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An Overview of OFDM Based Narrowb and Power Line Communication Standards for Smart Grid Applications

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Abstract: With the advancement in various fields of energy and communication sector, there is a strong need to upgrade the outdated power transmission and distribution grid to an intelligent and efficient Smart Grid (SG). An integral part of SG is a robust and ubiquitously available communication network that will enable various entities connected to the SG to exchange vital information at all times. Power line communication is the most pervasive network in the world and it can serve as a backbone in an overall hybrid communication network. SG applications like automatic meter reading (AMR) are mostly low data rate applications, for which narrowband power line communication (NB-PLC) is most suited. This article presents an overview of PLC and its role in SG communication, with particular focus on NB-PLC technologies and their performance comparison, such as G3 and PRIME, which are based on Orthogonal Frequency Division Multiplexing (OFDM) technique.

Key words: Smart Grid · PLC for Smart Grids · NB-PLC standards · G3 and PRIME

INTRODUCTION

For resilient, safe and efficient generation, transmission and distribution of electricity, the next-generation of power grid called Smart Grid (SG) had emerged out to be one of the promising solutions [1]. The SG incorporates, within a physical power system, Information and Communication Technologies (ICT). Sensors are deployed throughout the system to provide fine-grain monitoring, security and load balancing. Power line communication (PLC) is a suitable option to be used as a major part of a hybrid communication network that will connect SG applications [2]. PLC enables information transmission on existing infrastructure of power lines that are ubiquitously available and provide a cost-effective solution to communication problem within the grid. The generation of power in SG is mainly from distributed energy resources (DER), which challenges electric companies regarding high-quality power supply.

The power lines are laid for the transmission of AC power at 50-60 Hz. The use of power lines as a communication medium is limited by several degrading factors such as noise, frequency-selective fading and impedance mismatching [3]. However, bit-error-rate (*BER*) may be improved for high data rate applications by multicarrier modulation (MCM) techniques such as OFDM and Discrete Multitone (DMT) modulation. *S. Baig* and *M. Mughal* have proposed a Uniform DMT transceiver with variable power allocation for different subbands which provides improved *BER* performance in the noisy and frequency-selective PLC channel [4].

The worldwide interoperability and Electromagnetic Compatibility (EMC) friendliness are the key requirements for SG success [5], [6] for which two new OFDM based NB-PLC standards G3 and PRIME have emerged. Although, G3 and PRIME target multiple SG applications, they possess several distinguishing features from each other. In Section II, Smart Grid is presented.

Smart Grid (SG): Smart Grid (SG) has attained a lot of attention in the recent decade. SGs are a new generation of power grids with an economical and secure electricity supply and communication network that can intelligently integrate the actions of all users connected to it, generators, consumers and distributors. The advanced metering infrastructure (AMI), a pre-requisite for SG, is installed in Europe [2]. The main incentives for SG initiative include the following:

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Table 1: Comparison of Traditional Grid and Smart Grid

Traditional Grid	Smart Grid
Electromechanical	Digital
One-way power distribution and management	Two-way power distribution and management
Centralized producer- controlled networks	Decentralized user- interactive networks
Usually no energy integration	Energy integration
Manual restoration	Self-healing
Limited control	Pervasive control
Environment pollutant	Environment friendly

- Reduce carbon footprints
- Enable real-time two-way communication
- Encourage distributed generation of energy
- Provide control and monitoring features
- Self-healing from power system failure

The SG possesses several distinguishing features from traditional grids. Table 1 gives a brief comparison between traditional grid and SG. In traditional grids, power distribution and management was from the power provider to customers (unidirectional communication), whereas SG employs two-way power distribution and management systems that can bring about efficient utilization of power. Existing grids were centralized producer-controlled networks, while SGs are decentralized user-interactive grids supported by fine-grained monitoring, where consumers can feed surplus power back to the grid. Instead of using large power generators as in traditional grids, electricity in SG is produced from many small energy sources like wind, hydro units, offering the possibility of turning consumers into producers. The traditional grids generate power from coal, gas and oil. The burning of fossil fuels for power production results in carbon dioxide release in atmosphere and causes Global warming. SG employs environment friendly ways of power generation from renewable and sustainable energy sources. Energy integration from different sources in SG results in new challenges on the power system. Thus, the power system planning, power quality issue, etc, should be reconsidered to ensure efficient energy management [7].

Smart Metering System: A smart meter (SM) is a two-way communicating device that measures energy (electricity, gas, water, or heat) consumption and delivers that information back to the local utility. The information related to the significant changes in the power load can be conveyed either through wireless or PLC. The SM provides support for new services and improved operational control.

