WHITE PAPER

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Implementing PRIME for Robust and Reliable Power Line Communication (PLC)

Introduction

Power line communication (PLC) is a generic term for any technology that uses the power line as a communication channel. As such, PLC actually comprises several standards focusing on different performance factors and issues relating to particular applications and operating environments. One of the most well-known standards is PRIME (PoweRline Intelligent Metering Evolution). PRIME PLC technology or ITU G.9903/G.9904 is one of the most mature Orthogonal Frequency Division Multiplexing-based technologies to combat many kinds of harsh environments. Led by the Spanish utility company Iberdrola, PRIME has been successfully implemented in Spain to prove the high performance of automated meter reading in the Spanish grid and in other countries. Today, PRIME is a mature, consolidated and worldwide PLC standard for advanced metering, grid control and asset monitoring applications. With an increasing number of PRIME certified products, interoperability among equipment and systems from different manufacturers has been achieved and deployments are already over 2 million. Developers that can build products will be in a position to better capitalize on the emerging market opportunities by designing their systems with Texas Instruments, which provides a complete portfolio of PRIME-based PLC solutions.

Using power line communication (PLC) is economically attractive to utilities for growing smart grid applications. PLC applications include automated meter reading (AMR) (Figure 1), renewable energy communications, indoor/outdoor lighting control, communication between electric vehicle (EV) and electric vehicle service equipment (EVSE) through charging cables, and many more uses. The biggest advantage of using PLC is that no additional wiring is required other than the pre-existing power lines. One of the most important requirements for PLC applications is that all of the components need to be reliably connected all the time, in any environmental condition, and must be resilient to any interference. However, because power lines are a shared media, there is a lot of interference that hinders reliable data communication. Therefore, special care must be taken to make PLC work in harsh environments. PRIME (PoweRline Intelligent Metering Evolution) PLC technology or ITU G.9903/G.9904 is one of the most mature Orthogonal Frequency Division Multiplexing (OFDM)-based technologies to combat those kinds of harsh environments. The PRIME standard was developed out of the PRIME Alliance, which was led by the Spanish utility company Iberdrola. Iberdrola was one of the first utilities to deploy PRIME in large scale to prove the high performance of automated meter reading in the Spanish grid and in other countries.

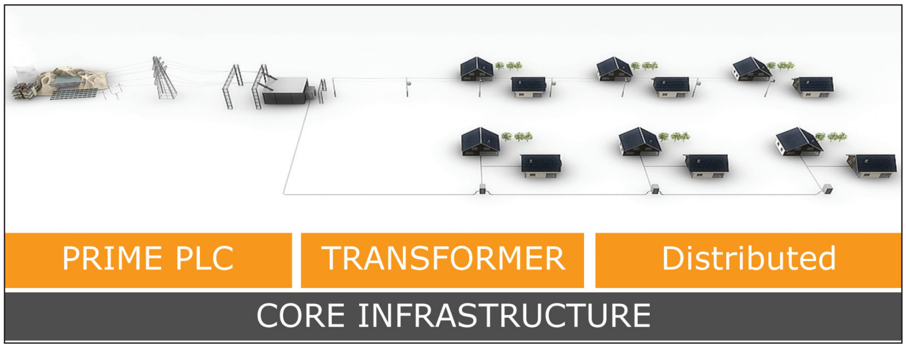

Figure 1. PRIME provides a forum for the definition, maintenance and support of an open and comprehensive standard for narrowband power line for smart grid products and services. (Courtesy: PRIME Alliance)

PRIME defines the Open Systems Interconnection (OSI) layer 1 and layer 2 protocols and has the following key advantages:

- Optimized for AMR and automated meter infrastructure (AMI) with its high efficiency
- Future-proof PLC technology supports large scale meter reading and management applications
- Open, royalty-free and multi-vendor interoperable standardized technology with staffed certification labs and certified solutions

