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Development of a Cost-effective Half-Duplex Power Line Communication System for Low Bandwidth Home Automation Applications

W. M. S. G. Wanninayake
Faculty of Engineering
University of Sri Jayewardenepura
Sri Lanka
en82734@sjp.ac.lk

B. U. Kumarasiri
Faculty of Engineering
University of Sri Jayewardenepura
Sri Lanka
en82677@sjp.ac.lk

M. N. Dharmaweera
Faculty of Engineering
University of Sri Jayewardenepura
Sri Lanka
nishanmd@sjp.ac.lk

B. Pilanawithana
Faculty of Engineering
University of Sri Jayewardenepura
Sri Lanka
bhathiya.pilanawithana@gmail.com

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***Abstract*—This paper proposes a novel, cost-effective power line communication (PLC) system for low bandwidth home automation applications such as switching, dimming control, and periodic status reporting. The proposed system consists of a main controller node and several appliance nodes. Electrical appliances to be automated are connected through the appliance nodes to the power outlets (i.e., sockets). The main controller node, which is plugged into one of the power sockets, has an active internet connection. The home network with a star topology, where appliances are centred around the main controller node, communicates over the powerline. The proposed solution, which is a half-duplex communication system, controls appliances by sending commands from the main controller and retrieve sensor data from the appliances. The developed system provides a low-cost alternative to available solutions in the market. This paper highlights novel electronic engineering techniques used to maximize cost-effectiveness without compromising the overall quality of the proposed system.**

Keywords— power line communication, AC mains, half-duplex, low bandwidth applications

I. Introduction

Recent advancements in engineering have made the term "Smart" a key descriptor of most emerging technologies. To enhance the comfort in lifestyle and time management, smart solutions are widely being adopted by consumers [1]. With the introduction of the concept of smart homes, tasks such as lighting, security, heating, ventilation, and air conditioning (HVAC) can now be controlled using a simple mobile application or fully automated [2]. In general, home automation is often carried out using wireless communication mediums such as Wi-Fi, Bluetooth, long-range infrared, and ZigBee. These technologies offer several advantages over wired mediums like Ethernet [2]. However, due to coverage issues, initial set-up costs, signal interferences, low battery life, security, and health-related concerns, alternatives to wireless mediums are sought by many researchers [3], [4]. Power Line Communication (PLC) has thus been proposed as a viable alternative [5].

The Internet of Things (IoT) based devices are expected to play a major role in smart homes. Consequently, a massive number of wireless IoT devices will interconnect in a smart home, and hence, the usage of wireless frequency resources will increase rapidly. Resultantly, the inadequacy of spectrum resources might limit the number of wireless IoT devices that can be connected in the near future [6]. In wireless communications, the transmission range of the signal and the strength of the received signal vary due to various reasons such as radio-frequency interferences, signal blockage by walls, environmental conditions, and the physical location of the targeted appliance [3]. Thus, signal repeaters (i.e., wireless extenders) are often needed to provide the required coverage in multistory and large buildings [3].

Although wired medium can alleviate some of these drawbacks of wireless systems, a few issues hinder their performance too [7]. A major shortcoming in most wired networking solutions is the requirement of newly laid channels, which makes house networking difficult, costly, and may negatively affect aesthetics. Thus, manufacturers and consumers seek novel solutions [8].

PLC addresses many of the issues pertaining to wireless technologies and provides a mechanism to transmit data using already existing household electrical wiring. PLC is currently being used in narrowband communication and in broadband communication, according to [9]. Home automation and industrial automation do not require high data rates whereas broadband power line communication requires higher data rates. This technology has already been standardized and used worldwide.

While smart homes are not a novel concept, people in developing countries are still hesitant to use them due to the associated high initial investment and lack of technical knowledge. Moreover, most of the products available in the market lack quality and often require proprietary sockets, devices, and technologies. Furthermore, the majority of these available solutions are not designed for low bandwidth applications and, therefore, are more complex and expensive [4].

