Narrowband Power line communication for Smart Grid

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Abstract— Smart grids reflect a modern day evolution of electricity networks in response to the need to minimize ecological impacts, improve system reliability and increase electrical and operational efficiencies. Smart grids also facilitate new applications and services and seamless integration of renewable sources. For a reliable communication and control, the communication technology used to implement the smart grid must have enough bandwidth to handle two-way data traffic. The technology must also be cost effective considering the sheer size and scale of electrical grids. Power Line communications (PLC) is a promising communication protocols for cost effective, secure and reliable realization of smart grids. This paper presents a disquisition on smart grid technologies with emphasis on PLC technologies. The role of PLC in the application of smart grids over the different voltage networks is also covered.

Index Terms— Power Line Communication, Smart Grid, OFDM, G3-PLC, PRIME, IEEE P1901.2

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1 INTRODUCTION

Established electric grids operate on a vertical structure of power generation, transmission and distribution with limited control and communication capabilities. Moreover, operating these power systems results in greenhouse gases emission and has a low level of security of supply [1, 2]. Vertically integrated power systems initially use Carrier Frequency System (CFS) for internal communication, remote measurement and control task [3]. In the same vein, Ripple Carrier Signaling (RCS) is used for load management in the medium and low voltage networks of electric grids [4]. These technologies were succeeded by the more popular Supervisory Control and Data Acquisition/Energy Management System (SCADA/EMS) platform. (SCADA/EMS) is usually installed at central and area control centres (CCC and ACC) [5]. SCADA is primarily responsible for remote measurement and control of the power system using distributed Remote Terminal Units (RTUs). The RTUs obtain digital data from Intelligent Electronic Devices (IEDs), which usually consist of microprocessor based equipment such as transformers, circuit breakers and capacitor banks. The SCADA system is also used for monitoring and control of analogue data associated with voltage levels, power injections, and demands at certain electric buses. EMS provides software platforms for optimization and control of the electric power system. Some applications of EMS include load forecast, restoration strategy, optimal power flow, economic dispatch and dynamic security assessment [5]. The major drawback of the SCADA system is the high latency associated with its architectural model coupled with the asynchronous manner in which measurements are captured in the system. These drawbacks have led to the development of alternative models that are distributed in nature such as Flexible AC Transmission System (FACTS), Distributed Web-Based SCADA Systems and Distributed Energy Management System.

In order to implement the various communication and control systems, efficient communications systems are indispensable. Smart grid which is a redesign of the power sector using information and communication technologies (ICT) is capable of accommodating renewable energy sources and optimizing the grid assets [6]. It is an excellent platform for delivering converged communication services, preparing for electric vehicles and implementing active consumer demand side. It is clear that the ICT platforms for realizing smart grids will consist of a combination of technologies and software solutions. For smart metering and communications applications, key technologies include wireless networks, optical fiber, and internet based technologies [7, 8]. Wireless communication protocols such as Global System for Mobile Communications (GSM) and Long Term Evolution (LTE) provide wide area networking capabilities while ensuring enough bandwidth capacity. Other mobile technologies such as Zigbee, Bluetooth and WiFi can be used at the end user premises for local area networking and control of various electrical appliances. Direct access to the utility assets and electricity meters can be realized using internet based technologies such as public broadband access and PLC. Furthermore, rapid advance in hardware and software development will continue to support more ICT based platforms for active distribution networks, micro grids, energy storage, and grid asset management among other applications [9]. Fig.1 depicts a conceptual illustration of smart grid architecture.

