The Journal of CPRI,
Vol. 11, No. 3, Sept 2015 pp. 505-516

Reliability and survivability analysis of narrowband power-line communication links in low-voltage building network applications

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Recent developments in power-line communication (PLC) based power automation and security systems are transforming into smart automation for low-voltage building network applications. This paper presents reliability and survivability analysis of G3-PLC compliant modems that aims to develop working pilot models for security as well as for complete NIT Kurukshetra campus buildings automation. In order to verify the proposed hardware design and implementation of G3-PLC system along with necessary theoretical background. Development of G3-PLC based virtual instrument to run-time couple local/remote monitoring and control of the building has been major outcome. The presented proposed design with open source platform, which is re-usable with requirement based customization, simple, user-friendly and validated through implementation. The system based on this logic can also be used for smart metrology meter (SMM) applications (i.e. metrological functions and real-time monitoring functions) and an effective tool for connecting the global consumers through energy efficiency and awareness corridor.

Keywords: *Building networks, G3-PLC, NIT kurukshetra, power-line communication*

1.0 INTRODUCTION

Power-line communication (PLC) technology is a promising solution, which provides operational and economic benefits for smart grid (SG) applications in terms of distribution automation, demand response, street lighting control, and integration of distributed generation. It reduces capital investments as well as operational costs by enabling data transmission over existing AC/DC, and non-energized electric power lines [1-2]. It offers intelligent monitoring and control of utility network operations by facilitating high-speed, long-range and extremely reliable communication and is especially beneficial for advanced metering reading (AMR), remote telemetry systems, broadband Internet access equipment, vehicle automation, as well as in micro-inverter for renewable energy applications, lighting and temperature monitoring applications [3]. The success of high-speed and low-voltage (LV) building network applications has been dependent not only on efficient power transmission, distribution and communication infrastructure, but also on efficient, effective and responsive solutions for building energy management on the customer end. In modern contexts, building automation and management has been rapidly growing phenomenon.

For high-data rate narrowband power-line communication (NB-PLC) based applications (i.e. machine-2-machine (M2M) communications, home/building automation, electric vehicle (EV) charging, G3-PLC standard is an enabler for local area networks (LANs) [4]. It employs fast Fourier transform based orthogonal frequency division multiplexing (OFDM) technology at physical

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layer. With the help of robust operation (ROBO) mode it provides stronger error correction and repetition against various types of noises and disturbances during LV smart house/building network applications. Such smart buildings shall provide high level of energy efficient optimization, security, communication and entertainment facilities. Since its inception in the early 2009's, G3-PLC has been specially designed to support worldwide PLC standards (i.e. CENELEC, ARIB and FCC bands in the frequencies range between 10-490 kHz during transmission/distribution of PLC signals [5]. It supports various different modulations techniques (i.e. DBPSK, DQPSK, and D8PSK), which are specially designed to provide a new benchmark for building energy management systems (BEMS) capabilities. G3-PLC standard is globally accepted [6] and their key features are shown in Figure 1 and can be termed as:

FIG. 1 G3-PLC KEY FEATURES

- Reduces infrastructure cost and provides the best performance and cost efficiency for Medium Voltage (MV) and LV power grids.
- Supports medium access control (MAC) level based advanced encryption standard (AES-128 bit) crypto mechanism for consumer data confidentiality, integrity and authenticity.
- Provides long distance communications and can effectively cross MV-LV transformers reducing the number of data concentrator units (DCUs) and repeaters needed. It also coexists with spread frequency-shift-keying (S-FSK) and broadband power-line communication (BPLC) applications.
- Improves communication under noisy channel conditions, operates at -1 dB signal-to-noise ratio (SNR).

Considering all necessary features regarding building network applications, in our project we used G3-PLC compliant modem and their key specifications are mentioned in Table 1.

TABLE 1

SPECIFICATIONS OF G3-PLC EVALUATION MODEM

Parameters	Feature Description
Operation frequency	10~490 kHz (with 72 carriers)
Modulation type	ROBO / DBPSK / DQPSK / D8PSK
Transmit power	+6 dBm ~ -10 dBm (can be adjust by software)
Power supply (All in DC)	Core supply: +4 ~ +5 V Line driver: +12~+12.5 V
Power consumption	Maximum: 3.6 W Average : 1.1 W
Storage temperature	-30°C to +70°C / 5% to 95%, non-condensing
Operation temperature	-40°C to +85°C / 5% to 95%, non-condensing

Considering G3-PLC advantages, this paper presents proposed test design set-up with the help of G3-PLC evaluation modem for reliability and survivability analysis at NIT Kurukshetra building network applications. Computer simulation and real-time implementation were performed on a notebook computer, intel® Core™ 2 Duo CPU P8700 @2.53 GHz with 4 GB RAM in Windows XP environment. These results will be useful for energy saving, fulfilling the gap between electricity demand and consumption, energy security and for the promotion of energy efficient building network applications.

2.0 DESIGN AND DEVELOPMENT OF HARDWARE

In order to perform following tests (i.e. reliability and survivability analysis) and speed up the application integration in NIT Kurukshetra campus, we analyzed transparent protocol with the help of G3-PLC standard compliant modems, were interfaced with STM 32F103 [7], a host micro controller unit (MCU) for software application development. G3-PLC modem includes MAX 2992 [8], which employs OFDM-based PHY/MAC layers and a 6LoWPAN adaptation layer to transmit IPv6 packets over the power line for applications can delivers half-duplex, asynchronous data transmission at PHY layer up to 250 kbps speed. The frequency usage of the OFDM signals upto 500 kHz. MAX 2991 [9], integrated analog front-end (AFE) transceiver interfaces with MAX2992, and along with the MAX 2992 G3-PLC firmware forms a complete ITU G.9903 or G3-PLC compliant modem solution. To allow for regulatory compliance, the MAX 2992 with line driver OPA2673 [10], and line coupler [11] incorporates a programmable tone notching mechanism. It allows the notching of certain frequency bands in the transmit spectrum of the modem to connect consumer application and terminal devices. It allows consumers to focus on their specific application development, and there is no need to put any effort on communication software. The transparent protocol provides an easier way to communicate from user application to terminal devices via various wired/wireless communication modules. In software aspect, consumer application program communicates with the coordinator communication module (CCM) via transparent protocol, and the data can be sent by CCM to destination terminal as communication module (TCM). In TCM side, there's no protocol between TCM and the terminal device. Therefore, the data or commands can reach terminal devices directly. The test-board are designed according to the block diagram shown in Figure 2 and can be better understand with the help of following components description. Cascading different parts of the system can be better understood with the help of this block diagram as follows-