Low-bandwidth smart home solutions are often used to automate lighting, dimming, and HVAC [2]. However, the PLC-based half-duplex smart home solutions can not only be used for controlling the appliances but can also be used to monitor their status [2]. Over the past few decades, several solutions have emerged to promote energy efficiency across all sectors. As explained in [2], [10], smart home solutions are

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now being developed to recognize the power consumption of individual appliances and inform the consumers. Such solutions will not only help in reducing the electricity bill of end consumers but will also help utility providers in optimizing and planning the energy generation and transmission networks. Although there are various power measuring mechanisms, most give an overall power usage in the house. Therefore, a well-resolved mechanism to measure the power consumed by each appliance is yet to be developed and popularized.

PLC-based smart home solutions can also be used to provide protection to connected devices. Studies show that people often experience damages in appliances due to over-current and overheat. At present, protection against such failures is performed using MCBs and fuses that generally disconnect the whole sub-circuit of the electric network when an abnormality is detected. However, a node-wise over-current and over-temperature protection method can simplify this operation and provide added protection.

This paper proposes a novel PLC-based solution that can be used efficiently and cost-effectively to accomplish home automation tasks that require low transmission speeds. The proposed solution is presented in the form of a physical device (i.e., node) and a novel power line communication protocol. The solution is designed and developed to enable cost-effective manufacturing without compromising reliability and to provide the required protection to the user and the devices. The performance of the proposed solution is validated experimentally by prototyping and running tests in actual home environments. Fig. 1 represents an overview of the proposed system. The main contributions of this paper are:

- Design, develop and prototype a cost-effective half-duplex PLC system targeting applications which require low data rates.
- Use an entry-level Texas Instrument's (TI) MSP430FR2355 microcontroller unit (MCU) and an AFE031 analog front-end IC to ensure minimum manufacturing cost.

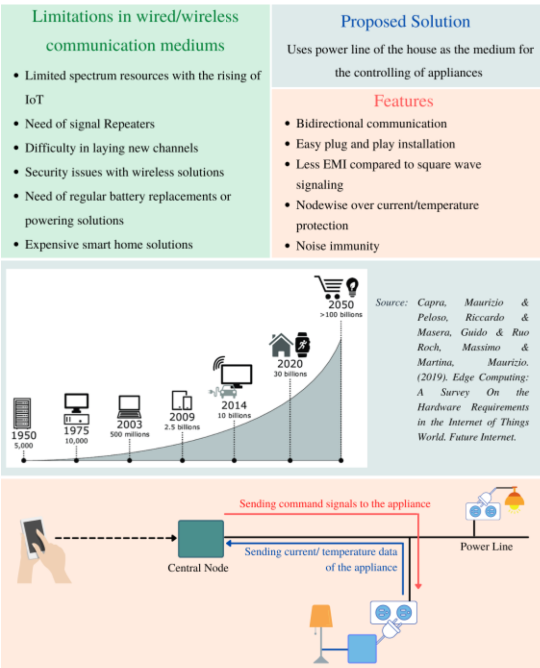

Fig. 1. Overview of the proposed system

- Use innovative techniques such as timer capturing and template matching, to accomplish RF sampling and noise immunity.
- Experimentally validate the performance; functionalities of the system, range, noise immunity, and electromagnetic interferences (EMI).

Section 2 of the paper reviews the existing protocols and products that utilize PLC technology. Section 3 presents the concept and the system architecture of the system. Section 4 discusses the techniques used for the reduction of cost without compromising performance. Finally, the tested results are presented in Section 5.

II. Related Works

The available PLC systems can be categorized according to the data rates, application, and environment. Narrowband PLC has low data rates and is often used in automation applications. On the other hand, broadband PLCs are used for high-bandwidth applications. PLCs are used in both indoor and outdoor environments.

A. Standards

IEEE, IEC, ARIB, CENELEC and FCC are some standardization organizations that have declared PLC standards [11], [12], [8]. Apart from them, PRIME, G3-PLC, KNX, and HomePlug are some groups that deploy PLC technologies declared by the above standards [13]. In [13], the authors have compared different standards according to their modulation method and the data rates. HomePlug which is used mostly for broadband applications employs Phase Shift Keying (PSK) and Quadrature Amplitude Modulation (QAM) schemes. PRIME and G3-PLC are narrowband PLC technologies used for smart metering and smart grid applications. They use Orthogonal Frequency Division Multiplexing (OFDM), enabling data rates up to 200 kbps. MAX2990 modem by Maxim Integrate also uses OFDM delivering 100 kbps of a data rate. IEC61334 and IEC14908-1 standards use Spread Frequency Shift Keying (S-FSK) and Binary PSK (BPSK) supporting data rates between 2.4 and 5.0 kbps.

