon reception. This project is crucial because it shows the implementation of the PHY layer APIs particular to powerline communications. Important functions such as PHY_txPpdu() which begins payload transmission and PHY_rxStart() which synchronizes the modem with the powerline were used here. The sci_echoback project is a simple program that allows the DSP chip to communicate with the host PC with the use of the hyperterminal, an application typically found in Windows OS which provides an interface to emulate terminals such as serial ports. The original echoback example was actually implemented using SCI-A (Serial Communications Interface) which is the RS-232 interface on the TMDSPLCKIT-V3. However, problems were encountered in implementing this interface so the

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USB/JTAG interface or SCI-B was used. An important component of initializing SCI-B was choosing the appropriate baud rate that will match with the host PC. The baud rate depends on the oscillator clock (OSCCLK) and sci_echoback sets this at 10MHz. However, this setting caused problems in the base node program. The clock was changed to 20MHz, the external oscillator clock setting used in a hidden program, InitSysCtrl(). Fortunately, this clock frequency worked for the BN program. Two other Baud Rate Registers (BRR), SCIHBAUD and SCILBAUD must be coded with the correct values. Equation 1 shows how the values are obtained.

$$BRR = \frac{\text{LSPCLK}}{\text{SCI Asynchronous Baud x 8}} \quad (1)$$

The third program contains Interrupt Service Routines (ISR) which is essential for payload transmission and reception. An interrupt sets a flag which latches an enable and consequently issues a global interrupt. When the main program halts, the data is saved and the ISR is called. The three programs were integrated to form the base node program. The base node's basic functionality is to receive commands from the graphical user interface and relay them to the appropriate service nodes. This means that the modem must always check for new commands from its host PC and transmit it immediately over the powerline. The program is then structured as a scheduler: an infinite loop continuously polling for event-driven interrupts. Figure-4 shows the flowchart for the BN program.

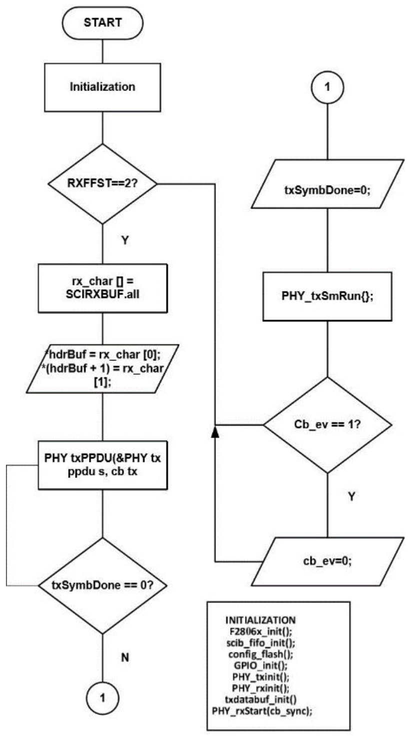

Figure-4. Base node flowchart.

3.3.2 Service node configuration

The program for the service nodes is based primarily on the PHY example project for F28069 provided by Texas Instruments. The said project demonstrated transmission and reception between two modems by calling the PHY library API. For this application, the service nodes operate only as receivers hence functions from the API such as PHY_rxStart() and PHY_rxPpduStart () were implemented. The PHY_rxStart() is called to start channel acquisition which includes analyzing of correct preamble and header. On the other hand, PHY_rxPpduStart () is called after the former function was completed successfully. This function is responsible for transferring the received data to the callback function. The service node flowchart is shown in Figure-5. Its initialization segment is similar to that of the base node except that the peripherals involved in the initialization of the scib_echoback were excluded. As soon as initialization is complete, the service node waits for any data transmitted by the base node. If it received anything, the ppdu is passed to the call back function, cb_ppdu. Once in the call back function, it compares the address of the received signal (placed on the first element of the header) to the address assigned to the service node. Given that the addresses are alike, LED2 on the controlStick toggles and it executes the value stored in the second element of the header, which is the command. Execution of command is done through the function periph_exec ().

