WHITE PAPER

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Developing robust power line communications (PLC) with G3

Introduction

Power line communications (PLC) is a global technology with worldwide interest in its development. In its simplest terms, PLC modulates communication signals over existing power lines. This enables devices to be networked without introducing any new wires or cables. This capability is extremely attractive across a diverse range of applications that can leverage greater intelligence and efficiency through networking. Initial market opportunities for PLC include:

Utility Meters: Utility meters represent a key volume application for PLC. PLC is the utility company's preferred technology of choice for Automated Meter Reading (AMR) and Automated Meter Infrastructure (AMI) communications because of the elimination of any need to install additional wires. It is also being driven by consumers who want to connect the meters to an energy monitoring device, i.e. In Home Display (IHD) to display their energy consumption and leverage lower cost pricing schedules based on time-of-day demand.

Home Area Network: As the home network extends to include appliances for more efficient consumption of energy, OEMs are turning to PLC to serve as the bridging technology between devices and the home network. One of the key challenges in this market is the high noise characteristic of appliances when they are in use. OEMs need a robust and cost-optimized implementation to provide reliable communications, making narrowband PLC the best choice when it comes to wired communication or bridging existing wireless techniques.

Lighting: Appropriate for both home and industrial automation, PLC enables OEMs to integrate intelligence into a wide variety of lighting products. Key functionality includes remote control of lighting, automated activation and deactivation of lights, monitoring of usage to accurately calculate energy costs, and connectivity to the grid. A key design requirement is the ability to implement a cost-effective single chip for control and PLC.

Solar: PLC serves as an important enabling technology for the mass deployment of solar equipment by providing a communication channel to solar inverters for monitoring and managing power across the grid by utility companies. While RF has made some headway in solar installations, PLC offers an ideal means for connecting equipment with high reliability at a low cost, on DC or AC lines.

G3: Robust and reliable communications

PLC is actually a generic term for any technology that uses the power line as a communications channel. As such, PLC actually comprises several standards focusing on different performance factors and issues relating to particular applications and operating environments (Table 1). Two of the most well-known are G3 and PRIME. In general, across multiple standards, G3 or its cousin IEEE P1901.2, focus more on robustness. Given the varied environments in which PLC can operate and the different kinds of interference present in them, the robustness of G3 to withstand noise often makes it a more compelling choice for worldwide deployments.

IEC61334, PRIME, G3 and IEEE P1901.2/G3-FCC

Parameter	IEC61334 S-FSK	PRIME (OFDM)	G3 (OFDM)	P1901.2 / G3-FCC (OFDM)
Modulation size	Spread frequency shift keying	DBPSK / DQPSK/D8PSK	DBPSK / DQPSK/ (D8PSK)	DBPSK/DQPSK/D8PSK/ coherent modulation
Forward error correction	N/A	Rate ½ Convolutional Code	Outer RS + inner rate ½ convolutional code	Outer RS + inner rate ½ convolutional code
Data rate	2.4Kbps	21, 42, 64, 84, 64Kbps (with coding)	20.36,/34.76/(46)Kbps (with coding)	Scalable up to 250Kbps
Band plan	CENELEC-A	Continuous 42–89 KHz (defined for LV scenario)	36–91 KHz with tone masking for SFSK	CENELEC-A, FCC band
ROBO mode	No	No	Yes	Yes
Tone mask	No	No	Yes	Yes
Adaptive tone map	No	Yes	Yes	Yes
MAC	IEC61334 MAC	PRIME MAC	802.15.4/G3 profile	802.15.4 based
Convergence layer	IEC61334-4-32	IEC61334-4-32/IPv6	6LoWPAN/IPv6	6LoWPAN/IPv6
Meter application	COSEM/DLMS	COSEM/DLMS, IP	COSEM/DLMS, IP	COSEM/DLMS, IP

Table 1. Power line communications (PLC) actually comprises several standards focusing on different aspects and issues relating to particular applications and operating environments.