- Millions of electrical meters armed with this PLC technology are being installed in the field and other countries, making it one of the most mature OFDM solutions
- The long Cyclic Prefix (CP) length in ISO layer 1 enables it to easily combat the frequency-selective channels
- Can be seamlessly integrated with either IPv6 or IEC61334-4-32 link layer to support COSEM/DLMS applications
- Supports automated network formation with “tree” topology
- Addresses security and data privacy

PRIME communication is bi-directional with an effective data rate of 21-128Kbps in the CENELEC-A band. The most recent PRIME standard to be released is version 1.4 and covers the frequency band from CENELEC-A (regulated in Europe) to the full FCC/ARIB band (3kHz – 490kHz) to provide a higher data rate: 40Kbps-1Mbps. Support for IPv6 enables PRIME to converge to IPv4 and IPv6 networks in an efficient manner so no additional router is needed to run on IP network.

PRIME OFDM modulation provides high resiliency to interference and attenuation. PRIME devices (called service nodes) automatically form a “tree” type network topology when plugged into the power line and are managed by a centralized “root” of the “tree” called a base node (BN) following PRIME MAC (media access control) protocols.

Several factors impact PRIME PLC performance, including line noise, impedance and frequency-selective channels. At the network level, a developer must consider the number of nodes connected to the BN, the number of levels from the “leaf” node to the “root” node, the reliability of the switch node, locations and length of the low voltage lines in order to run a reliable automated meter reading and control application.

Factors impairing physical performance

Noise has been the most studied factor in PLC systems. Since power lines are a shared medium, they have all kinds of electric devices connected to them so there can be significant noise impacting the system performance. The two prevalent noises are periodic impulsive noise (PIN) synchronous to 50Hz or 60Hz mains and narrowband interference (NI). Time domain noise taken in the field from the Spanish grid (Figure 2) shows noise bursts every 10 ms (=1/100Hz). Special care is needed to handle this kind of impulse noise with forward error correction, interleaving, etc. The PRIME specification defines interleaver to protect burst errors caused by impulse noise.

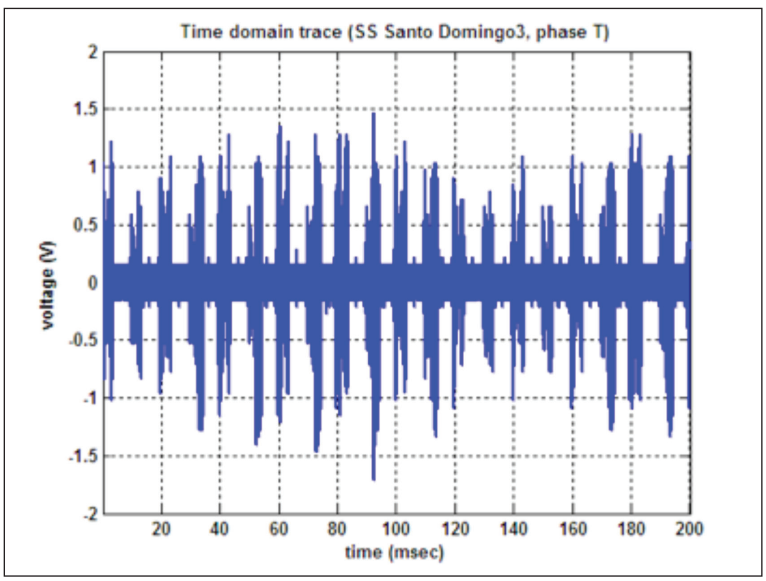

Figure 2. Time domain noise trace (8-bit ADC) at secondary substation (SS) in the Spanish low voltage grid.

Time-varying line impedance is another factor in low voltage (LV) grids. The PRIME Alliance Technical Working Group has performed impedance measurements in various places across Spain [4]. Figure 3 shows one of the LV impedances measured at certain secondary substations (SS) in the CENELEC-A band. Impedance changes from 0.1ohm to 1.5ohm relative to the frequency. This is because multiple other devices are plugged into the power line, which lowers the line impedance significantly. Different colors in the figure mean that impedance is changing across the AC mains cycle and also shows that line impedance is increasing across the frequency band.