B. Available frequencies and the effect of noise

The recommended frequency bands for home automation according to CENELEC EN50065 and FCC standards are 95 kHz - 148.5 kHz and 148.5 kHz – 500 kHz, respectively [5]. Frequencies above 1.6 MHz can also be used according to [9].

The channel characteristics of indoor environments have been analyzed at different frequency ranges in [5], [13], [14]. One major factor that should be considered in PLC is channel noise. According to [13], the noise can be categorized as narrowband noise, background noise, and impulsive noise. The background noise depends on the environment of the PLC system. A higher noise is observed in indoor PLC when compared against outdoor PLC. The noise (i.e., narrowband noise) originating from radio broadcasting services affect broadband PLC due to the use of similar frequencies. Impulsive noise is generated by electrical appliances that are connected to the wiring. These appliances can produce periodic synchronous/asynchronous or aperiodic noise.

According to [9] narrowband PLC applications often use frequencies in the range of 3 kHz – 500 kHz, while the broadband PLC applications use frequencies in the MHz range. When considering the channel characteristics of communication, power lines exhibit deep notches in the frequency response after a few MHz, which indicates that they act as notch filters in higher frequencies [5]. Due to differences in the length, material, and insulation, these notch frequencies vary, making it difficult to generalize an operating frequency that would suit all the channels. Simply put, at higher frequencies, the PLCs attenuate the signal more than in wireless channels. Also, most of the radio broadcastings are done using MHz frequencies. Thus, to minimize the interferences, severe filtering processes have to be adhered to in high-frequency PLCs.

Using low frequencies in the range of 3 kHz to 50 kHz has noise-related issues due to switch-mode power supplies and appliances such as CFL bulbs that generate noise in this frequency region [5]. Amateur radio transmissions use frequencies in the kHz range where the power lines may cause electromagnetic interferences. However, the use of the kHz frequency range for signalling in PLCs will not affect radio broadcasting much as only a few countries use the kHz range for radio transmissions.

C. *Modulation formats*

From [13], it is clear that single-carrier modulation techniques are less complex than multi-carrier techniques. The most popular multi-carrier modulation scheme used is OFDM. Some of the single carrier modulation schemes used are MQAM, MPSK, FSK and SFSK.

Broadband PLC has achieved higher data rates using OFDM, allowing several data streams to be transmitted simultaneously. However, this increases the cost due to the complexity in manufacturing.

Amplitude shift keying (ASK) is also a simple, easy to implement modulation method, but it is well susceptible to noise and to signal attenuations in the power lines. Therefore, PSK/FSK and OFDM are widely used in PLC protocols in the market.

D. *Available protocols and limitations*

Here we list some of the available protocols for home automation and highlight their key limitations.

Although X10 is well regarded as a worldwide protocol and a standard, it is less reliable and has limitations such as low immunity to noise and packet losses [15]. However, its popularity has not diminished over time since X10 provides easy plug and play capability, and thus, is used by electrical appliance manufacturers such as Leviton in their products. X10 is a simplex protocol that offers mostly lighting and switching control. According to [5], X10 experiences large attenuations of signals in transmitting in 3 wire systems.

According to [16], Insteon is a dual mesh topology where the data communication is carried out in both the powerline and wirelessly. It has often been referred to as the RF backbone. It uses (Phase-Shift Keying) PSK for the communication in the power line and Frequency Shift Keying (FSK) in the RF backbone. Insteon devices are capable of co-existing with X10 devices. Insteon allows a bit rate of 180 bps, which is higher than that of X10. This protocol uses a simple mechanism of sending a high-frequency burst signal. These mechanisms in Insteon and X10, tend to introduce many harmonics due to the square wave signalling and thus create high electromagnetic interferences (EMI), according to [17].