The evolution of G3 as a standard has been managed by the G3 Alliance. G3 operates over the CENELEC-A band (3-95KHz) in Europe and can be extended across the full FCC band to provide a higher data rate in other countries. G3 is bi-directional with an effective data rate of 20–40 Kbps in the CENELEC-A band and up to 200–400 Kbps across the FCC band (G3-FCC). It co-exists with S-FSK and other legacy PLC technologies and seamlessly supports DLMS/COSEM (IEC 62065 series) as well as offers layer 2 128-bit AES for CCM to provide extra data security. Support for IPv6 currently enables G3 to converge IPv4 and IPv6 devices and networks in an efficient manner.

G3 uses Orthogonal Frequency-Division Multiplexing (OFDM) modulation to provide high resiliency to interference and attenuation. As a result, it can achieve reliable communications up to 6 miles while crossing between medium voltage transformers. The standard also enables communications over the low voltage and medium voltage (LV/MV) transformation crossing for a total distance up to 2–3 miles, depending upon the channel condition.

The ability of G3 to pass through a transformer is an important capability, especially for rural areas where population density is low. Specifically in North America, the low-voltage transformation between the house and utility may only extend 3 to 4 meters. Placing a concentrator before this transformer simply cannot achieve the necessary density to justify the cost of the concentrator.

G3 was designed to address this issue by enabling PLC signals to pass through the low-voltage transformer and out to the medium-voltage line. This enables the concentrator to be placed where it can aggregate data from substantially more locations, thus improving the cost effectiveness of connecting the home/business with the utility company.

G3 also forms the Annex-A and Annex-D (G3-FCC) parts for ITU G.9955 (G.9956 for the G3 MAC). The IEEE is developing a worldwide version of G3 under the name of P1901.2. This final standard is expected to be completed by the end of 2012. Other OFDM-related standards include G.9955/9956 main body or G.hnem.

In order to support increased data rates and coverage, G3-FCC utilizes coherent modulation option. Effectively, when the channel can be reliably estimated through the use of pilots, performance can be improved over differential modulation. G3-FCC supports coherent demodulation for Robo-mode, BPSK, QPSK, 8PSK, and 16-QAM and provides up to 5 dB gain. Known challenges associated with coherent modulation include crystal oscillator drift and managing channel changes within an AC cycle.

Beyond G3

In the search for the most appropriate PLC implementation, many countries have begun their evaluation by characterizing how well G3 serves under noisy operating conditions typical to the region. In Korea, for example, many cables are installed underground. At the time, the Korean government believed it would be possible to use broadband PLC technology through these cables. However, broadband reliability suffers when used underground. A narrowband implementation such as G3 is more suited to these operating conditions.

While a number of countries have standardized on G3, notably France, some like Spain have chosen other technologies, such as PRIME. The real battle of the standards, however, has just started. Countries such as China, Indonesia and Japan have yet to standardize on a particular flavor of PLC. OEMs that can build products that support multiple standards will be in a position to better capitalize upon these emerging market opportunities.

Texas Instruments (TI) provides a PLC platform that can realize all standards in Table 1 on page 2. On top that that, it offers PLC-Lite™, as a non-standard-based, lower cost and a very flexible approach to PLC. Because it isn't a fixed standard, developers can exploit the flexibility of PLC-Lite to optimize an implementation to specific channel characteristics to improve link robustness in environments where G3 and PRIME experience difficulty because interference on the line requires exceptional handling.

PLC-Lite offers a maximum data rate of 21 Kbps and supports both full-band and half-band modes (Table 2 on the following page). It has been designed to provide added robustness to certain types of interference, including narrowband interference that can affect G3 links. It contains a simple CSMA/CA (Carrier Sense Multiple Access/Collision Avoidance) MAC which can be integrated with any application-specific stack.

Because of its simplicity and lower data rate, it can be implemented at a substantially lower cost per link. PLC-Lite™ also offers tremendous flexibility and allows developers to customize channel links outside the constraints of an industry standard.