The 'intelligence' of the SM is integrated in the electricity meter (or gas meter coupled to electric meter). The electricity meter communicates by means of a modem. Smart metering is often referred to as automatic meter reading (AMR) which is one-way meter reading, or in the case of real-time, two-way communications, as advanced metering infrastructure (AMI).

The smart metering system consists of four parts namely; meters, terminals, concentrators and a central system. Fig. 1 shows the vision of a smart metering system. The terminal is typically integrated in the meter which communicates with the meter and delivers the data to the concentrator or directly to the central system. Concentrator/collector controls the communication between all meter terminals and the central communication system within a specific area. The central system collects the data from the meter terminals and performs reasonability control of the data and fault management control [8]. For communication in SG applications such as smart metering, the most economical and widely available solution is PLC, the role of which is highlighted in the following Section.

The Role of PLC in Smart Grids: PLC is in operation since 18th century [9]. In recent years, the improvements in modulation techniques and advanced digital signal processing and error detection and correction techniques had made PLC capable of providing high data rates. PLC is currently being utilized for SG services, Internet access and in-home local area networks (LANs).

Power lines are basically designed for the transmission of AC power at 50-60 Hz and at most 400 Hz [10]. Power line communication is a “No New Wires” technology which enables information transmission on existing power lines infrastructure that are widely available. For telecommunication industry, PLC can provide cost effective networks that are capable of providing high data rates. Despite the essential benefits that PLC can provide, PLC-channel suffers from unpredictable noise and fading, which will be briefly discussed in the following subsection.

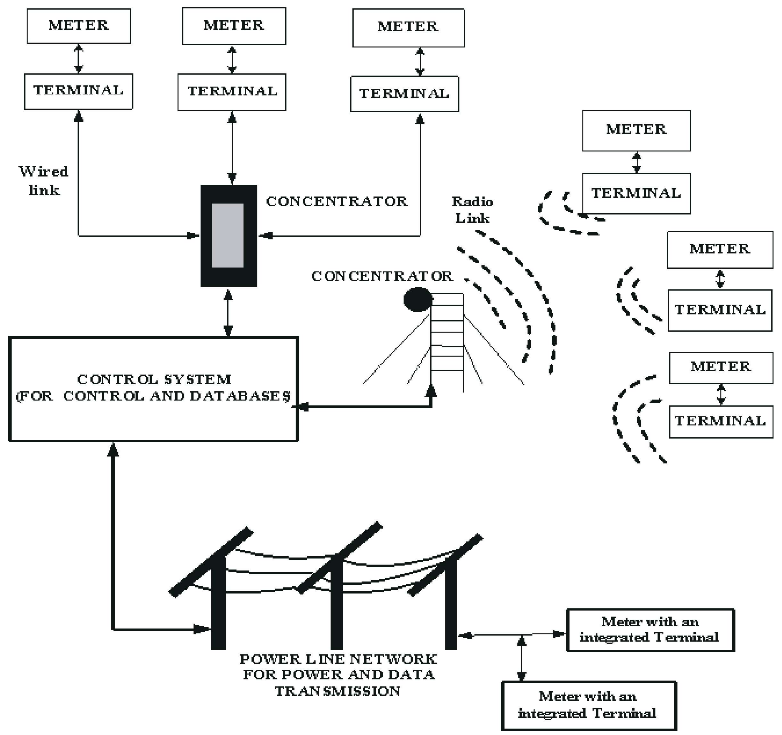

Fig. 1: Schematic overview of a smart metering system

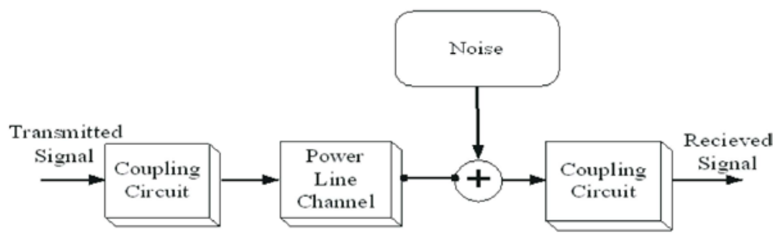

Fig. 2: Graphical illustration of the PLC channel

Power-Line Channel: A typical PLC system with transmitter and receiver is depicted in Fig. 2. The PLC performance is degraded by factors such as insertion losses, the PLC channel itself and unpredictable noise that adds into the signal during its propagation through the power line. In addition, the PLC signal also goes through multipath effect due to impedance mismatching. Such parameters make PLC a hostile and challenging communication medium. In order to connect the PLC transceivers to the mains line, coupling circuits are used [10]. The coupling circuit provides two main functions; it drives PLC signals into the power line and secondly it prevents the damaging 50 Hz mains signal used for power distribution from entering the digital communication equipment. The three main distortion factors that mitigate PLC channel performance are noise, attenuation and multipath effect. These channel impairments are discussed below.