PRIME specifications define a Line Impedance Stabilization Network (LISN) by modifying the original LISN defined in CENELEC EN 50065-1 to reflect very-low line impedance conditions [5]. The effective impedance is 2ohm and PRIME specifies 1 Vrms (120 dBuV) injection over 2ohm load, which is a unique feature that is different from other PLC specifications. This can be used to define minimum performance requirements in this small impedance.

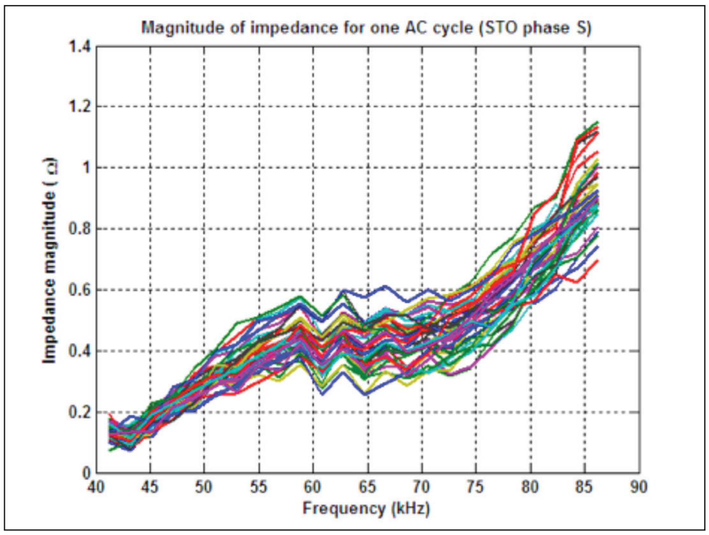

Figure 3. Impedance at the SS in the Spanish electricity grid.

Frequency-selective channels are another factor typically impacting PLC performance. Power line channels are normally frequency selective because of line impedance and channel delay due to distance. Modeling of PLC channels has been addressed using ABCD parameter and transmission line theory [6]. The frequency selectiveness of the power line channel measured at one of the substations in the Spanish grid is shown in Figure 4. The calculated root mean square (RMS) delay spread is 23.2µs. Since PRIME cyclic prefix (CP) length is 192µs, which can handle large delay spreads [2], PRIME is therefore extremely resilient to frequency-selective channels.

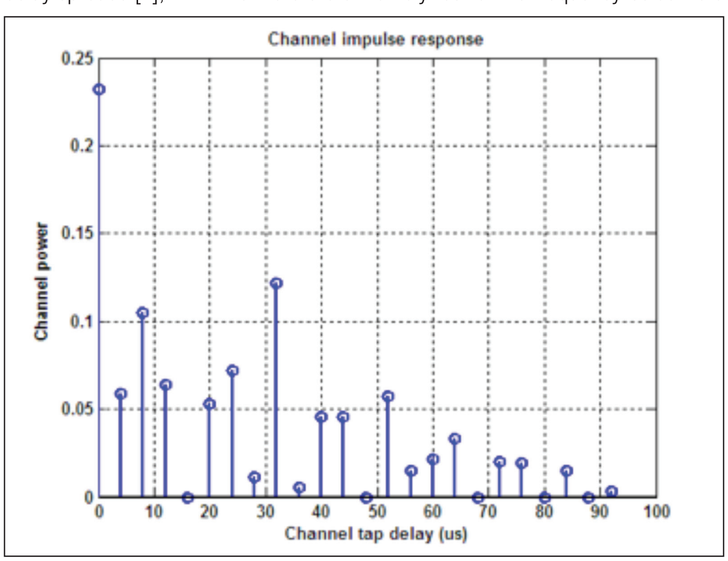

Figure 4. Channel profile at the substation in the Spanish electricity grid.