TI PLC-Lite feature parameters

Band	A/B/C/D half band, configurable at run-time CENELEC compliant	CENELEC A full band
Bandwidth	23 kHz	47 kHz
Sampling frequency	500 kHz	250 kHz
Data/Header symbol duration	2.24 ms	2.24 ms
Preamble duration (each)	2.048 ms	2.048 ms
PHY data rate	21 kbps (BPSK) 11 kbps (BPSK + FEC) 2.6 kbps (Robo-4) 1.3 kbps (Robo-8)	42 kbps (BPSK) 21 kbps (BPSK+FEC) 5.2 kbps (Robo-4) 2.6 kbps (Robo-8)
FFT size	1024	512
CP size	96	48
Number of subcarriers	49	97
MAC	CSMA/CA	CSMA/CA

Table 2. Because of its simplicity and lower data rate, PLC-Lite can be implemented at a substantially lower cost per link than either G3 or PRIME. In addition, PLC-Lite offers tremendous flexibility by allowing developers to customize channel links.

PLC-Lite is appropriate for very cost-sensitive environments and applications where the complexities of G3 and PRIME are not required, but a robust communications channel is still needed. In the same way that a television remote does not need the full capabilities of Wi-Fi™ to change channels and adjust the volume, not every application needs the advanced functions and data rate of PRIME and G3. For example, PLC-Lite is the perfect solution for a simple light bulb or wall switch within a home network – where only a few Kbps will be sufficient.

PLC-Lite is especially well-suited for devices beyond the power meter, including solar converters, home and industrial lighting, and network appliances. It offers strong value in many applications with a cost-effective approach that provides the robustness required for reliable operation in noisy environments. Its optimized memory footprint and required computation performance allows developers to implement light control or inverter control on top of the PLC communication, which offers a very unique integration level on one single chip.

PLC flexibility through software

With its plcSUITE™ software, TI provides a full working solution for all major flavors of PLC with complete PHY and MAC layer processing as well as an API to the application (Figure 1 on page 5). Implementing the PLC system in software also gives developers tremendous flexibility by enabling them to support each flavor of G3, including G3-FCC, in addition to the PRIME standard for devices requiring higher data rates and

PLC-Lite™ for low-cost applications.

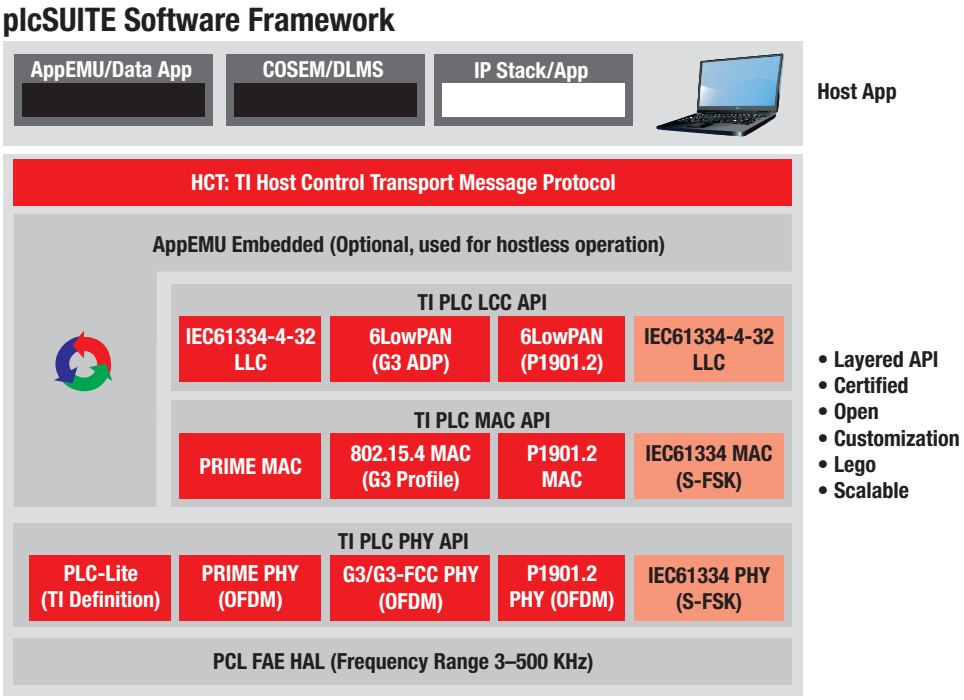


Figure 1. TI's plcSUITE™ software provides a full working solution for all major flavors of PLC with complete PHY and MAC layer processing as well as an API to the application. For example, the stack provides a seamless interface all the way up to the metering application, thus simplifying PLC design and substantially accelerating development.