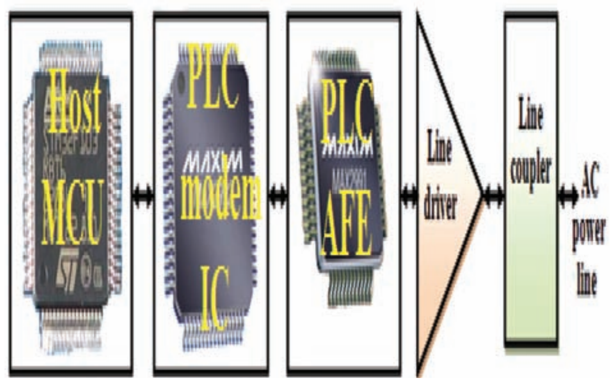


FIG. 2 BLOCK DIAGRAM OF G3-PLC TEST-BOARD

2.1 Micro Controller Unit (MCU) [7]

The family of STM32F103 microcontroller units (MCUs) consists of advanced reduced instruction machine (ARM) cortex-m3 32-bit reduced instruction set computing (RISC) core, high speed embedded memories (i.e flash memory is upto 128 Kbytes and static random access memory (SRAM) upto 20 Kbytes), input/output (I/O) lines and peripherals which they are cooperating together by connecting to two advanced peripheral bus (APB) buses. It includes many peripherals as well as two 12-bits ADCs, an advanced control timer, three general purpose 16-bit timers and also a pulse width modulation (PWM) timer. It is also provided by two inter-integrated circuits (I^2Cs) and serial peripheral interface (SPIs), three universal synchronous / asynchronous receive transmitter (USARTs), an universal serial interface (USB) and a controller area network (CAN) as the communication interface system. Figure 3, presents the block diagram for the STM32F103 family which is used in this project application.

2.2 Power line communication (PLC) modem integrated circuit (IC) [8]

The MAX 2992 delivers half-duplex, asynchronous data communication over AC/DC power lines at speeds up to 300 kbps speed. It is a system-on-chip (SoC), which combines the physical (PHY) and MAC layer with the help of inbuilt MAXQ30, a 32-bit MCU. The MAC layer is derived from IEEE 802.15.4, an interface between logical link control (LLC) and PHY layer. It adopted low-power wireless personal area network (6LoWPAN) specification to facilitate IPv6 interaction at the network layer. To allow for regulatory compliance, it incorporates a programmable tone notching mechanism. This allows the notching of certain frequency bands in the transmit spectrum of G3-PLC test board.

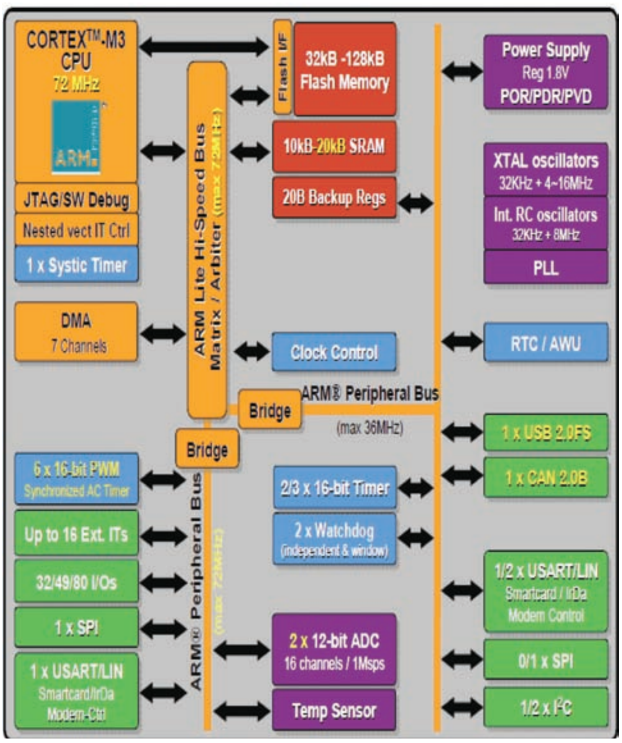


FIG. 3 BLOCK DIAGRAM OF STM32F103 MICROCONTROLLER UNIT

2.3 Analog front-end (AFE) [9]

The MAX2991 is an analog front-end (AFE), which delivers high integration and superb performance, while reducing the total system cost. During operation, it interfaces seamlessly with the MAX2992, and together with the MAX2992 G3-PLC firmware, forms a complete G3-PLC-compliant modem solution. It is the first AFE specifically designed for OFDM modulated signal transmission over AC/DC power lines. Operating in 10-490 kHz band, the programmable filters allow compliance with CENELEC, FCC, and ARIB standards using the same device. It provides transmit (Tx) path and receive (Rx) path. The transmit path injects an OFDM modulated signal over power line. The transmit path is composed of a digital IIR filter, digital-to-analog converter (DAC), followed by a low pass (LPF) filter, and a pre-line driver. The receiver path is for the signal enhancement, filtering, and digitization of the received signal. The receiver is composed of a low-pass and a high pass filter, a two-stage automatic gain control (AGC), and an analog-to-digital converter (ADC). The integrated AGC maximizes the dynamic range of the signal up to 60 dB, while LPF removes any out-of-band noise, and selects the desired frequency band. The ADC converts the enhanced and amplified input signal to a digital format. An integrated offset cancellation loop minimizes the DC offset.