Characterization of Noise in PLC: In PLC channels, noise is mainly generated by the electrical appliances and coupling of the radio broadcasters. This noise is colored in nature with time and frequency-varying characteristics.

Attenuation and Multipath Effect in PLC Channel: In PLC, attenuation is the loss of the power of the signal during its propagation through the power lines, couplers and transformers. Attenuation depends on the physical length of the channel and the transmission frequency band. Multipath effect causes the transmitted signal to reach the receiver by two or more paths with different delays and amplitudes. This leads to the problem of frequency-selective fading. In the power line channel, multipath effect stems due to impedance mismatches and depends on the physical topology of the channel and physical characteristics such as power line cable length [11].

Table 2: CENELEC Bands for Power Line Communications

Band	Frequency range (kHz)	Max. Transmission Amplitude (V)	User Dedication
A	9-95	10	Utilities
B	95-125	1.2	Home
C	125-140	1.2	Home
D	140-148.5	1.2	Home

NB-PLC Classification and Standards: PLC can be sub-divided on the basis of their frequency bandwidth into two categories; broadband PLC and narrowband PLC.

Broadband PLC: Broadband PLC (BB-PLC) is used for high data rate communications such as video phone. The wideband systems operate in HF/VHF bands (1.8-250 MHz). Compared to narrowband PLCs, wideband system provides high data rates from 10-100 Mb/s. The operation of PLC systems in HF band is restricted in some countries due to the interference from other systems [12].

Narrowband PLC: The preliminary communication on power lines was restricted to narrowband PLCs with low data rate applications such as telemetry and power-consumption measurement. NB-PLC systems use low or medium frequencies and supports low and medium data rates. NB-PLC has narrower frequency band but it is still wide enough for control and management purposes.

The frequency range specified in Europe under CENELEC has been specified between 3 and 148.5 kHz and below 450 kHz in Japan. The CENELEC standards supports maximum data rates up to 128kbps and are one of the very first published standards for PLC systems [13]. The NB-PLC systems operate within the frequency bands specified by the CENELEC Norm as shown in Table 2. This frequency range is divided into four bands; A, B, C and D with maximum transmission amplitude and dedicated to specific users.

The NB-PLC systems provide data rates up to a few thousand bits per second (bps). For this reason, NB-PLC may serve as a choice for implementation of SG networks where low data rates are sufficient for control and management functions. For NB-PLC systems, the modulation schemes such as Quadrature Shift Keying (QPSK), Binary Phase Shift Keying (BPSK) and OFDM are usually utilized [14].

NB-PLC Standards: The NB-PLC is an excellent choice for SG related applications due to the following benefits:

- It is a reasonable and cost-effective as NB-PLC provides reliability and low power consumption.
- NB-PLC signals have ability to easily cross transformers between MV and LV lines.
- NB-PLC has scalable bit rates from few Kbps upto 500 Kbps.

The NB-PLC systems utilize the frequency band (3-500 KHz) including the CENELEC band (3-148.5 KHz) for communication purposes. The existing NB-PLC standards, including both single and multicarrier techniques, do not exactly address SG requirements as they are complex, non-scalable and do not offer enough throughputs.

The two new and prominent interoperable OFDM technology based NB-PLC standards known as G3 and PRIME have gained widespread popularity. The multiple standardized bodies are actively working for defining a unified and global specification optimized for SG and home automation. Among these regulatory, the IEEE Standards Association and ITU-T strives for a global standard by initiating the P1901.2 and G.hnem projects. Their objectives include the following:

- Promotes worldwide interoperability and scalability
- Electromagnetic compatibility (EMC) friendliness
- Coexistence with already installed devices
- Reliability over power line channel

Both projects are intended for advancement in existing technologies where ITU-T G.hnem adds new features by integration of G3 and PRIME, while the IEEE P1901.2 initiates the enhancement of the G3 protocol to a frequency range 160-478 kHz.