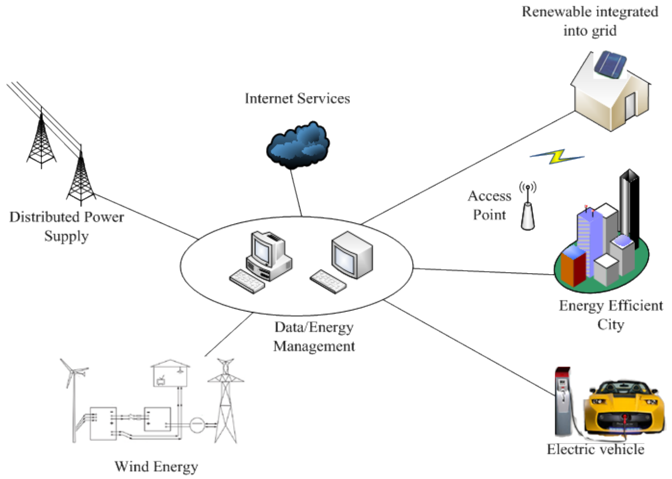

Fig.1 conceptual model of a smart grid

2 POWER LINE COMMUNICATION SYSTEM

The choice of communication technology for smart grid must consider cost as a prime factor considering the sheer size of electric power grids. Power line communication (PLC) uses the existing electrical network to provide communication and control capabilities across the grid. Hence, it is a cost effective platform for implementing smart grids applications. PLC technology consists of many standards and technologies covering the spectrum of Ultra Narrowband, Low Data Rate Narrowband, High Data Rate Narrowband and Broadband Communications. The platform for PLC is a cyber – physical infrastructure that supports the various PLC communication standards on High Voltage (HV), Medium Voltage (MV) and Low Voltage (LV) electric networks. The Wide Area Network (WAN) usually implemented on the HV networks spans long-haul distances from the Central/Area Control Centre to actuation sites and sensor networks [7]. The most important alternative to PLC for implementing WAN is the use of wireless network infrastructure such as WiMAX (Worldwide Interoperability for Microwave Access) and LTE, which offers extensive coverage and large bandwidth but must be rented at a periodic cost. Some applications across the WAN include: implementing SCADA for remote surveillance, opening and closing of circuit breakers and real-time sag monitoring. PLC technologies gain increasing importance and application along the NAN (Neighbourhood Area Network) implemented on the MV networks and the HAN (Home Area Network) implemented on the LV electric networks. Some applications over the NAN and HAN networks include: substation automation, smart metering, industrial/home automation, voltage dispatch, electric vehicle-to-grid communications etc. The diagram of Fig.2 illustrates an example of an automated meter management system implemented over the PLC link. The PLC link facilitates the exchange of information between meters and concentrator over the LV/MV electric network.

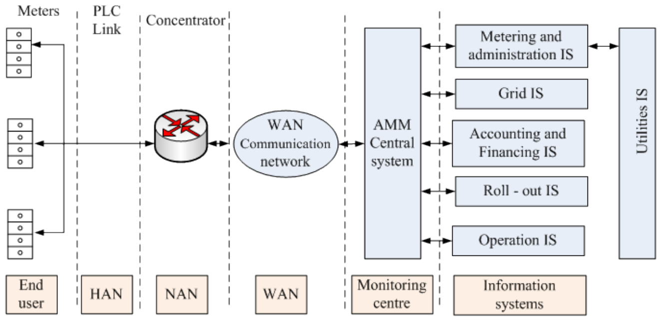

Fig.2 Automated Metering Management System

Although PLC provides a cost effective structure for communication, it is associated with a number of issues which need to be critically considered for the multi-faceted applications of smart grids. These issues include noise disturbances, electromagnetic compatibility issues as well as varying channel characteristics and models (topologies).

2.1 Noise Disturbances

Noise disturbances in power line channels are critical because they emanate from a variety of appliances with different electrical properties. Consequently, the power spectral density is not constant over the transmission domain, which makes reception of signal more challenging. An Integrative description of PLC noise disturbances is given in [10]. In this paradigm, noise disturbances were classified into five (5) types based on their intensity, time duration, origin, and spectrum occupancy. The combination of these noises gives rise to the effective noise disturbance of the channel as illustrated in Fig. 3 Type 1 noise otherwise known as coloured background noise is characterized by a low spectral density which tends to decrease with increase in frequency. Type 2 noise (narrowband noise) is a background noise that is caused by amplitude modulated (AM) signals especially from broadcast stations. Periodic impulse noises that are asynchronous and synchronous to the main power supply frequencies are referred to as type 3 and type 4 noises respectively. The type 5 noise known as asynchronous impulsive noise has the most pronounced effect on digital data transmission over PLC due to its high power spectral density (up to 50 dB). These impulses results from switching transient circuits in the networks. The power spectral density of colored background noise can be expressed as [11]:

$$N_{cb}(f) = n_0 + n_1.\left(\frac{f}{f_1}\right) \qquad (1)$$

Where n_0 is constant noise density, $n_1$and $f_1$are parameters of the exponential function approximated for industrial and residential environments in [12]. Type 3 noises have a very high repetition rate which allows its frequency to be approximated as a narrowband spectrum. Thus Type 2 and Type 3 can be approximated as background narrowband noise given by [11]:

$$N_{nb}^{(k)} = a_k . e^{-\left[\frac{(f-f_{0,k})^2}{2b_k^2}\right]} \qquad (2)$$

Here, a_k is amplitude, b_k is the bandwidth of the Gaussian function and $f_{0,k}$ is the centre frequency. For the impulsive noises of type 4 and type 5, the PSD can be expressed as [10]:

$$N_{imp}(t) = \sum_{i=-\infty}^{\infty} A_i . p\left(\frac{t-t_{ai}}{t_{wi}}\right) \qquad (3)$$

Here t_w is the pulse width, t_a is the inter arrival time of the pulses A is the amplitude and $p\left(\frac{t-t_{ai}}{t_{wi}}\right)$ is a generalized pulse function. Considering the serious impact of impulsive noise on PLC systems several methods have been proposed to mitigate its effect [13, 14, and 15].

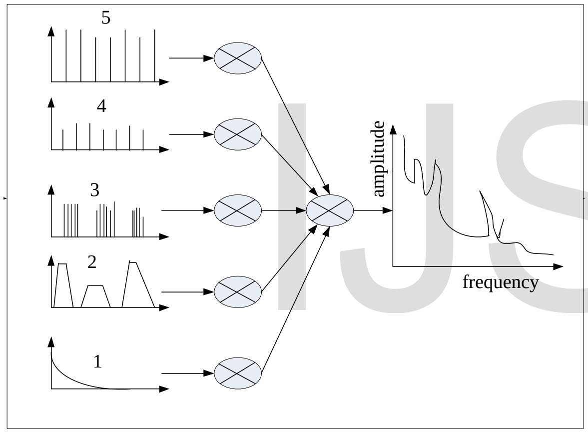

Fig.3 Combined noise disturbances in PLC Systems

2.2 Signal Transmission Characteristics

The topology of electrical grids differs from home to home. This differential electrical wiring model affects signal interference, impedance and attenuation between coexisting PLC networks, which are more pronounced on the LV distribution networks. Some factors affecting the topologies of LV power supply networks include [4]: Network location, subscriber density, network length, and network design. Business locations and urban centres invariably uses more PLC/smart grid services than residential quarters and rural dwellers, thus, their PLC characterization greatly differs. Subscriber density refers to the number of users attached to a voltage network. Network design considers network factors such as segmentation, cabling as well as the type of topology: radial, ring or interconnected.

Channel noise, impedance and attenuation are unpredictable and stochastic. They change with change in network topology, frequency and time. There are two established methods that can be used for the channel characterization of high frequency PLC channels namely: measurement based approach and intrinsic parameters approach. The former method relies on measurements derived from network parameters such transfer function and characteristic impedance [16]. This method is easy to implement and requires less computational power. However, it solely relies on the measurement techniques or algorithm employed, which is subject to measurement errors and accuracy limitations. In the latter method, the distributed primary constants are used to deduce the propagation constant and characteristic impedance, which can be used to derive the transfer function [17]. The transfer function is derived using matrices whose parameters increases with increase in complexity of the network topology. The distributed circuit representation of the two wire transmission medium for PLC is illustrated in Fig. 4.