TI's easy-to-use plcSUITE software libraries allow developers to customize their PLC designs in less time and bring their products to market faster. The software libraries are an end-to-end product that provide solutions for both end-point side (e-Meters and data concentrators), or the controller side of the solution so developers can learn and control the complete network. In addition, plcSUITE can either be used as a "black box" solution or can also be used as a "platform" enabling developers to add their own IP on top of the PLC libraries providing greater market differentiation.

Developers can request a licensed version of TI's source code, giving them the option to use just the components they want. They can also customize code if they need to adjust the implementation for a particularly difficult operating environment. In addition, TI's G3 implementation supports additional enhancements that further improve robustness for applications operating in harsh or noisy environments. For example, developers can utilize coherent modulation, a longer preamble, Robust Receiver Algorithms and automatic frequency detection or tone mask setting based on dynamic channel conditions.

TI's G3 and PRIME software is alliance-qualified and enables developers to support every aspect of the standards. TI also offers application-specific implementations such as its auto-REM PLC software developed especially for electrical vehicles (EV).

Part of TI's value proposition is that its PLC software runs on devices across its MCU portfolio. For applications requiring PLC implemented as an independent subsystem, the PLC83 microcontroller provides an integrated, cost-effective approach. For systems where developers want to run the application and PLC software on the same processor, the C2000™ Concerto™ platform of microcontrollers offers a variety of options with different memory density and processing capabilities. Concerto processors also have the capacity to support the higher data rate and processing requirements of G3-FCC. For low-cost applications that can use PLC-Lite™, TI offers its C2000 Piccolo™ F280x processor.

The flexibility of TI's PLC portfolio to support multiple PLC standards also enables OEMs to select the optimal processor and then bridge between devices and networks. For example, consider a factory with intelligent lighting. The lights themselves could be controlled and monitored using PLC-Lite to achieve the lowest per unit cost. A single concentrator supporting both PLC-Lite and G3 could manage multiple nodes and send the consolidated data to a central aggregation point using G3 for maximum robustness. Finally, the central aggregator could bridge the G3-FCC network to the utility company's PRIME network.

Accelerating development of PLC-based applications

To assist developers in their initial evaluation of PLC technology, TI offers its TMDSPLCKIT-V3 evaluation kits with plcSUITE and Zero-Configuration GUI Tool. This is a powerful tool that allows characterization of a channel link. In its zero-configuration mode, developers are able to transmit data between nodes without having to define any configuration parameters. This substantially simplifies the evaluation process, especially for developers not as familiar with the implementation details of PLC.

The tool also serves to accelerate product development by supporting an expert mode in which developers can fine-tune a channel's configuration to collect more data about the channel. This provides important information about a channel's characteristics that are required to optimize an implementation for a particular market (Figure 2 below). Texas Instruments uses the same zero-configuration GUI for customer field tests around the world, but allows customers to access and develop with this technology.