Universal Powerline Bus (UPB) is an advanced proprietary protocol as mentioned in [18]. Although X10 and Insteon devices are plug-n-play devices, UPB devices are not plug-n-play capable and, instead, it has to go through an initial installation process. When compared with X10, UPB devices have a lower market share. The protocol uses a Pulse Position Modulation (PPM) in communication. Therefore, both the receiver and the transmitter have to be accurately synchronized.

HomePlug Green PHY is a popular PLC protocol used in applications such as smart grids, smart metering, home appliance controlling [19], and electric vehicle charging [20]. GreenPHY devices do not require technical support from the manufacturers. However, the manufacturing costs are relatively high when compared with X10 because of the high computational complexity.

Analyzing the aforementioned information, it becomes evident that there is a trade-off between reliability, features, and cost in selecting a specific PLC technology among the available protocols.

Moreover, several companies like Texas Instruments, Maxim Integrated, STMicroelectronics and Develo have developed modems and development platforms for the ease of use and development of PLC systems, mostly with OFDM and variations of PSK modulation schemes [13].

In [21], the authors have used a TDA5051A modem that uses ASK and an ATMEL microcontroller. The computer sends data to the transmitter side modem, and received data from the receiver side modem is sent to the microcontroller. The microcontroller then operates the devices accordingly. However, the results and the reliability of the proposed transmission method are not well presented. Further, the operation of the system is less user-friendly.

The PLC-based home automation system presented in [22] uses an XM10 power line transceiver, which integrates the X10 protocol with an ATmega microcontroller.

In PLC systems, the most widely used couplers are transformer couplers. In [23], a transformerless coupler with a passive coupling filter is analyzed and tested in the CENELEC band. It shows that passive coupling filters can be designed for narrowband PLC by carefully choosing the components, reducing the cost significantly.

In summary, the use of OFDM increases cost, usage of ASK results in high attenuation with noise and square wave signalling would add more harmonics to the powerline, hence, creates high EMI. Also, complex installation and high cost of the products have made the public hesitant to use PLC. The proposed system in this paper addresses these problems identified by providing a reliable and economical solution. The major problem of signal detection under channel noise is achieved here using an innovative mechanism. An added feature of the system is that it will enable remote measuring of power consumption and temperature of connected devices/nodes and provide protection against excess current and temperature. It will lay the foundation for better smart home solutions and thereby broaden the usage and increase the availability of home automation solutions.

III. Concept and Structure

The objective of the proposed system is to provide a reliable low-cost narrowband PLC system that can be used for controlling simple lighting and switching devices and provide a communication medium to low bandwidth applications while maintaining less EMI.

The system uses the existing electrical wiring of the house to transfer data. The system consists of a main controller node and multiple appliance nodes. The user will communicate with the main controller node via the mobile application as shown in Fig 1. Electrical appliances are connected to the home wiring via the appliance nodes. The main controller node will communicate with appliance nodes through PLC. According to the inputs from the user, the main controller node transmits data over the power line to the corresponding appliance node for the control of the electrical device. The system is a half-duplex communication system with the added feature of retrieving temperature and current sensor data from appliance nodes.

The signals at the transmitting end will be injected to the power line or the AC mains line at the zero-crossing of the AC mains and retrieved from the zero-crossing at the receiver end. This supports in achieving synchronization of the data frames. The system uses ON/OFF keying. A 78 kHz sinusoidal wavelet is injected to the power line from the transmitting end at the zero-crossing of the AC mains to represent a recessive bit (HIGH, bit value 1). No signal is injected at the zero-crossing to represent a bit zero. The signals comply with the CENELEC band standards. In further advancing, the system can be developed into the use of 4-FSK, increasing the data rate by two times.

Each node consists of 4 major sections: main control unit, Analog Front End (AFE), Signal Coupler and I/O section. The I/O section comprises of the zero-crossing detection pre-processor, current sensor, temperature sensor, TRIAC controller and other relay signal outputs. Fig. 2 represents a functional block diagram of a node.

A. Main Control Unit

The main control unit of the system is an MSP430FR2355 microcontroller from Texas Instruments. This is intended to carry out the following functions.

- Detection of the zero-crossing of the AC mains using the signal from the zero-crossing detector pre-processor.
- Sending digital data to the AFE to construct the injected wavelet using the inbuilt digital-to-analog converter (DAC).