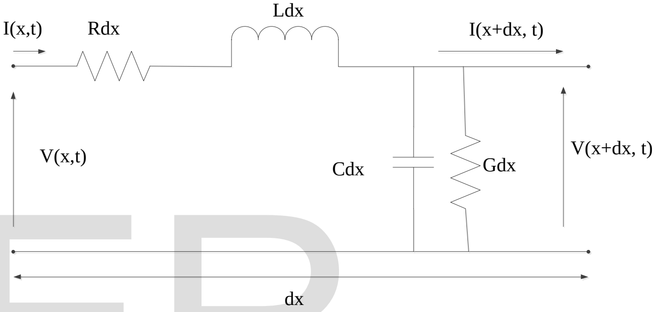

Fig.4 Equivalent Primary elements circuit of PLC line

Applying Kirchhoff's voltage and current law on the circuit, we can deduce the propagation constant as:

$$\gamma = \alpha + j\beta = ((R + jwL)(G + jwC))^{1/2} \qquad (4)$$

Where α is the attenuation constant (Np/m) and β is the phase constant (rad/m). The characteristic impedance of the line is expressed as:

$$Z_0 = \left(\frac{R + jwL}{G + jwC}\right)^{1/2} \qquad (5)$$

The frequency domain and time domain response of the RLCG transmission line are illustrated in Fig. 5 and 6 respectively.

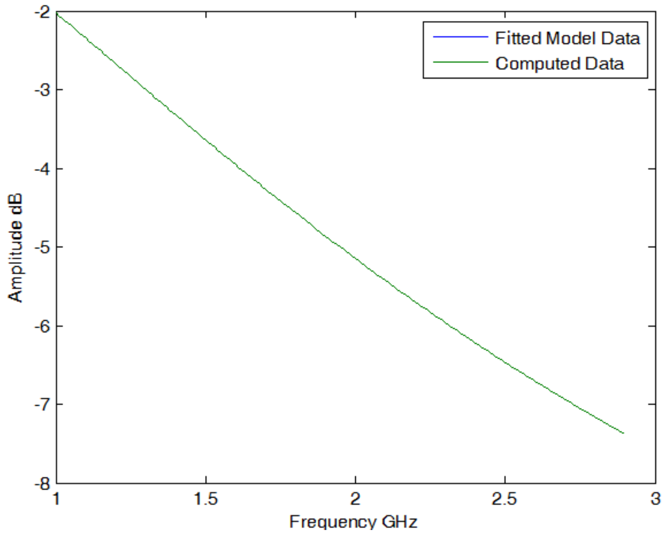

Fig.5 Frequency response of RLCG Transmission Line

The 'echo' channel model can be used to account for narrowband notches that occur in the transfer function. The notches result from a number of reflections at impedance discontinuities [4]. Based on the echo model, the transfer function can be expressed as function of medium attenuation, impedance fluctuation and multi path effect by the expression:

$$H(f) = \sum_{i=1}^{N} g_i . e^{(a_0+a_1.f^k).l_i} . e^{-jw\tau_i} \qquad (6)$$

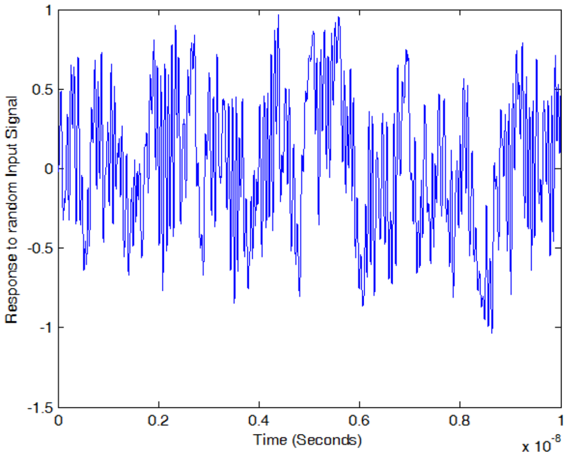

Fig. 6 Time Response of RLCG line to a Random Signal

Here, g_i is a weighing factor which accounts for the product of transmission and reflection parameters along the channel. τ_i is a function of path length l_i, and phase velocity and is the delay introduced by channel path i. a_0, a_1 and k are constants [18]. The steps involved in the design of PLC system considering the signal-transmission characteristic can be summarized as follows [19]:

i. Draw the distribution network diagram
ii. Derive the network model for simulation
iii. Use a simulator for frequency domain analysis
iv. Evaluate simulation result using field measurements and system design goals
v. If system design is not achieved, go to step ii. use field measurement experience to redesign model