2.4 Line driver [10]

The PLC media for any residential/commercial building applications usually carries 50-60 Hz power signal. Typically, a PLC modem has to connect with this media using a power outlet. Actually this media was originally designed to distribute power throughout buildings, carrying the primary 120-230 V at 50-60 Hz frequency. Since a dwelling must be connected to the broader power distribution grid, and can be subject to lightning surges. Therefore, following characteristics for PLC media apply for 50-60 Hz frequency, and can be termed as:

- Large transient events (i.e. lightning strikes, equipment malfunction, abruptly disconnecting a plug from the outlet, etc.) occur on the power network with amplitudes up to 6 KV.
- Signal path loss from 0 >70 dB, mostly depends on remote connection and how many times PLC signal goes back to the fuse box.
- Multi-input-multi-output (MIMO propagation exists because of PLC media is not terminated.
- The output impedance of power line varies from less than 10 Ω (mostly resistive) to greater than 1 kΩ (mostly reactive).
- Noise will be present on the line as a result of the power supply of any device connected to the line.

Note that because the PLC modem must be powered externally and does not require additional wiring to transmit data, often called wireless. For analysis purpose, the load considered as 50 Ω. For this we used OPA2673 to achieve sufficient linearity with the environment described above 15dBm signal into a 50 Ω load, the line driver requires a combination of minimal supply headroom and maximum output current capability. It works on single +12 V supply, and consumes a low 16 mA per channel quiescent current to deliver upto 700 mA output current. This output current supports PLC modem requirements with greater than 460 mA minimum output current (+25°C minimum value) with low harmonic distortion. Schematic of OPA2673 based line driver is shown in Figure 4.

2.5 Line coupler [11]

Line coupler is designed for G3-PLC modem for 10-490 kHz as illustrated in Figure 5. Here line coupler with suitable combination of resistor and inductor behaves like high pass-filter (HPF). Inductor with isolation transformer (BEL 0557-7700-31) provides isolation between DC voltage side and PLC LV side application. Here metal-oxide varistor (MOV) protect the modem from overvoltage spikes.

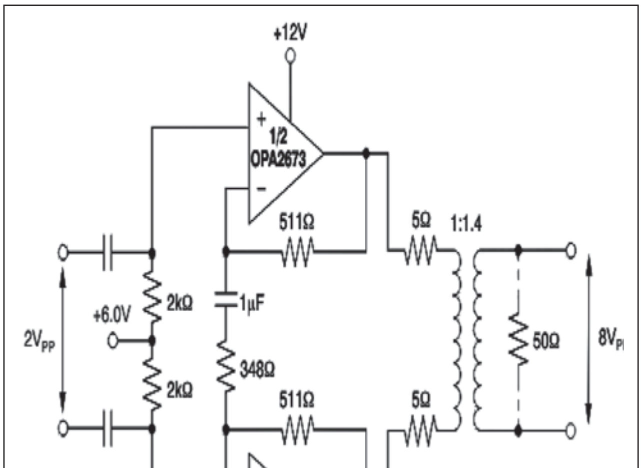


FIG. 4 SCHEMATIC OF LINE DRIVER

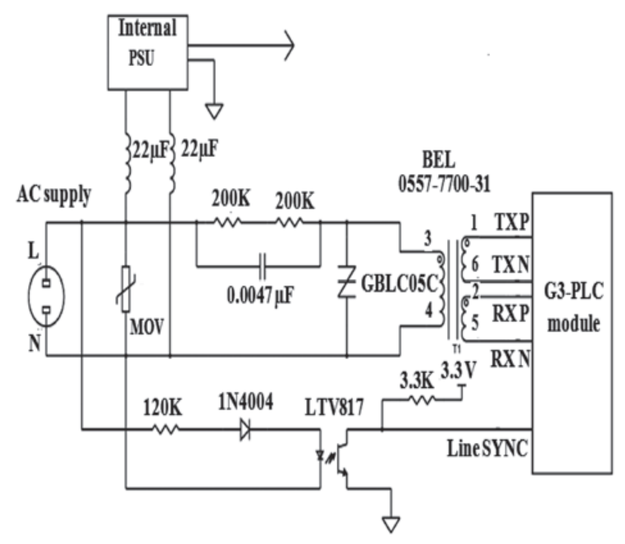


FIG. 5 SCHEMATIC OF LINE COUPLER

The following schematic diagram shows some typical applications combinations for high-speed PLC modules with appropriate couplers and associated circuitry and during connections following points should be observed:

- The first transient protection device MOV should be rated at 240 V for 115 V and at least 400 V for 230 V AC operations.
- Inductors provide high frequency isolation which is particularly important with switching power supplies where a capacitor is present across the input terminals. Therefore inductors should have good performance as per specified PLC band.
- DC blocking capacitor should be an X2 class device.
- Series resistors across capacitor may be replaced by a single 390 K series but only if it has a working voltage of greater than 350 V operation.

3.0 DESIGN AND DEVELOPMENT OF SOFTWARE PROGRAM

With the help of technological development with latest computers, MCUs and software can be easily configured together for many applications (i.e. research, education and industrial). They can be applied to calculate very complicated mathematical operations accurately. They are cheap, can be prepared and used conveniently in various SG applications. Considering the same approach, a software program is written on the basis of following parts:

3.1 Software architecture

The G3-PLC board embodied with host MCU can perform two different roles of communication. One termed as coordinator communication module (CCM), while second termed as terminal communication module (TCM). We proposed a transparent protocol between CCM and user device 1 as shown in Figure 6, where the TCM directly connects with user device 2 through UART interface. Then G3-PLC modules will handle the network formation (i.e. connect, data transmission, forwarding etc). If we implement the application program in user device 1, then advanced protocol interface (API) provides transparent protocol, which can communicate with user device 2 throughout PLC media. If there are more TCM nodes within the network, then transparent protocol provides a peer-to-peer (P2P) connection directly with all other nodes.