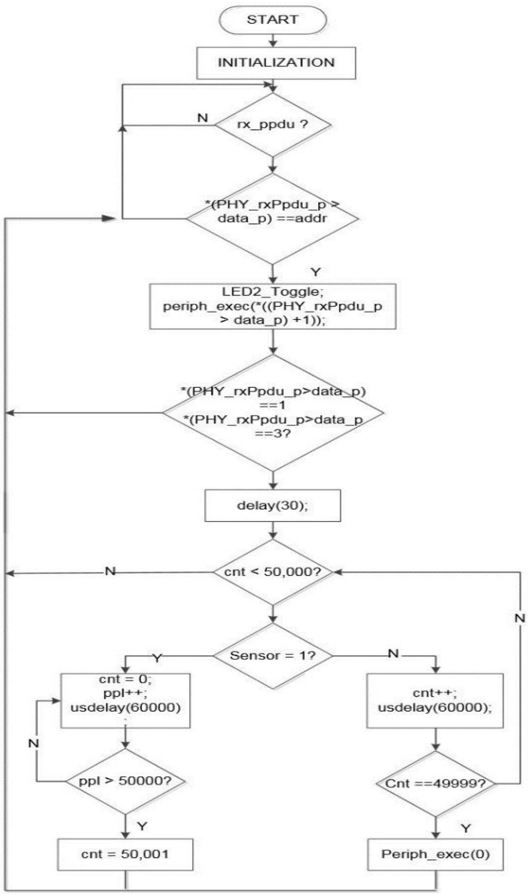

Figure-5. Service node flowchart.

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3.4 Electrical interface

Two types of relay are used to drive the appliances, namely, relay card and solid state relay (SSR). The relay card is used to drive the lights and fans, while the SSR is used to drive the air conditioner. SSR can handle high current which is typical of ACU. The logic high produced by the modem would turn the appliance ON while the logic low turns the appliance OFF.

4. TEST MEASUREMENTS

Tests are done to determine the effect of the modulation and distance on the PLC transmission as well as test on the reliability of the system.

4.1 Modulation scheme test

The test set-up used for this test is shown in Figure-6. The base node and the service nodes are placed along a stretch of electrical wiring in the research building of our University. An extension wire was added to put SN3 in the farthest point. Loads are plugged in to the available outlets to determine its effect on the transmission. The loads consist of the ACU, the lights and fans, and two blenders. In all the tests, the data sent by the BN to the SN are successfully received with and without loads for all the modulation schemes used, that includes D8PSK, DQPSK, D8PSK +FEC, DQPSK +FEC, and DBPSK + FEC. Comparing this with the test using the modem's firmware, the latter provides a reliable transmission at DBPSK with FEC only.

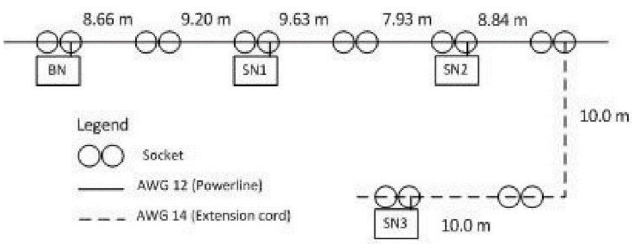

Figure-6. Test Set-up for modulation scheme test.

4.2 Distance test

In this test, the PLC modem is characterized by varying the distance between two modems. Using the DBPSK + FEC modulation scheme and the service node program developed, the signal-to-noise ratio (SNR), the received signal level (RSL), the receive quality (RQ), and the Noise Level (NL) are measured. The test set-up is shown in Figure-7. This test was conducted by placing the base node in a stationary reference point, and one service node was moved across different points with increasing distance. A script was written in MATLAB to provide an interface that could easily read the data. The summary of the various parameter values for all the distances is shown in Table-2. Expectedly, the SNR worsens as the distance increases and so with the quality of the signal where 0 are bad and 7 very good.

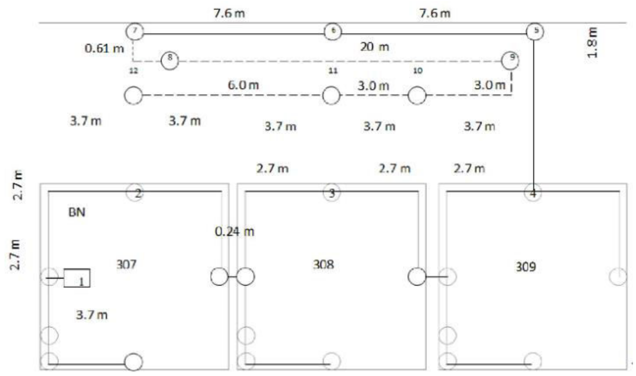

Figure-7. Test set-up for distance test.