2.3 Electromagnetic Interference

PLC signals impressed on power cables causes the electric cable to act as an antenna which causes electromagnetic radiation and hence, disturbances in the environment. This raises electromagnetic compatibility (EMC) issues with other systems. The electromagnetic disturbances in a PLC network can be modelled using the diagram of Fig. 7 [20].

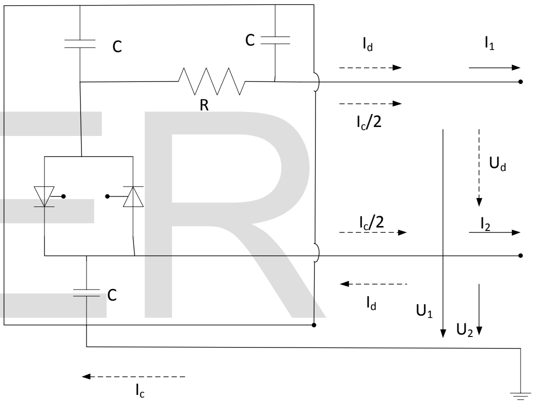

Fig.7 Typical Electromagnetic interference model

Where:

$U_d = U_1 - U_2$ is the differential-mode volage componet

$I_d = \frac{I_1 - I_2}{2}$ is the differential- mode current component

$U_c = \frac{U_1 + U_2}{2}$ is the common-mode voltage component

$I_c = I_1 - I_2$ is the common-mode current component

The differential component of the PLC signal is symmetrical, thereby cancelling the effect of I_d. The common mode current is asymmetric and therefore generates an electric field that creates electromagnetic radiation interference. The electric field generated can be measured using a magnetic sensor.

2.3 Interoperability and Coexistence

Another important issue associated with power line communications is interoperability and coexistence of the various standards. The various narrowband standards are not interoperable, thus, coexistence mechanisms were developed to cater for simultaneous deployment of the various standards. Some of the coexistence mechanisms include:

- Frequency separation: This involves the use of non-overlapping band plans for different standards or applications. For example, the use of different sub bands in the CENELEC (European Committee for Electrotechnical Standardization) standard provides frequency division.
- Tone-masking: otherwise known as frequency notching is adopted to avoid or notch out one or more subcarriers that are already dedicated to other applications or standards. This allows different standards to coexist over the same frequency band
- Preamble-based: This is a relatively new coexistence mechanism which uses a fixed amount of neutral coexistence preamble symbols at a certain frequency or multiples of the specific frequency. The objective of this mechanism is to ensure fairness and minimize disruption of service among different narrowband power line standards.

3 ENABLING TECHNOLOGIES AND STANDARDS

As earlier highlighted, there are a number of power line technologies that can be used for realizing smart grid and smart metering applications. Narrowband PLC consist of technologies that operate within frequency range of 3 to 500 kHz. Frequencies below 500 KHz are characterized by low attenuation, which enables them to attain longer distances than their broadband counterpart. This trait makes low frequency narrowband technologies more suitable for smart metering and other smart grid applications. There are a number of standardized and non-standardized solutions to narrowband power line technologies. Different standardization organization (SDOs) have played key roles developing various standard. Some of the major SDOs include: European Committee for Electrotechnical Standardization (CENELEC), Federal Communications (FCC), The International Telecommunications Union Telecommunication Standardization Sector (ITU-T), Association of Radio and Businesses (ARIB) and the Institute of Electrical and Electronics Engineers (IEEE). The frequency bands allocated by various regional SDOs are summarized in Table 1.