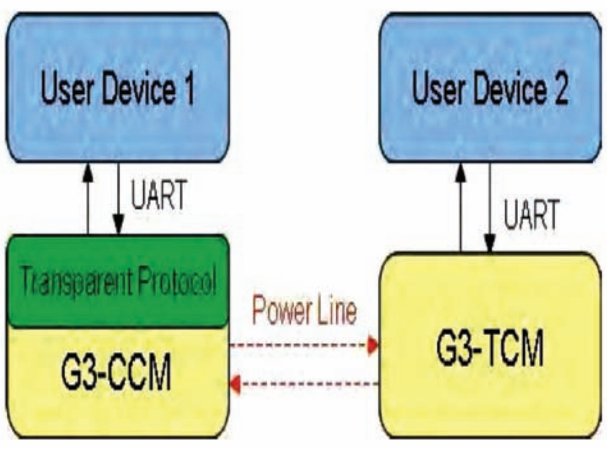


FIG. 6 G3-PLC MODULE SOFTWARE ARCHITECTURE

3.2 G3-PLC test-boards interfacing

G3-PLC boards with the help of suitable connectors are able to connect with other G3-PLC modules, and support PLC signal across overhead-line/cable. The test-board consists of a DC power jack and a DB9 connector for power adapter and RS232 cable connector, respectively. There are two ways to inject PLC signal for communication, the first one is AC power jack for AC line and the second one is coaxial cable feed connector for DC line. There is a reset button on test-board. When the reset button is pressed, both host MCU and MAX2992 will be reset. After cascading all necessary PLC components, test-board as shown in Figure 7, is available for successful deployments for G3-PLC standard based SG applications.

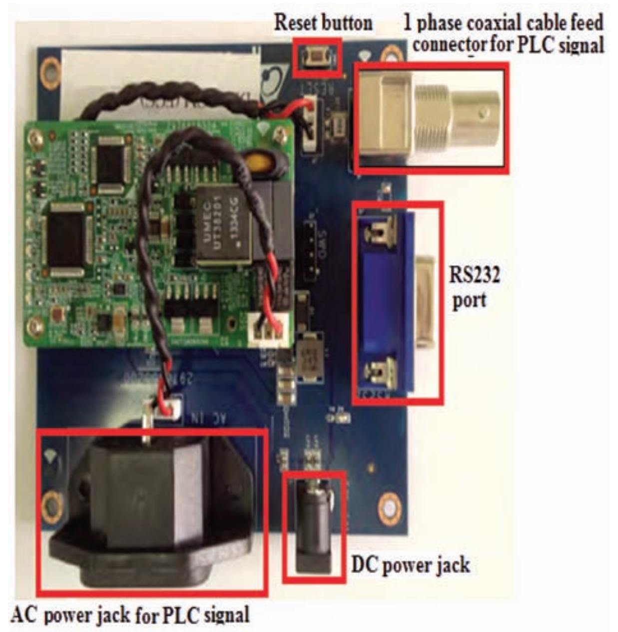


FIG. 7 SNAPSHOT OF G3-PLC TEST-BOARD

3.3 Transparent protocol simulation tool installation

For successful testing of G3-PLC boards on a 32-bit, Windows XP platform, a graphical user interface (GUI) based software such as Microsoft .net framework 2.0 required. Therefore all necessary computer simulation and real-time implementation were performed on a notebook computer, intel® Core^{TM}2 Duo CPU P8700 @2.53GHz with 4 GB RAM on Windows XP environment. When .net framework 2.0 installation successfully finished, then transparent protocol simulation tool will show the program menu of windows and on the desktop. If transparent protocol program successfully connects to CCM, then left-top icon will become green. The device ID column will show the MAC address of CCM as shown in Figure 8.

In user mode page of transparent protocol program, all other G3-PLC nodes including CCM and TCMs during network will also be listed. When we click on the CCM or TCM icons, we can see all necessary information of device and available actions in a new window as shown in Figure 9.

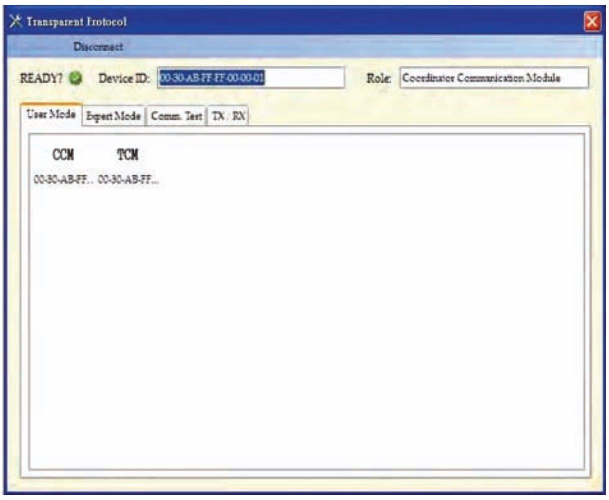


FIG. 8 CCM AND TCM MODULE STATUS ON SIMULATION TEST TOOL

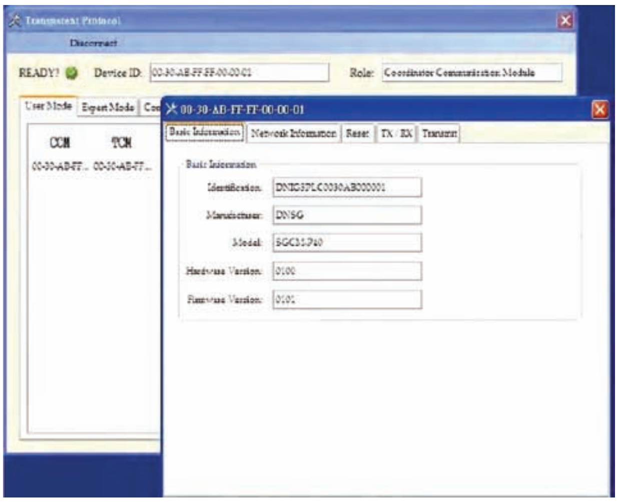


FIG. 9 MODULE STATUS OF CCM

In network information page of CCM or TCM node, during user mode application, the network necessary information about G3-PLC test module will be listed as shown in Figure 10. In Tx/Rx mode page of CCM or TCM node during user mode, the window shows the message flow throughout host MCU UART interface between G3-PLC module and user application will be as shown in Figure 11. With the help of GUI, we can easily understand about the data transmission/ reception at both sides. This helps the user to easily check the functionality of G3-PLC test boards.