Salient features of PRIME MAC

PRIME is a synchronous network, where the BN sends periodic beacons at every sub-frame time interval. The nodes that forward packets to other nodes that cannot directly reach the BN are called switch nodes. These nodes are promoted by the BN during the registration process of nodes that directly cannot reach the BN. The switch nodes also transmit beacons in a periodic fashion in a multiple of the number of sub-frames. The topology created by the PRIME network is "tree" type with the "root" being the BN. The route formation occurs naturally during the node registration, based on the distance of the node and beacons transmitted by the BN or the switch node. There is no notion of periodic route maintenance and the routes formed by the "tree" during node registration process are maintained as long as the nodes are registered. The topology formed by the PRIME network can potentially span multiple levels depending on the proximity of the farthest nodes to the BN and the channel characteristics of the nodes as discussed in previous section.

The BN also transmits periodic control frames to every node in the network, called "keep-alive" frames, to monitor the nodes that are currently connected to the network. When a node receives a keep-alive frame from the BN – ALV_B – it responds with keep-alive frame response, also known as ALV_S. There is a notion of keep-alive timeout maintained at the BN for each of the nodes. If an ALV_B is not received within a keep-alive timeout, the node considers itself to be unregistered to the BN and starts the re-registration process. Similarly, if the BN does not receive an ALV_S frame from the node within the timeout, it removes the node from the registered list, causing the eventual deregistration of the node (due to lack of ALV_B) and will trigger a re-registration process.

In addition to the control frame transmission, there is a MAC-level error recovery mechanism called Automatic Repeat reQuest (ARQ) that is applied to any data packet transmission. The ARQ mechanism in PRIME is end-to-end, with only the source node can repeat a particular data transmission, in the event of a lack of acknowledgement from the final destination node. Note that the final destination node can potentially be several levels away from the source node. The MAC ARQ timeout is used by the source node to trigger re-transmission of unacknowledged frames. In addition, if a negative-acknowledgement is received, the source node will use this information to retransmit the frame. Control frames such as promotion, registration and connection establishment frames are subject to a similar end-to-end retry mechanism that uses a different parameter for control retry timeout and the number of attempts before declaring the node to be unregistered to the service node.

Table 1 illustrates the key MAC layer features of the PRIME standard.

MAC Functions	PRIME
Topology	Tree
Network formation	Beacon discovery, Automatic promotion
Multi-hop routing	Yes
Keep-alive monitoring	Yes
Connection management	Yes
Medium access	CSMA/CA
ARQ	Selective ARQ end-to-end
Security	128-AES in CBC
Link adaptation	PRM
Aggregation	Optional in Switch Node

Table 1. Overview of MAC features in PRIME.

PRIME certification and deployment

PRIME has been successfully deployed in various harsh environments across Spain with millions of units and multiple vendors. Before the devices are deployed, PRIME certification needs to be performed. There are two third-party PRIME certification labs in Spain to perform the PRIME certification: KEMA and Tecnalia. TI was one of the first semiconductor vendors to achieve the independent PRIME certification and currently has a testing facility in Dallas to perform pre-certification for customers using TI's PRIME solution (i.e., pre-certification was conducted in TI's labs before applying for the official certification.) As an example, Iberdrola has installed 1.3 million PRIME-enabled smart meters by multiple e-Meter vendors as of August 2013. Those smart meters are connected to secondary substations in locations representative for various environments and installation scenarios: urban, suburban and rural; dense and disperse; industrial and residential areas. All of the secondary substations were monitored and analyzed before entering the production environment.

Along with the deployment, a set of tools and lessons learned were developed that are applicable for any future smart meter deployments. These firsthand experiences are helpful for other utility companies who are currently engaged in or planning future smart grid and smart meter deployments. The model deployed in Castellon will be extended to other grids all over the world. Iberdrola continues its deployment at approximately 1 million new smart meters per year and expects to maintain that pace through 2018.