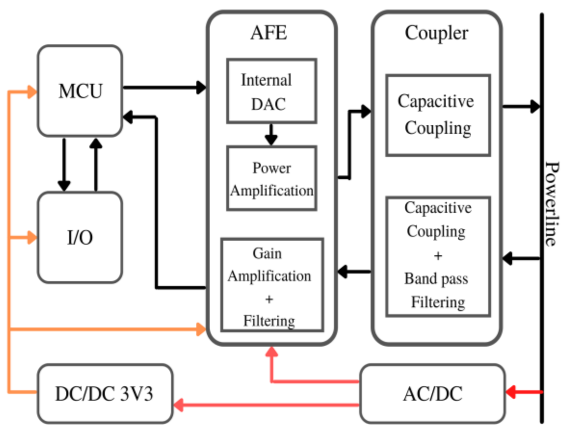

Fig. 2. Functional block diagram of a node

- Determining bits from the output of the AFE's signal receiving path (Rx path).
- Processing temperature sensor and current sensor values.
- Controlling TRIACS and executing other switching commands.

The zero-crossing pre-processor gets the AC mains voltage waveform as the input and outputs the same waveform by fitting it to the range of the MCU analog-to-digital converter (ADC), 0V-3.3V. Then the MCU samples the miniaturized 50/60 Hz signal. Once the sampled and quantized value falls into a pre-determined range near the zero-crossing, the ADC will generate an interrupt. Once the zero-crossing of the AC mains is detected, it will proceed with communication as in the Interrupt Service Routine (ISR).

When the node is in transmitting mode, the MCU sent digital values to the AFE's inbuilt DAC through the serial peripheral interface (SPI) between MCU and the AFE.

The MCU carries out the task of bit determination when the node is in the receiving mode. It listens for incoming wavelets at every zero-crossing using the signal output from the Rx path of the AFE.

Apart from communication-related tasks the MCU reads the sensor values using inbuilt ADCs and maps the ADC values into real-world values corresponding to those values.

Finally, the MCU carries on actuation tasks. It is capable of controlling TRIACs for dimming applications along with other switching tasks. The ADC interrupt for zero-crossing detection is used to generate pulses required for TRIAC switching.

B. Analog Front End

The power line communication analog front-end IC AFE031 from Texas Instruments is used as the communication interface to the power line. Mainly, the AFE has four functions in the system.

- Generation of the wavelet using the inbuilt DAC.
- Power amplification of the wavelet.
- Gain amplification of the received signals from the band-pass filter of the signal coupler.
- Additional filtering in order to comply with CENELEC bands.

The inbuilt DAC generates waveforms from the digital data fed through SPI. The generated waveforms are then power amplified. The Rx path of the AFE consists of two gain amplification stages. The gains in both Rx path amplifiers are software programmable along with the gain of the power amplifier.

C. Signal Coupler

The generated signals are injected to the power line through this circuit which is presented in Fig. 3. The signals are coupled to the powerline using capacitive coupling. The Rx path of the circuit is a bandpass filter having the cut-off frequencies, 56 kHz and 200 kHz. The transmitter path filter is a bandpass filter. Additionally, an LC resonator is included to resonate with the injected wavelets.

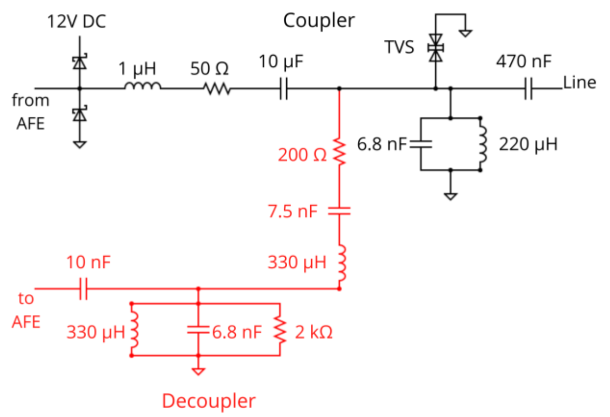

Fig. 3. Circuit for the signal coupler

D. I/O section

1) Zero-crossing Detector Preprocessor

This circuit which is given in Fig. 4, consists of a differential amplifier with an integrator. This operational amplifier has a fractional gain so that it attenuates the AC mains peak-to-peak value 620 V signal into a signal with a peak-to-peak value of 3.3 V. Additionally, it adds an offset of 1.56 V to the output signal so that it does not fall into negative values making the output suitable to be sampled by the MCUs ADC.