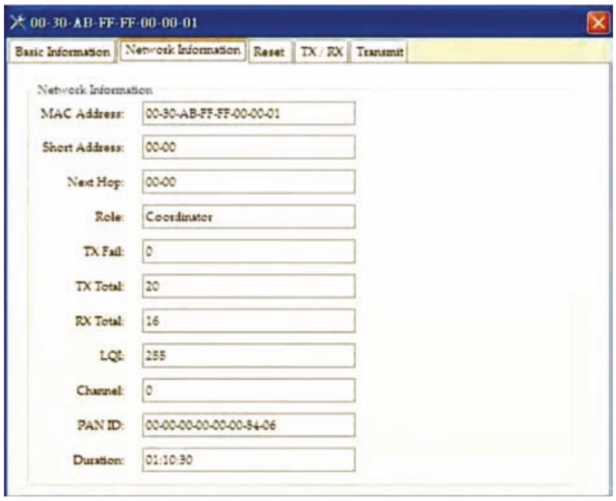


FIG. 10 NETWORK INFORMATION STATUS OF CCM OR TCM MODULE

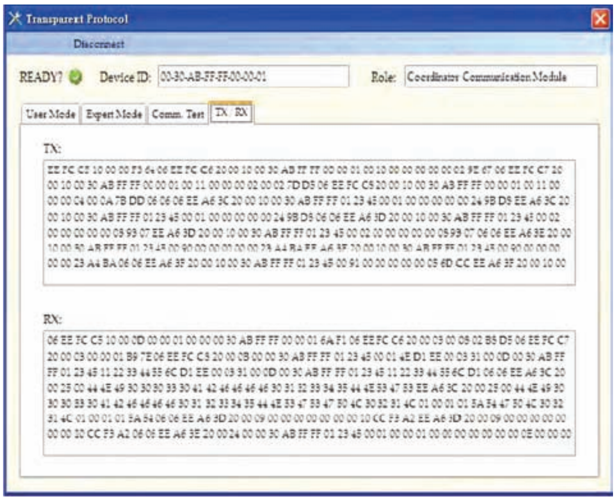


FIG. 11 DATA INFORMATION STATUS OF CCM OR TCM MODULE

3.4 Algorithm

For communication testing with the help of transparent protocol test tool, the transparent protocol firmware should be ready with G3-PLC test module. Therefore test-module should be connected with different communication ports.

- When G3-PLC boards are powered up, the light emitting diode (LED), D11 on TCM will start to toggle. When CCM finished formation a network, the LED, D12 on CCM and LED, D11 will turn on and become steady.

- If TCM successfully establishes a connection, then LED, D11 will become steady. Otherwise, the LED D11 will keep toggling. The LED, D12 in TCM will always off in order to distinguish from CCM.
- When CCM and TCM, both initializes, then transfer sample signal and wait until it reaches to its destination.
- When it reaches to its destination, then display it on display device, and repeat the process for continuous data transmission.

On G3-PLC test board LED positions as shown in Figure 12, help us to easily understand the operating algorithm.

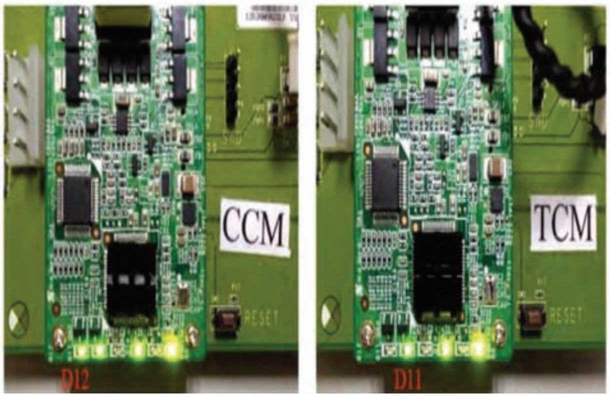


FIG. 12 LED STATUS OF G3-PLC TEST BOARDS

3.5 Flow chart

According to the algorithm, working flow of program of program written for G3-PLC test board can be drawn with the help of flowchart as shown in Figure 13.

4.0 FIELD TRIAL RESULTS AND ANALYSIS

For the testing of G3-PLC boards in real environment, a complete test-bed on top floor roof of Electrical Engineering Department, NIT Kurukshetra, was implemented having 1 kilometer span of aluminium conductor steel reinforced (ACSR) conductor and RG58 cable parallel as shown in Figure 14. A close snap-shot of ACSR conductor (i.e. for AC signal testing purpose) and RG58 cable (i.e. for DC signal testing purpose) are shown in Figure 15 and their specifications are also mentioned in Table 2.