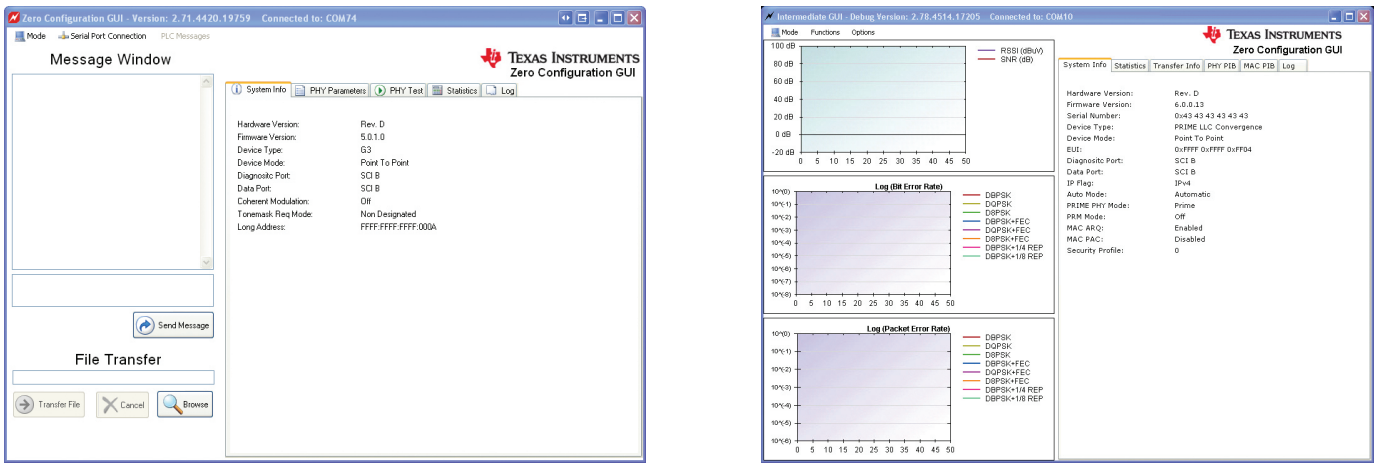


Figure 2. The Zero-Configuration Tool accelerates product development by enabling developers to quickly change a channel's configuration to collect more data about the channel and optimize an implementation for a particular market.

While use of the FCC band is prohibited in Europe, support for G3-FCC is anticipated to be quite useful for many countries. For developers wanting to test G3 over FCC performance, TI has the F28M35x controlCARD available. This plug-in module enables quick evaluation of FCC-based G3 on many of TI's development boards, including the PLC Thumb.

By having hardware and software available today as PLC standards continue development, OEMs can begin development and be able to quickly release product as standards become official. The ability to jump start PLC design is critical to capturing market share once each of the standards becomes official.

In addition to providing the hardware, software and tools required to process PLC signals, TI also offers an extensive portfolio of analog components to further improve robustness. The AFE031, for example, is integrated into TI's PLC solutions and provides developers with an analog front-end with integrated power amplifier that provides superior performance and increases overall system reliability and range. TI is committed to using this same technique in upcoming devices.

TI is dedicated to advancing the development of PLC and actively contributes to both the G3 Alliance and IEEE P1901.2 working group, in fact Texas Instruments holds a board of director position on the PRIME and G3 alliances and is a founding member of P1901.2. TI also has a worldwide PLC research and development center based in Dallas, Texas that innovates PLC software and hardware and is opening a G3-PLC competency center in France.

Industry-leading field expertise and innovation

In order to better understand the issues that arise with PLC in real-world networks in different countries and regions, TI has performed extensive G3 field testing worldwide (Table 3 below) to measure how varying operating environments impact signal performance and robustness.

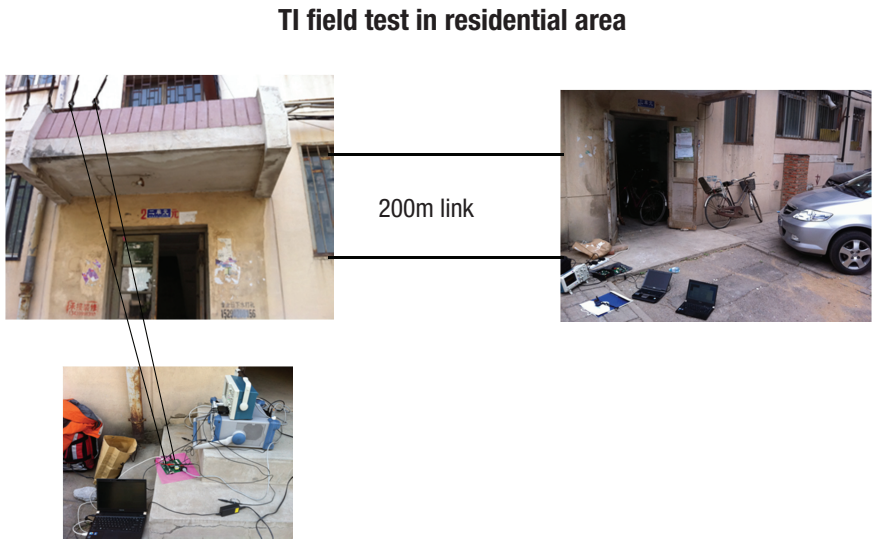
G3 Field Tests Summary (2011–2012)