PRIME Standard beyond v1.3.6

Within the PRIME Technical Working Group, there have been significant efforts to improve system performance of PRIME version 1.3.6, such as adding a set of new modes called "robust modes", extending the frequency coverage up to 500kHz to achieve higher data rates, and adding new components in MAC for securities. The addition of robust modes in the CENELEC-A band gives more reliability in communication at lower data rates (i.e. 5Kbps and 10Kbps). The PRIME Technical Working Group performed extensive channel measurements to validate the performance of PRIME robust modes. Two robust modes are DBPSK + ¼ repetition and DQPSK + ¼ repetition ith longer preambles (=8.192ms) for protection from power line impulse noise. These robust modes enable with communication across the medium voltage (MV) to low voltage (LV) transformers. One of the unique features of the PRIME robust modes in comparison to similar technologies such as ITU G.9903/G3 and IEEE P1901.2 is that the repetition is done at the OFDM symbol level instead of the bit level.

Table 2 shows the new parameters defined in PRIME robust modes.

Parameter	Robust PRIME (OFDM System)
Sampling frequency	250kHz
IFFT length	512
Carrier spacing	488.28125Hz
CP length	192 µs
Modulation size	DBPSK/DQPSK/D8PSK/robust DBPSK/robust DQPSK
Preamble length	8.192ms
Forward error correction	Rate ½ convolutional code + symbol repetition by 4
Data rate	5, 10, 21,42,64,84,128Kbps
Band plan	42-89kHz
MAC	PRIME Standard MAC with enhancement for ROBO rates support
Convergence layer	IEC61334-4-32/IPV6
Metering application	DLMS/COSEM, IP

Table 2. PRIME parameters with newly defined robust mode.

In addition to more robust modulation schemes, the PRIME alliance has recently focused on scalability and ubiquitous access by providing the IPv6 convergence layer. This IPv6 convergence layer provides an efficient method for transferring IPv6 frames over the PRIME network between the BN and the service nodes, or from an external network to the PRIME network. Both service nodes and BN support the standard IPv6 protocol [7] as well as IPv6 addressing architecture [8] and global unicast IPv6 addresses, link local IPv6 addresses, and multicast IPv6 addresses as described in [8]. Packets within the PRIME sub-network are routed according to Node Identifier (NID), which is based on a combination of service node's local connection identifier (LNID) and switch identifier (SID). At the convergence sub-layer, the BN maintains a mapping of IPv6 unicast addresses to the EUI-48 of each service node to perform address resolution. Other service nodes can query the BN to resolve an IPv6 address into EUI-48 address. Optionally, UDP/IPv6 addresses may be compressed, as part of the connection establishment phase. The PRIME specification describes one such approach for header compression of IPv6 packets known as LOWPAN_IPHC1, as defined in RFC 6282[9]. Additional compression techniques may include not transmitting the link local IPv6 addresses for service nodes, which can be derived from a combination of service nodes' LNID and SID.

Bandwidth extension to 500kHz also gives higher data rates up to 1Mbps for applications such as automotive pilot wire communication, LED lighting communication, etc. PRIME FCC/ARIB technology also incorporates the robust modes and longer preambles for reliable communication.

Parameter	PRIME Band Extension (OFDM System)
Sampling frequency	1MHz
IFFT length	2048
Carrier spacing	488.28125Hz
CP length	192µs
Modulation size	DBPSK/DQPSK/D8PSK/robust DBPSK/robust DQPSK
Preamble length	8.192ms
Forward error correction	Rate ½ convolutional code + symbol repetition by 4
Data rate	40, 80, 168, 336, 512, 672, 1024Kbps
Band plan	42-472kHz

Table 3. PRIME parameters with band extension to FCC/ARIB band

In searching for the most appropriate PLC technology, Europe and many other countries such as Poland, Mexico, Indonesia, and so on... have begun their evaluation by characterizing how well PRIME serves under noisy operating conditions in those regions. Taking into account those considerations, developers that can build products will be in a position to better capitalize on the emerging market opportunities by designing their systems with ICs from Texas Instruments, which provides a complete portfolio of PRIME-based PLC solutions.