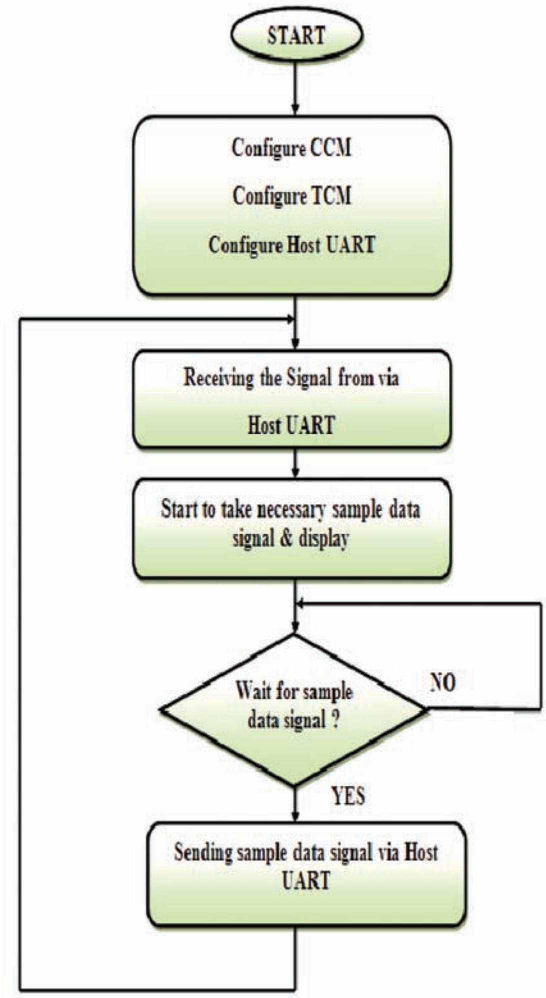


FIG. 13 FLOWCHART FOR THE SOFTWARE PROGRAM

4.1 Test-bed results

During our experimental verification with test-boards, with 4 kb data, approximately 12 kbps speed transmitted at various lengths and the channel performance were measured with GUI software, which were running on the laptops. To perform this application test-bed consists of ACSR conductor for AC signal testing and RG58 cable for DC signal testing (i.e. dotted red line) as shown in Figure 16 at various lengths (i.e. 200 meters, 400 meters, 600 meters, 800 meters and 1000 meters) as mentioned in Table 3 for data transmission across ACSR conductor and Table 4 for data transmission/reception across RG58 cable to check their functionality during building network applications.