2) Temperature Sensor and Current Sensor

A positive temperature coefficient (PTC) resistor is used in a voltage divider circuit with another 10 resistors as the temperature sensor. The current sensor was designed by measuring the voltage across a shunt resistor. This voltage measured across the resistor is amplified using a differential amplifier and then fed to an ADC of the MCU to be sampled. As for the purpose of reducing the bill of material (BOM) count, this current sensor is planned to be replaced by an off-the-shelf current sensor IC in the market.

3) TRIAC Control and Switching

MCU can give signals to switch on/off the relays for switching purposes. The system is capable of providing variable power to loads for dimming purposes. This task is accomplished using periodic switching of TRIACs. Once the zero-crossing is detected, it initiates a timer to generate an interrupt at a given time point according to the dimming value. In that timer ISR, the MCU generates a voltage pulse with a satisfactory time duration to switch on the TRIAC. This continues after every zero-crossing. All the switching signal ports of the MCU are isolated using opto-triacs.

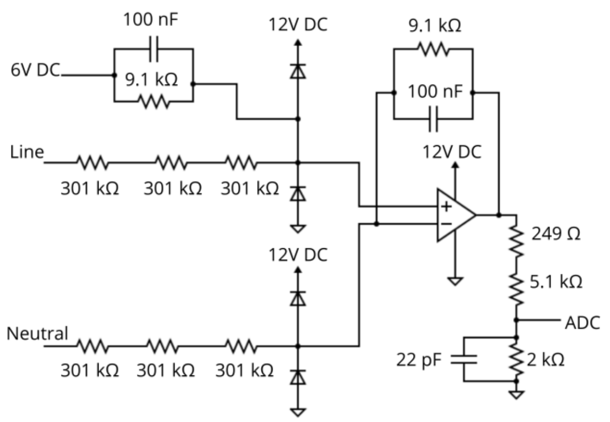

Fig. 4. Zero crossing detector preprocessor circuit

E. Data Link Layer

The frames are designed with 16 bits including an 8-bit frame delimiter of 01111110 (0x7E in Hex) as in high level data control (HDLC) protocol. Frame delimiter is followed by 3 address bits, 1 read/write bit and 4 data bits in the initial stage. This is to be further improved by introducing cyclic redundancy check (CRC) bits, which can be implemented within the in-built module for CRC in the MCU by increasing the address and data bits.

All the nodes use the same physical layer hardware. The main controller node has an additional connection to the internet. The bi-directional communication was achieved using the designed data link layer for the system given in Fig 5.

IV. Optimization Techniques for Cost Reduction

A. Generating High-Frequency Signals Using Low-Cost General Purpose MCUs.

The AFE031's SPI block runs on 16-bit and 10-bit frames. It uses 16-bit SPI frames when configuring system settings, and uses 10-bit frames when feeding data to the DAC. In order to reduce the cost of a node, we chose a low-cost MCU (MSP430FR2355) where the SPI hardware block only supports 8-bit and 7-bit framing. Therefore, the SPI communication between the MCU and the AFE031 was implemented manually using a software-based approach.

B. RF Sampling Without Using an ADC

The MCU's inbuilt ADC is having a low sampling rate of 200 ksps. Thus, an adequate RF sampling for the system was accomplished using an innovative technique. The sampling of received signals was carried out using a timer capture method without using the ADC. After a zero-crossing is detected, a timer is set to count, and the timer captured values in every rising edge of the clock are stored. When all the stored values