TABLE I: REGIONAL FREQUENCY BANDS FOR PLC

CENELEC BAND		
Frequency Band	Range (kHz)	Application
A	3 – 95	Utility services
B	95 – 125	Any application
C	125 – 140	Home networking
D	140 – 148.5	Alarm/Security
FCC BAND	37.5 kHz – 478.125 kHz	
ARIB	10 kHz – 450 kHz	

Most of the narrowband PLC technologies currently deployed today are based on single carrier or spread spectrum modulation techiniques. Some of these technologies include CENELEC EN50090 (Konnex protocol), LonWork/LonTalk, LnCP (Living network Control Protocol), CEBUS (Consumer Electronics Bus) and HNCP (Home Network Control Protocol) protocols. The CENELEC 50065 standard uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol in the CENELEC C band to allow networking of devices. It also uses the Band in Use (BU) detector for sensing signals between 131.5 kHz and 133.5 kHz of at least 86dBμV. When used for home networking, the medium access protocol of each device utilizes the frequency 132.5 kHz to show that an active transmission is in progress. Some of solutions currently available in the market that are based on the CENELEC 50065 framework include: Amis-30585 modem, Echelon PL3150/PL3120 modules and ST7540 modem solution.

However, these standardized protocols are low-speed protocols which tends to limit their use to automation applications. In order to implement smart grid application, high data rate technologies are equired. The hostile nature of the power line also necessitates the need to use a robust and resilient modulation technique. These requirements generated interest in the development of high data rate narrowband solutions such as PRIME (PoweRline Intelligent Metering Evolution) and G3-PLC [22, 23, 24]. These standards are bi-directional and use OFDM (Orthogonal Frequency Division Multiplexing) for a sustained resiliency against attenuation and interference. They can pass through a transformer which makes for the concentrator to be placed on the MV side where it can aggregate data from several LV locations. These high-data rate technologies are highlighted in subsequent sub-sections.

3.1 ITU-T G. 9902 Recommendation: ITU-T G.hnem

The G.hnem (home networking and energy management) standard is geared towards realizing important smart grid applications such as plug-in electric vehicle (PEV) charging, in-home energy management and advanced metering infrastructure. The generic network architecture of the ITU-T G.hnem standard is illustrated in Fig. 8. The architecture is designed around a number of logical domains, each of which is identified by a unique domain identity ID. Nodes of the various domains exchange information over inter-domain bridges (IDB). The global master function implemented in one of the nodes is responsible for coordinating the operations of domains in the same network. In each domain, the nodes are identifiable by a unique node ID. Nodes of the domain are either connected directly or via relay nodes. One of the nodes in each domain serves as the master node and is responsible for coordinating the operation of the nodes in the domain.

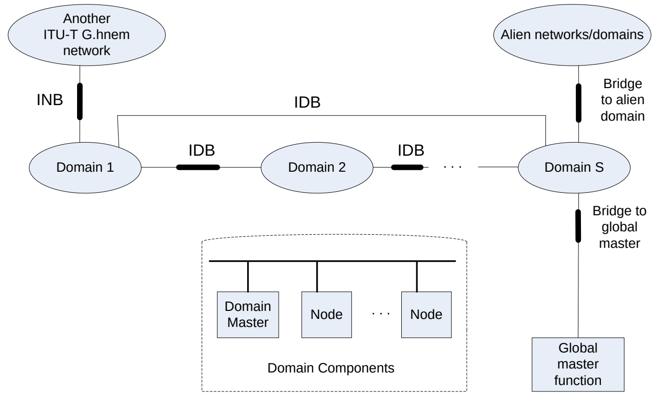

Fig.8 Generic Network Architecture for ITU-T G.hnem [25]

The standard is based on OFDM transmission technology and adopts many features of G3-PLC and PRIME such as the use of IPv6 as the default network layer protocol.