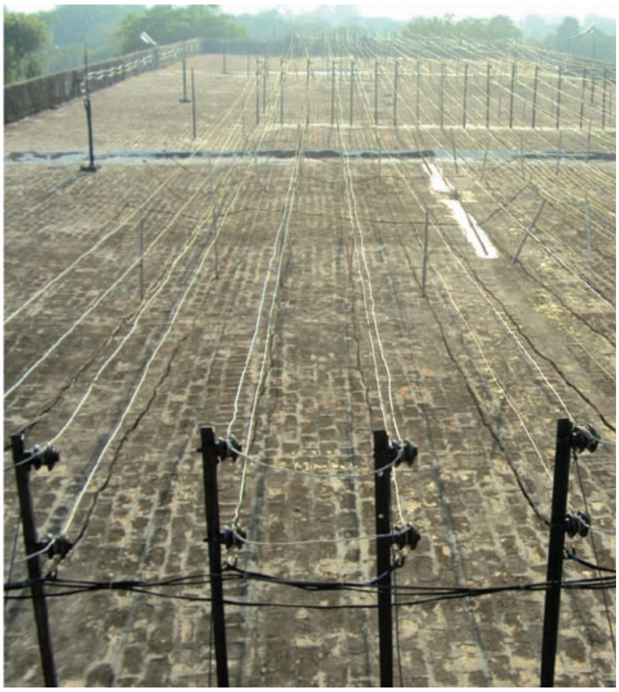


FIG. 14 EXPERIMENTAL SET-UP AT ELECTRICAL ENGINEERING DEPARTMENT, NIT KURUKSHETRA

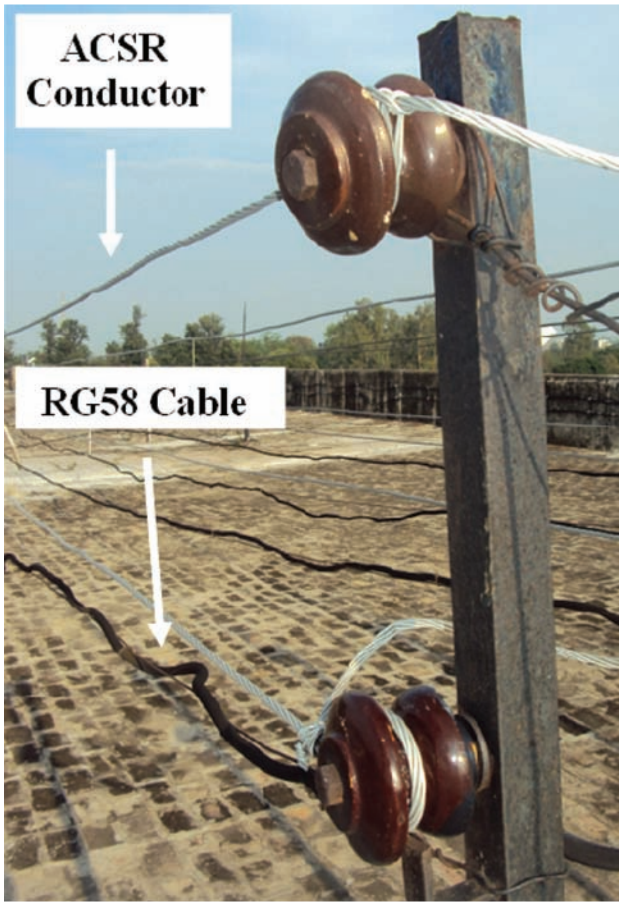


FIG. 15 CLOSE SNAPSHOT OF ACSR CONDUCTOR AND RG58 CABLE

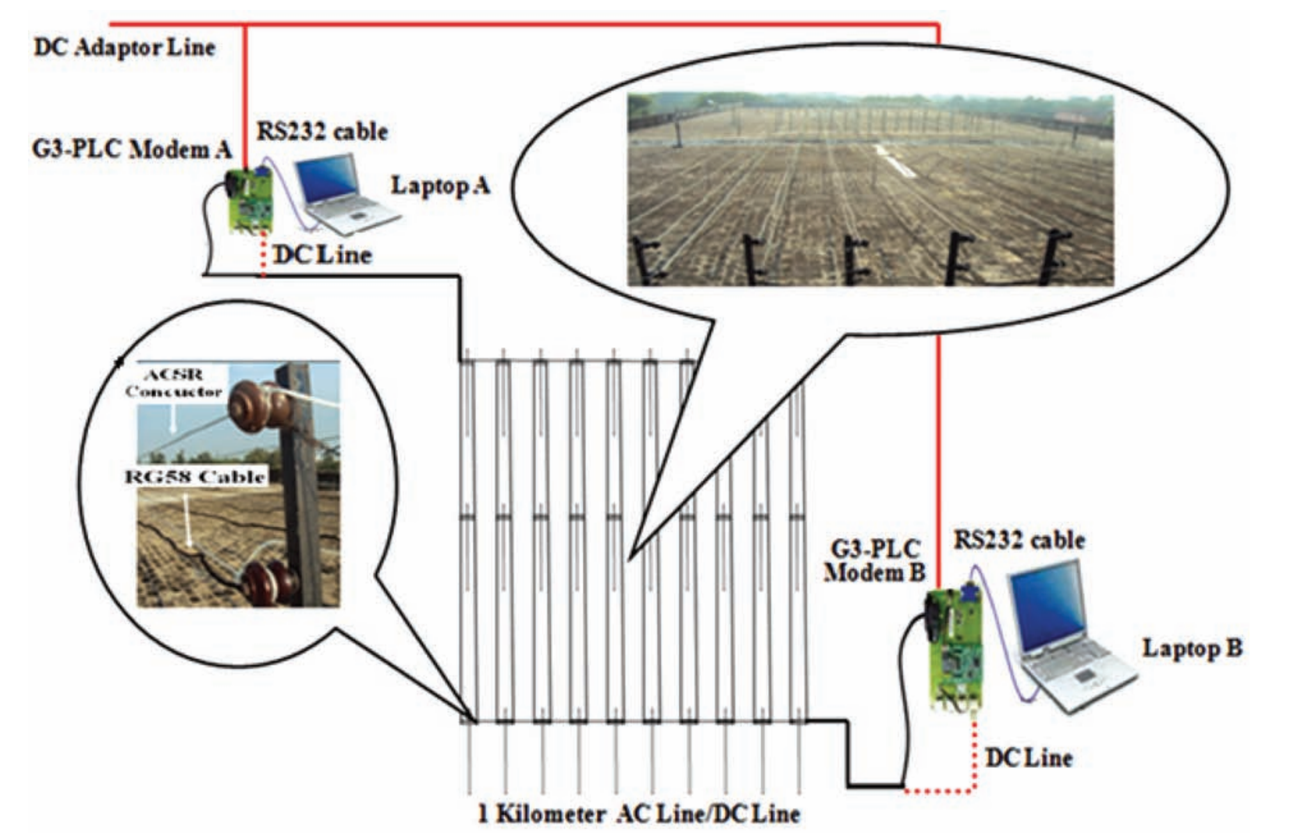


FIG. 16 EXPERIMENTAL TEST-BED FOR G3-PLC PERFORMANCE ANALYSIS

TABLE 2

OVERHEAD POWER-LINE/CABLE SPECIFICATIONS USED FOR G3-PLC TEST-BED APPLICATIONS

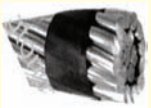
Cable length	Cable type	Cable image	Cross sectional area (mm²)	Standard	Voltage (KV)	Frequency range	Application
1000 meter	(i) RG58 (ii) ACSR	 	(i) 5 (ii) 185	(i) MIL-C17D (ii) IEC 61089	0.3- 0.5	10-148.5 kHz	Power distribution

TABLE 3

DATA TRANSMISSION ACROSS ACSR CONDUCTOR AT VARIOUS DISTANCES

Distance (meters)	Modem A to modem B (kbps)	Modem B to modem A (kbps)	Packet error ratio (PER) (%)
200	11.13	11.71	0.0105
400	11.18	11.93	0.0106
600	11.28	11.73	0.0103
800	11.37	11.73	0.0103
1000	11.50	11.71	0.0101