Comparison of G3 and PRIME: G3 and PRIME (Power line-Related Intelligent Metering Evolution) are the standards based on PLC specification. Both technologies are royalty-and-patent free, promoting equipment interoperability in SG implementations worldwide. G3/PRIME operates in the NB-PLC range and use OFDM for data transmission over power lines. The selection of OFDM as a modulation technique is due to its excellent performance in frequency-selective channels and robustness against impulsive noise.

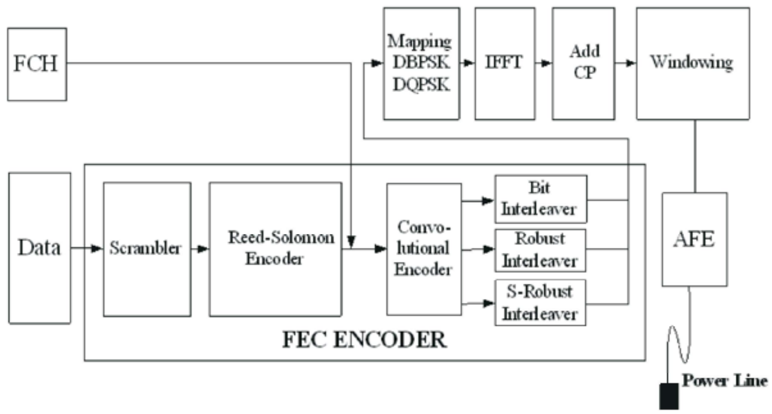

Fig. 3: Block Diagram of G3 Communication System, FCH: Frame Control Header. FEC: Forward Error Correction. IFFT: Inverse Fast Fourier Transform. AFE: Analog Front End

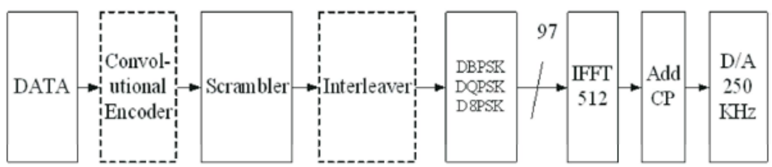

Fig. 4: Block Diagram of PRIME Transmitter

Fig. 3 shows a transmitter side of G3 communication system while PRIME transmitter is depicted in Fig. 4. The two standards are OFDM based techniques; however, they have considerable differences which are discussed below.

Targeted Electric Grid Network: The G3 specification had designed this NB-PLC protocol for both MV and LV networks in the electricity grid. Thus, a signal has a capability to cross a MV/LV transformer and signal attenuation is compensated by receiver using AGC (Automatic Gain Control) while PRIME has been designed for LV electricity grids with low noise, thereby, targeting high data rates.

Allocated Frequency Bands and Sampling Frequency: The G3 Specification supports the functionality of modems in portion of frequencies between 35.9 *kHz* to 90.6 *kHz* of the CELENEC-A band where there is an option to extend the upper frequency to 180 kHz, while "PRIME" specification is intended to support the functionality of modems in the 42 kHz to 89 kHz frequency range [15]. The sampling frequency of G3 is f_s = 400 *kHz* with an FFT size of [illegible] = 256 leading to a subcarrier spacing of Δ[illegible] = 1.5625 kHz ($\Delta f = f_s/M$) between OFDM carriers. In PRIME the sampling frequency is f_s = 250 *kHz*, use the FFT size of M = 512 leading to a subcarrier spacing of Δf = 488 *Hz* [16].

Modulation Techniques and Data Rates: G3 employs OFDM for data transmission with three modes; Robust, normal DBPSK and normal DQPSK modulation schemes per carrier. The data packets for these modes have maximum bytes of 133,235 and again 235 respectively. PRIME uses OFDM modulation with data loaded on 97 (96 data and one pilot) equally spaced subcarriers with a short cyclic prefix (CP). All the 97 subcarriers are modulated by using DPSK (differential phase shift keying) with a modulation order of 2, 4 or 8 that corresponds to DBPSK, DQPSK and D8PSK (differential 8PSK) constellations respectively. PRIME supports D8PSK modulation, but G3 does not. Moreover, in G3 the so-formed PSK symbols are differentially encoded per subcarrier in time ([illegible]-DPSK) while in case of PRIME differential encoding is performed per OFDM symbol across the subcarrier in frequency ([illegible]-DPSK). In G3, the maximum data rate of 33.4 *kbps* is achieved in DQPSK mode. In PRIME, theoretical uncoded speeds of approximately 47 *kbps*, 94 *kbps* and 141 *kbps* (without accounting for CP overhead) can be obtained for DBPSK, DQPSK and D8PSK respectively. The maximum PHY data rate that PRIME supports for uncoded D8PSK mode is 128 kbps and 64.3 kbps for coded D8PSK.