3.2 ITU-T G. 9903 Recommendation: G3-PLC

The ITU-T G.9903 is the official standard of G3-PLC adopted by the G3 alliance. G3-PLC is another high data rate narrowband specification that is based on OFDM. It operates within the frequency range of 10 kHz to 490 kHz. It is capable of achieving a peak data rate of approximately 300 kbps by leveraging on phase shift keying (PSK) constellation mapping coupled with concatenated convolutional Reed-Solomon forward error coding. G3-PLC is capable of running standard internet services as its IEEE 802.15.4-2006 based MAC layer is adapted to IPv6. Fig. 9 below illustrates the block diagram of the transmitter for a G3-PLC system. The sampling frequency for the transceiver is selected to be 400 kHz, while the FFT size uses a modulation size of 256. A comparison of the physical layer aspects of G3-PLC and PRIME is presented in [27]. It is noted that PRIME is less complex, thus it is cheaper to implement. On the other hand, G3-PLC is more robust in the presence of Additive White Gaussian Noise (AWGN) and narrowband interference.

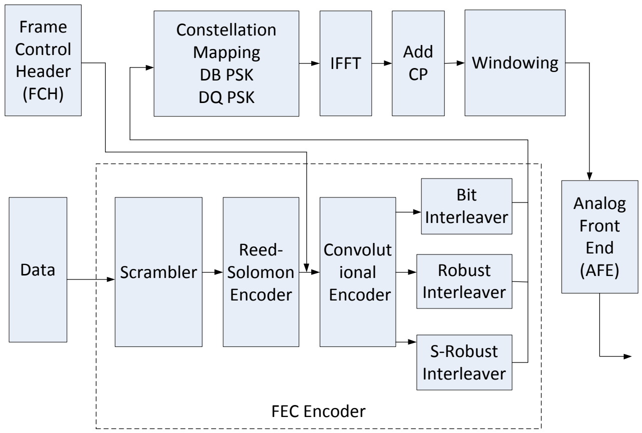

Fig. 9 Block Diagram of G3-PLC (according to [26])

The G3-PLC network is composed of domains referred to as personal area networks (PAN). The nodes in each domain are designated a PAN ID and a 16 bit ID known as short address. The function of coordinating the operations of other nodes and domain management functions as well as connectivity to other domains are implemented in a PAN-coordinator node. One of the main revision of this G3-PLC standard by the ITU-T is the replacement of the routing algorithm specified in the original G3-PLC specification. The Lightweight On-demand Ad-hoc Distance-vector Routing Protocol – Next Generation (LOADng) specified in [28] was adopted as the routing algorithm for the G.9903. LOADng algorithm allows blacklisting of unidirectional connections. It also enables the use of separate forward and reverse routes and support for route cost estimation.

3.3 ITU-T G. 9904 Recommendation: PRIME

PRIME uses frequencies range of 42 kHz to 89 kHz divided into 96 OFDM subcarriers. It adopts ½ rate convolutional code forward error correction and dual QPSK, 8PSK and BPSK (Quadrature/8/Binary Phase Keying) modulation sizes to realize up to 128 kb/s data rate. The MAC layers of PRIME uses CSMA/CA for contention based access and TDM (Time Division Multiplexing) for contention free access. The PRIME specification defines various security profiles for data integrity, authentication and privacy. Security profile 0 does not provide any encryption. Security profile 1 utilizes 128-bit Advanced Encryption System (AES) to provide encryption [29]. Fig. 10 below shows the block diagram of a PRIME Transmitter system. The components highlighted in green are optional. The PRIME network made up of subnetworks, each of which is associated with a transformer station [30]. A subnetwork has a tree-like structure with a base node and services nodes. The base is originally the subnetwork itself and is responsible for managing the subnetwork connections and resources. Service nodes are points on the mesh of the subnetwork and are capable of behaving as traffic terminals or as switches capable of routing data information to and from other nodes in the subnetwork.