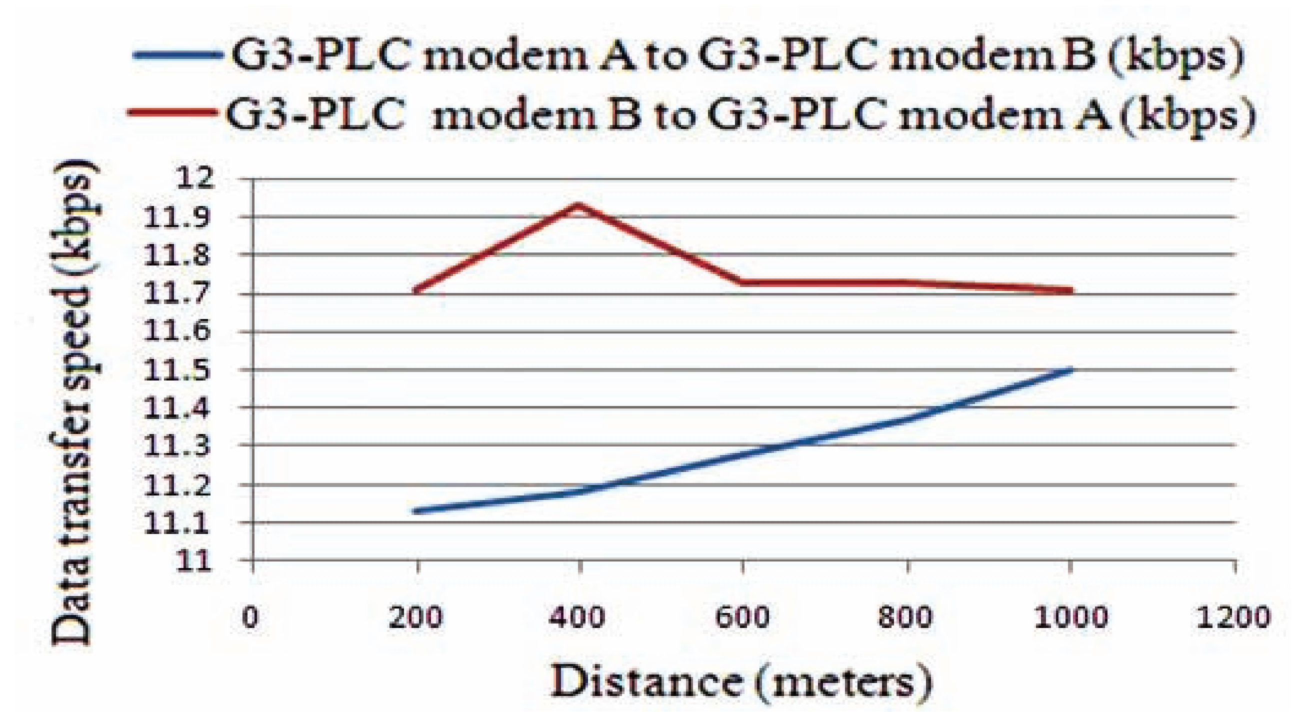


FIG. 17 DATA TRANSMISSION ACROSS ACSR CONDUCTOR AT VARIOUS DISTANCES

TABLE 4			
DATA TRANSMISSION ACROSS RG58 CABLE AT VARIOUS DISTANCES			
Distance (meters)	**Modem A To Modem B (Kbps)**	**Modem B to Modem A (Kbps)**	**Packet error ratio (PER) (%)**
200	11.15	11.18	0.0100
400	11.14	11.21	0.0100
600	11.18	11.21	0.0100
800	11.21	11.23	0.0100
1000	11.25	11.28	0.0100

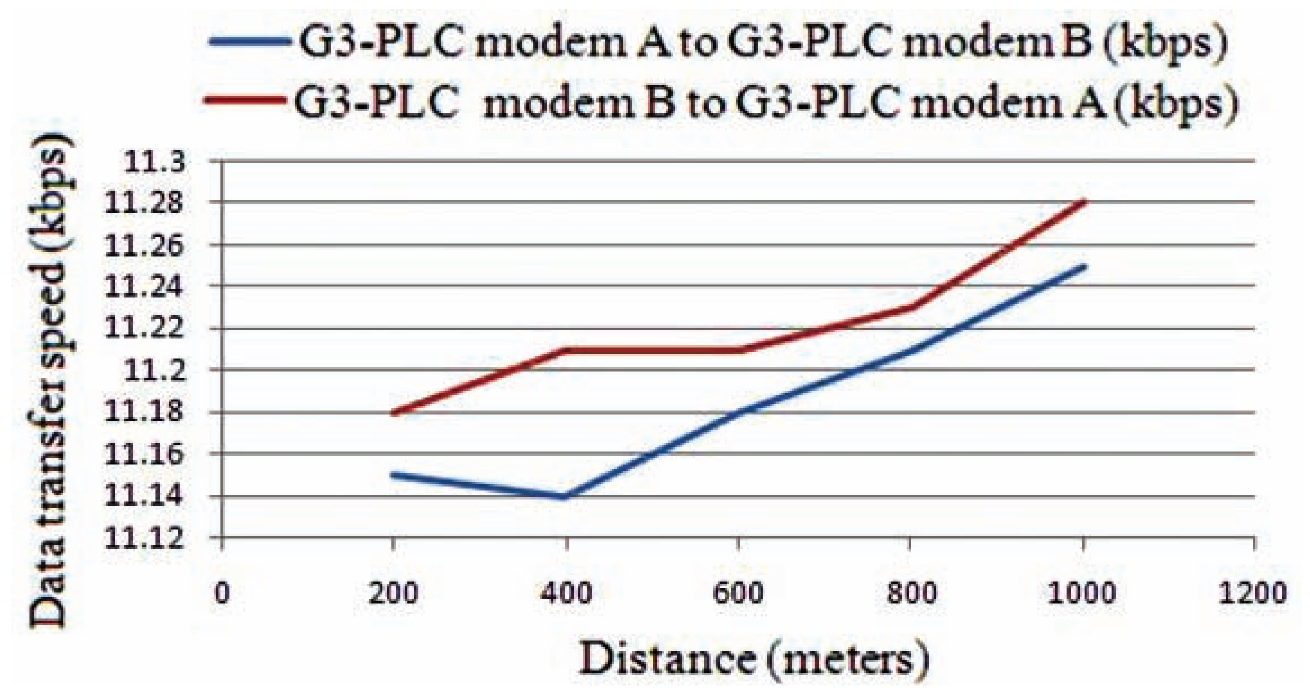


FIG. 18 DATA TRANSMISSION ACROSS RG58 CABLE AT VARIOUS DISTANCES

As it can be observed from the results shown in Figure 17 and Figure 18, verifies that packet error ratio (PER) across ACSR conductor and RG 58 cable is negligible during data transmission /reception and confirms that G3-PLC is a viable solution for LV building network applications.

5.0 CONCLUSION

G3-PLC standard renders a very significant service to electric utilities who in turn supply power to building area network (BAN) applications. BAN is a critical infrastructure that delivers electricity from power generation sources to consumers. This type of network could be characterized by high data rate requirements and provides necessary communication infrastructure for smart metering applications. Considering the problem of BANs, this paper focused on reliability and survivability analysis of PLC networks in NIT Kurukshetra campus by implementing G3-PLC modems to converge existing power grid with information and communication infrastructure. The experiments showed that G3-PLC modems in future can safely accommodate the new load profiles for demand side management (DSM) based applications. In future we would like to implement whole institute equipped with G3-PLC modems to monitor/control real-time based AMR purposes for energy efficient applications.

ACKNOWLEDGEMENT

This work was supported by Department of Electrical Engineering, National Institute of Technology Kurukshetra, India, and also by the Ministry of Human Resource Development (MHRD), Government of India.

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