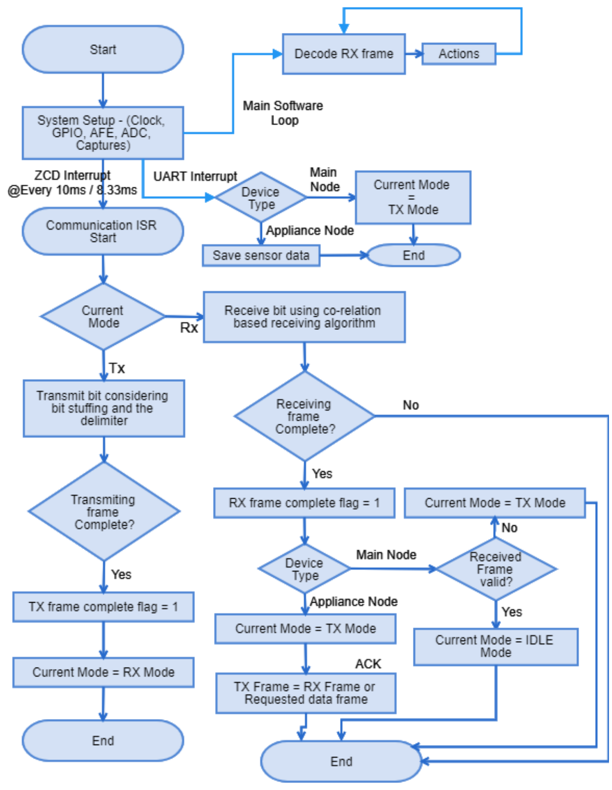

Fig. 5. Data link layer operation flow diagram

are non-zero, the received bit is recognized as a HIGH bit, and when all the stored values are zero, it is recognized as a LOW bit.

C. Power Line Noise Compensation

The impact of noises on the signal detection was removed by fine-tuning the bandpass filter to narrow down the pass bandwidth. Further, noises that were not susceptible to filtering were compensated using a correlation-based template matching algorithm. The timer capture values stored as mentioned above were compared with a template of timer capture values in an ideal power line without noise. The correlation coefficient between the template and the present capture values are calculated from which the bits are determined, eliminating erroneous bit detections.

V. RESULTS

The prototype of the system was built with the main controller node, two appliance nodes and the mobile application for testing as shown in Fig. 6 and Fig. 7. The prototype in Fig 6 was designed in the initial stage with the objective of providing the opportunity for modifications while testing. The finished nodes will be small in size and confined within an enclosure.

A. Testing for Zero-crossing Detection

The zero-crossing detection was initially tested by supplying a generated signal of 50 Hz and 60 Hz and proceeded by plugging to the AC mains.

B. Testing in conditions with different noise levels.

The system was initially tested in an ideal environment where no noise was present in the power line without the correlation-based template matching algorithm. The bit determination could be accomplished. Then the system was tested in an environment with noise from various power-electronic switching and the bit determination was achieved successfully using the correlation-based template matching algorithm. Finally, the noise test was conducted in an environment by adding a severe EMI noise generated by an induction cooker. The correlation-based detection algorithm could successfully determine the received bits.

Fig. 6. Prototype of the main controller node

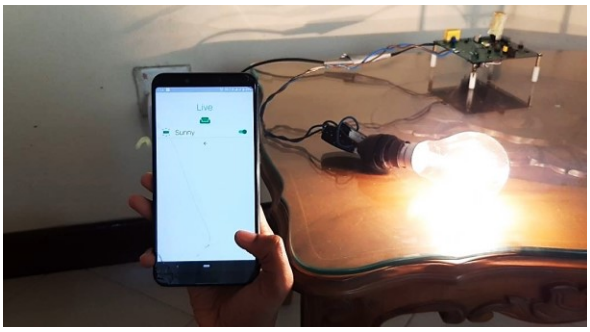

Fig. 7. Testing the prototype

Fig. 8 shows an instance where a data frame is transmitted. Channel 1 (yellow) shows the waveform to the MCU at the receiving path and channel 2 (blue) shows the recognized bit pattern. Noise can be seen in the received signal. However, with the capturing and the correlation-based method, the noise has not been wrongly detected as a signalling bit of 1. It can be seen that the presence of noise has not affected the detection of the bit pattern.

C. Testing for the range

The range of the system was tested by plugging the nodes at different places in a house. After positioning the main node in the living room, an appliance node was plugged at different places in the house. The communication could be achieved even between two different stories. The communication does not pass from one phase to another. To achieve interphase communication, a phase coupler will be developed in the future.