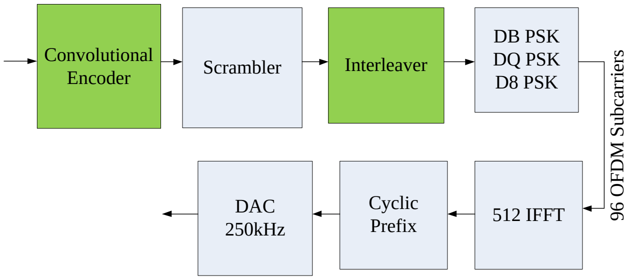

Fig. 10 Block Diagram of PRIME (according to [31])

The protocol layer reference model of the G.9904 is illustrated in Fig. 11. The convergence sublayer associates each traffic with its MAC connection. It can also provide compression functions. The MAC layer handles functions such as topology resolution, bandwidth allocation and connection management. The PHY layer transmits and receives MAC Protocol Data Units (MPDU) using OFDM. No robust modes are defined for the PRIME standard.

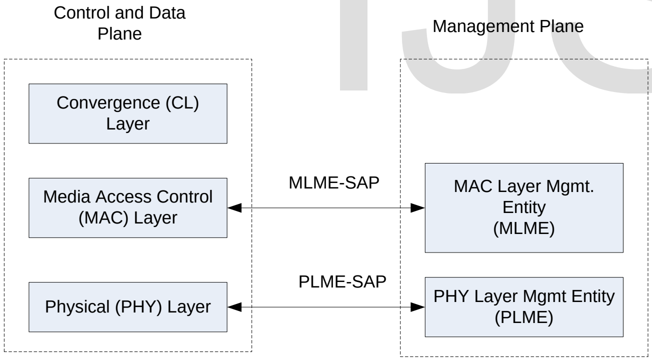

Fig. 11 Reference Model of G.9904 Protocol Layers [32]

3.4 IEEE P1901.2

The IEEE sponsored the IEEE P1901.2 standard which is designed around several coexistence mechanisms geared towards a straightforward implementation of the various standards [33]. IEEE P1901.2 operates in the 10 – 490 kHz frequency band which accommodates various countries band regulations. It is capable of achieving data rate of up to 500 kbps over both AC and DC lines. It supports communication from HAN to NAN and vice versa with internet networking capability. The standard also provides interoperable profiles with G3 and PRIME in the CENELEC A band. The standard also specifies Adaptive Tone (Subcarrier) Mapping (ATM) for maximum robustness. Transmission between the PHY and MAC layers is managed using various Data and management primitives. The IEEE P1901.2 and ITU-T G.9903 (G3-PLC) share several similarities but are actually non-interoperable technologies with marked differences. Some of the major differences include [34]:

- The MAC sublayer of IEEE 1901.2 can support up to 1280-Byte Maximum Transmission Unit (MTU), which is significantly higher than 511-Byte MTU for ITU-T G.9903
- ITU-T G.9903 specifies a collision avoidance mechanism for fragmented packets known as Subsequent Segment Collision Avoidance (SSCA).
- The use of Information Elements in IEEE P1901.2 is limited to the PHY and MAC layers. In contrast, the ITU-T G.9903 incorporates an adaptation layer based on 61oWPAN which specifies additional mechanisms for bootstrapping (allows a node to join a domain), authentication of domain and nodes encryption key obtained during bootstrapping and defines a default reactive Layer 2 routing algorithm (LOADng) which is capable of handling unidirectional links.

4 CONCLUSION

The power line is a cost effective means of providing monitoring, communication and control for power systems. This is especially useful in present power systems that are distributed in nature and involve a variety of energy sources. The cyber-physical structure of the power line and some issues associated with the transmission of high frequencies on power lines were discussed in this chapter. Various legacy narrowband standards as well as next generation OFDM-based standard are also presented in this chapter. However, in order to meet the bandwidth intensive home networking application, broadband technologies have been developed. The most promising broadband technologies include ITU G.hn, IEEE 1901, HomePlug AV2 and IEEE 1905.1. The last standard in particular provides an abstraction for convergent digital home networking of both wired and wireless technologies. The major merit of using narrowband technologies for smart grid is their ability to bye-pass transformers. Attenuation at frequencies below 500 kHz are comparatively lower than at higher frequencies, thereby allowing narrowband standard to reach longer distances than their broadband counterpart.

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