Industry-leading field expertise and innovation

In order to better understand the issues that arise with PLC in real-world networks across countries and regions, TI has performed extensive PRIME field testing worldwide to measure how varying operating environments impact signal performance and robustness. Especially for grids in Indonesia and Mexico, PRIME signals were able to reliably travel 500m distances in direct low voltage connections without any assistance from intermediate switch nodes with 40Kbps throughput. With PRIME robust modes, 700m distances are achieved with 5Kbps without any switch nodes in between. In addition to TI PRIME field tests, many countries worldwide developed interoperable PRIME solutions and field tests with numerous nodes. In 2009, for example, MAC and PHY interoperability tests were performed in Spain, and are now massively deployed with 100,000+ meters.

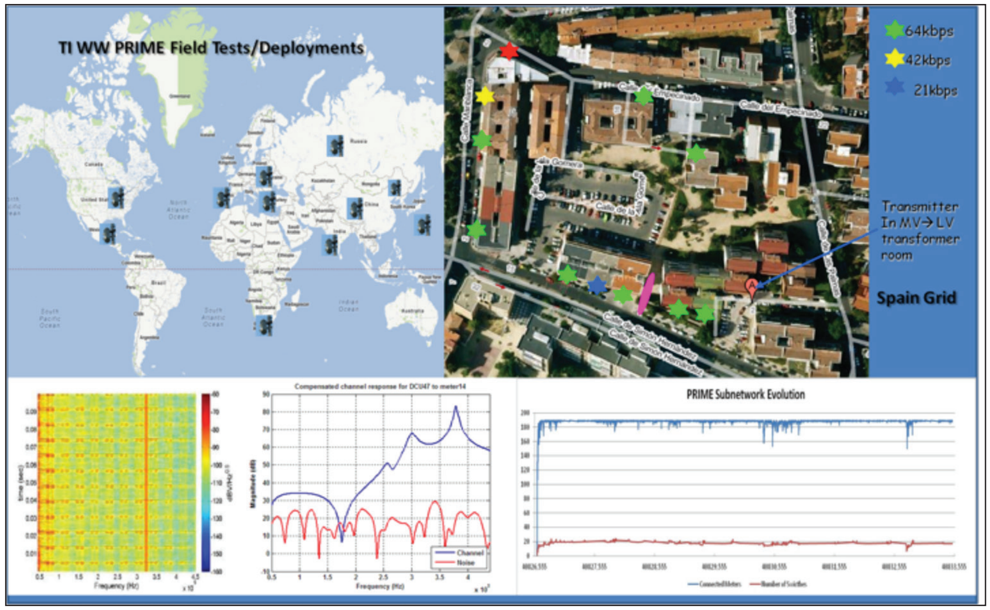

Figure 5. TI has performed extensive PRIME field testing worldwide to measure how varying operating environments impact signal performance and robustness. The field tests covered a comprehensive variety of operating environments, topologies, distances and test times to verify that PRIME links could communicate under dynamically changing operating conditions.

TI has also extensively partnered with customers in lab stress tests, which are performed for Iberdrola to gauge the system performance of different meter manufacturers. Among the many stress lab tests, "Test 7" is of particular importance because it attempts to re-create the worst-case field conditions with 350 meters and multiple levels, and compares the network performance of various vendors. The performance metrics of key importance are the meter connectivity during network bring-up and during long-cycle reading, and the meter reading percentage during long-cycle reading.