OFDM and PSD: The PHY specifications for G3 and PRIME states that both standards are OFDM based, however, there is difference regarding number of carriers used by for transmission of data; G3 has 36 widely spaced carriers, while PRIME employs 97 narrowly spaced subcarriers (96 data and one pilot). Hence, the narrow subcarrier spacing results in compact PSD in PRIME. However, in order to reduce the out of band emission and spectral side lobe for compact PSD, G3 employs windowing.

Guard Interval: Guard interval (GI), which is the interval containing the CP in G3 is 0.035 ms, while 0.192 ms in PRIME, which is a difference by a factor of 5.5.

Forward Error Correction: G3 supports two modes of operation, normal and robust mode. The forward error correction (FEC) encoder for normal mode comprises of Reed-Solomon and convolution encoder. For robust mode, Reed-Solomon and convolution encoder plus an extra encoder, namely, Repetition Code (RC) is used. Therefore, the use of both convolutional encoder and Reed-Solomon coding in all G3 modes is mandatory with extra Repetition Code (RC) for robust mode. However, in PRIME, the FEC that only consists of the convolutional encoder can be switch off if channel condition are favorable and higher throughputs are needed.

Interleaver: Data is interleaved to transmit it over power lines to decrease information sensitivity to time-domain impulsive noise. Both standards employ interleaver, yet they differ in the way they perform the channel interleaving. PRIME supports interleaving per OFDM symbol (2.048 ms), while G3 performs interleaving over the whole packet, which consists of upto 252 symbols, each 640 μs. The long G3 interleaver puts additional burden in increasing the receiver memory and complexity of decoding.

The comparison between G3 and PRIME is given in Table 3.

Analysis of G3 and PRIME: In the view of above discussion about G3 and PRIME, it is suggested that G3 and PRIME can be integrated for further improvement in terms of efficiency, throughput, interoperability and reliability. Under favorable power line channel scenarios, PRIME is specifically designed for LV power lines and targets high data rates by employing high order modulation schemes. However, enhancement is required to extend PRIME for MV lines. A significant drawback regarding existing NB-PLC standards (including G3 and PRIME) is their non-interoperability. In order to ensure

Table 3: Parameters of G3 and PRIME (according to [16])

Parameter	G3	PRIME
Frequency range	35-91 KHz	42-89 KHz
Subcarrier spacing Δ[illegible]	1.5625 kHz	0.488 KHz
OFDM		
FFT size M	256	512
Length of CP L_{CP}	30	48
CP Interval ([illegible]s)		192
Windowing	yes	no
Subcarrier spacing Δf	1.5625 KHz	488 Hz
Carriers used (one-sided)	36	97
Sampling frequency [illegible]s	400 KHz	250 KHz
Maximum data rate	33.4 Kbps	128.6 Kbps
Interleaving	per data packet	per OFDM symbol
Modulation	DBPSK, DQPSK	DBPSK, DQPSK,
D8PSKDifferential encoding	in time	in frequency

interoperability, efforts are required to develop a unified NB-PLC standard for which the ITU-T G.hnem and IEEE P1901.2 projects are already in progress. The receiver complexity increases as the interleaver size increases. Instead of performing interleaving over single symbol (PRIME) and the whole packet (G3), a best performance complexity tradeoff can be obtained by having interleaver size to be as long as the inter-burst duration of impulsive noise, which is same as AC line period.

In literature, the preambles of both G3 and PRIME are non-ideal. When sending fixed preamble that has to be pre-stored in the transmitter, as in PRIME, result in significant overhead when short packets are sent. The preamble effectiveness and reliability can be enhanced by utilizing spectral shaping and applying fast AGC adjustment.

CONCLUSIONS

Data communication networks in SGs are a crucial part that can facilitate two way flow of energy between the consumers and utilities. PLC is an important option for such a communication network, since it is already in place and ubiquitously available. However, a growing trend is to establish a hybrid communication network consisting of wireless technologies as well as PLC. Intense research is going on in various fields to help establish the new "Smart Grid". However, PLC is continuously evolving area of research in the context of SG, therefore, work is going on regarding the security and robust and reliable communication using such networks. In view of this, it is suggested that hybrid communication networks consisting of PLC and wireless communication can be an attractive choice, provided some impediments are resolved.

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