Table-2. Received parameter values for each socket location.

Socket No.	Distance (m)	RSL (dBμv)	NL (dBμV)	SNR (dB)	RQ
1	6.4	83.6	92	20.4	7
2	10.1	76.8	92	10.2	4
3	10.34	76.8	92	10.2	4
4	23.14	75.6	92	8.4	3
5	31.34	75.6	92	8.4	4
6	38.94	76.6	92	9.9	3
7	46.54	76.4	92	9.6	4
8	47.15	76.4	83.7	9.6	4
9	67.15	76.4	92	9.3	3
10	70.15	76.2	92	6.9	4
11	73.15	74.6	92	9.9	3
12	79.15	76.6	92		3

4.3 System test

This test aims at verifying the functionality of the EMS. Three consecutive classes with one hour and one and one half hour duration are inputted to the scheduler program and are shown in Table-3. The status of the airconditioning unit (ACU) and the lights and fans (LF) are recorded in Table-4.

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Table-3. Class schedule in three rooms where the SNs are deployed.

SN1		SN2		SN3	
09:00-1030	Class	09:00-10:30	Class but called-off	09:15-10:15	Class
10:31-11:14	No class	10:45-12:15	Class	10:45-12:15	Class
11:15-12:45	Class but called-off	12:30-1330	Class	12:30-1330	Class but called-off

Table-4. Appliance Status relative to class schedule in the prior table.

Time	ACU	LF	SN
8:45	ON	OFF	SNI, SN2
9:00	ON	OFF	SN3
	ON	ON	SN1, SN2
9:35	OFF	OFF	SN2
10:16	ON	OFF	SN3
10:30	ON	OFF	SN2
10:31	OFF	OFF	SN1
10:45	ON	ON	SN2, SN3
11:00	ON	OFF	SN1
11:15	ON	ON	SN1
11:50	OFF	OFF	SN1
12:16	ON	OFF	SN2, SN3
13:05	OFF	OFF	SN3
13:31	OFF	OFF	SN2

The command program in the host PC is sending the service node a 'turn ON the ACU' command fifteen minutes before the class period starts. The lights and fans are turned ON at the exact time the class starts. The first row in the Table shows the turning ON of the ACU for the first room at 8:45 am. The lights and fans are turned on at 9:00. The room where SN3 is placed has a class that starts at 9:15, and it can be seen that the ACU in this room is tuned on at 9:00. The class event is simulated by asking students to stay in the two rooms where the class is supposed to be taking place where the other room where the class is supposed to be called-off is left vacant. Since the motion sensor in room SN2 is not detecting any movement, it sends this status to the base node. As per policy in the school where this project is implemented, the students can leave the room if the professor does not arrive after thirty minutes. To accommodate this in the program, the base node inquires the status of the motion sensor thirty minutes after the start of the class for rooms with scheduled classes. Given that SN2 room is empty, the ACU is turned OFF by 9:35. The ACU is turned off right after the class if the scheduler shows that there is no class following the previous schedule with duration of at least 30 minutes. The table records this at 10:31. The rest of the test shows that all the commands were executed successfully.

5. CONCLUSIONS

The Energy Management System in this study comprises three components, the GUI, the PLC network, and the electrical interfaces to the appliances. The power line network implemented used a base node and three service nodes.

The utilization of narrowband PLC using the PRIME standard is a promising technology for EMS application. The modulation scheme that was noticeably robust for this type of implementation using the basic PRIME program embedded in the modem is DBPSK+FEC. The revised PRIME program for the base node and service node allowed transmission in all the modulation schemes, namely, DBPSK, D8PSK, and DQPSK with or without FEC. As to the distance test, it was prominently observable that as the distance between the modems increases, the SNR gets worse and so the received quality of the signal. It was also observed that the transmission time takes longer. The load test shows no significant effect on the transmission.

One of the problems encountered during the initial test was that the modem could not handshake the host PC. It was rooted to the use of the 10MHz which was inherent to the firmware program. Apparently, this clock frequency does not synchronize with the PC. The clock frequency at which the modems interfaced successfully with the PC is set at 20MHz. This clock frequency ensures that the baud rate of the PC synchronizes with the baud rate of the modem.

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