Through those tests, TI gained a better understanding of what is required for a robust PLC solution that is reliable, scalable and cost-effective. TI has collected various channel modeling data and contributed to the development of the PRIME Technical Working Group channel measurements campaigns such as impedance measurements, channel measurements and noise measurements by providing measurement tools and methods. Channel models play a key role in enabling developers to create technology that can address the particular characteristics of a channel under a variety of operating conditions. For example, researchers have developed thorough and complete models of the channel characteristics for wireless communication. These models enable the industry as a whole to provide consistent and reliable wireless products. Without such models, the performance, robustness and interoperability of wireless products would be compromised. TI is at the forefront of research to achieve the level of understanding of PRIME PLC technology required to ensure a smooth adoption and migration to power line-based communication.

As a leader in PLC technology, TI continues to aggressively identify and solve problems that arise as the numerous PLC standards mature. With its advanced field testing, TI has acquired an intimate knowledge of the specific requirements for PLC in each country and region. TI is continuously bringing higher performance and improved robustness to PLC technology. TI is a global company equipped to handle technology variations around the world and provide the volume production these applications will require. TI is also unique in its ability to support so many applications beyond the utility meter.

For more information about TI's PRIME PLC technology and solutions, visit **www.ti.com/PRIME-wp** or contact your local sales representative.

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Resources

IEEE Smart Grid Communications (SmartGridComm) 2012

Performance Results from 100,000+ PRIME Smart Meters Deployment in Spain, A. Sendín, I. Berganza, A. Arzuaga, A. Pulkkinen, I.H. Kim, Tainan City, Taiwan, November 2012.

IEEE Smart Grid Communications (SmartGridComm) 2011

PRIME on-field deployment. First summary of results and discussion, I. Berganza, A. Sendín, A. Arzuaga, M. Sharma, B. Varadarajan, Brussels, Belgium, October 2011.

IEEE Smart Grid Communications (SmartGridComm) 2010

PRIME interoperability tests and results from field, A. Arzuaga, I. Berganza, A. Sendín, M. Sharma, B. Varadarajan, Gaitersburg, Maryland, USA, October 2010.

References

[1] M. Nassar, A. Dabak, I. H. Kim, T. Pande, and B. L. Evans, "Cyclostationary noise modeling in narrowband powerline communication for smart grid applications," *International Conference on Acoustics, Speech, and Signal Processing*, Kyoto, Japan

[2] M. Nassar, J. Lin, Y. Mortazavi, A. Dabak, I. H. Kim, and B. L. Evans, "Local utility powerline communications in the 3-500kHz band: channel impairments, noise, and standards," *IEEE Signal Proc. Mag.*, to appear

[3] B. Varadarajan, I. H. Kim, A. Dabak, D. Rieken, and G. Gregg, "Empirical measurements of the low-frequency power-line communications channel in rural North America," *International Symposium on Power Line Communications and Its Applications (ISPLC)*, pp.463-467, 3-6 April 2011.

[4] PRIME Alliance – Technical Working Group, "PRIME Specification", version 1.3.6, Nov 2011, available: **http://www.prime-alliance.org** (May 2012).

[5] EN 50065-1:2011, "Signaling in low-voltage electrical installations in the frequency range 3 kHz – 148.5 kHz – Part 1: General requirements, frequency bands and electromagnetic disturbances", CENELEC, April 2011.

[6] A. Dabak, I. H. Kim, B. Varadarajan, and T. Pande, "Channel modeling for MV/LV AMI applications in the frequency range < 500kHz," *Workshop on Power Line Communications*, Arnhem, The Netherlands, 2011.

[7] Neighbor Discovery for IP Version 6 (IPv6), RFC 2461, Standards Track.

[8] IP Version 6 Addressing Architecture, RFC 4291, Standards Track.

[9] Compression Format for IPv6 Datagrams over IEEE 802.15.4-Based Networks, RFC 6282, Internet Engineering Task Force (IETF), Standards Track.

[1][2][3] provide detailed spectro-temporal noise characterization over a frequency range 0 - 500 kHz.

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