D. Consideration of EMI from the system

The signal injected to the power line adds fewer harmonics to the power line compared to square wave signalling. Fig. 9 and Fig. 10 show the Fast Fourier Transform (FFT) of the channel before injecting the signal and when the signal is injected respectively. From these observations, it is clear that the addition of the harmonics to the power line from the system is low. Hence, the EMI from the system can be considered minimal.

At a given instance, only one signal (data frame) for the actuation of one appliance is transmitted. These signals are transmitted only when an appliance needs to be controlled. When controlling multiple appliances, the signals for the appliances are transmitted consecutively. Hence, the noise added to the power line due to signaling will be the same as given in Fig. 10.

E. Bi-directional communication

Bi-directional communication was tested by transmitting arbitrary data frames from two different nodes. These frames were inserted and observed using the Code Composer Studio software, which was used in implementing the system. Both nodes could successfully receive and decode the received frames. Fig. 11 shows a transmitting frame of 0x7EAE with the frame delimiter 0x7E. Fig. 12 shows the stored received frame at the receiver end excluding the frame delimiter.

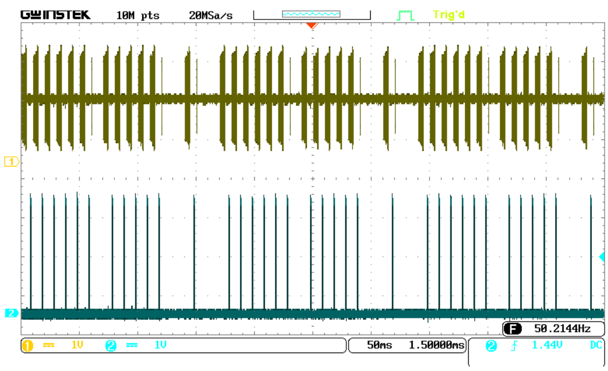

Fig. 8. Waveforms of the received data frame (yellow) and the decoded data frame (blue)

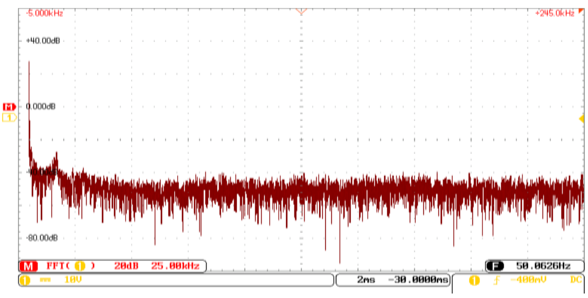

Fig. 9. FFT of the power line before adding the signal

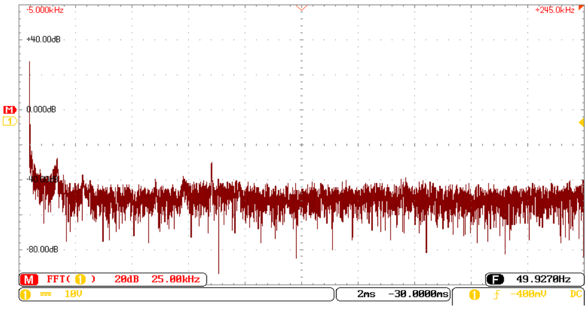

Fig. 10. FFT of the power line when the signal is added

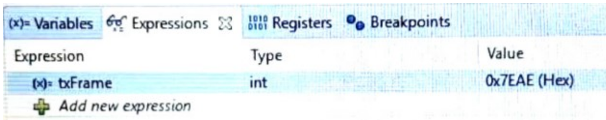

Fig. 11. Transmitted frame (0x7EAE)

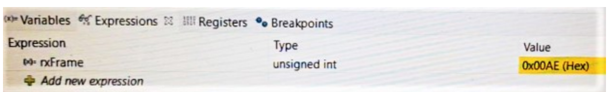

Fig. 12. Information bits of the received frame

VI. Conclusion

This paper presents a cost-effective power line communication system optimized for low bandwidth applications. The system consists of a main controller node and multiple appliance nodes. The system is capable of bi-directional communication and could communicate at a data rate of 100 bps which is adequate for lighting control, HVAC controlling, light dimming and other switching tasks.

The system is developed for a single-phase electrical network and it is to be further developed for a multi-phase network by including a suitable phase coupler.

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