Where	When	Tests	Results
Milwaukee, WI	Mar 2011	G3-CEN/FCC	Passed with the erasure channel with actuators
Southern US	Mar 2011	G3-CEN MV/LV	Crossed MV/LV transformer up to 2miles with adaptive tone mask
Hiroshima, Japan	April 2011	G3-ARIB LV/LV	Passed all the LV/LV connectivity test cases
Beijing, China	April 2011	G3-CEN residential test	Achieved up to 200m in out-door grid to meter tests
Mexico City, Mexico	May 2011	G3-CEN circuit room	Passed 2 circuit-breakers
Turkey	June 2011	G3-CEN factory test	Passed all test cases where competitor either pass or fail
Eastern US	Sept 2011	G3-FCC MV/LV	Crossed MV/LV transformer up to 2 miles with adaptive tone mask
Tangshan, China	Nov, 2011	G3-CEN grid to meter	Passed 95% of test points with only CEN-A tone mask
India	Nov. 2011	G3-CEN LV/LV	Passed all LV/LV test cases.
Japan	Dec. 2011	G3-ARIB network test	30 node grid-to-meter tests with interference. Formed stable network with minimal # of Hops comparing with competitor. MAC tests.
Tokyo, Japan	Feb, 2012	G3-ARIB for MV/MV and LV/MV	100% coverage for all test routes. Coherence added performance gain in certain cases.
Taipei, Taiwan	Feb., 2012	G3-CENLEC with current transformer	Passed majority of noise scenarios
Korea	Mar. 2011	CENELEC/FCC	Passed all the underground cable up to 150m

Table 3. TI has performed extensive G3 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 G3 links could communicate under dynamically changing operating conditions.

The field tests covered a comprehensive variety of operating environments and configurations ranging from point-to-point topologies to an interconnected multi-hop network of more than 30 G3-based nodes. The distance between nodes was increased throughout testing, as well as their locations changed, to test the limits of the technology. Tests were also conducted at different hours as well as with different noisy loads added to lines to verify that G3 links could communicate under dynamically changing operating conditions.

Through this testing, TI has gained a better understanding of what is required to robustly connect devices using PLC (see section: Sidebar, Issues Impacting G3 Performance and Reliability). In addition to its own engineers having a better understanding of the characteristics of PLC channels, TI has contributed what it has learned to the IEEE in the development of P1901.2. For example, TI has shared its research on sub-banding



3a. Field test in China

3b. Field test in India

Figure 3. Texas Instruments conducts field tests around the globe to examine and assess various PLC techniques in real-world settings. These tests provide TI with unique knowledge on PLC technology.

technology to improve channel robustness. Sub-banding uses the frequency diversity of the PLC channel to determine the best sub-band to use based on dynamic channel conditions.

TI has also contributed much to the development of the P1901.2 channel models for PLC. 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 communications. 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 G3 PLC technology required to ensure a smooth adoption and migration to power line-based communications.

PLC technology enables cost-effective networking in a diverse range of applications. OEMs wanting to take advantage of opportunities in these markets need to support a flexible implementation that enables them to develop products that can support the different PLC standards so they can be used in multiple countries and regions.

With its fully programmable approach to PLC, TI provides the flexibility OEMs need to leverage a base PLC design across a range of applications, standards and markets. Flexibility through software is the key to addressing the diversity of noise conditions inherent in different applications. Using a software implementation also allows developers to leverage the PLC IP they develop today into the future and across product lines.

With its wide range of processors that can support PRIME, G3 and low-cost alternatives like PLC-Lite™, TI is providing the technological foundation for introducing PLC into many new markets. Combined with its direct field experience and application expertise, TI is able to provide the hardware, software, and tools developers need to meet the varying requirements to deploy PLC worldwide.

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.

Through its independent research and work with the IEEE and G3 Alliance, TI is continuously bringing higher performance and improved robustness to PLC technology. TI is a global company equipped to handle technologies 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. In addition, it is the only company today offering DC concentrator software for both G3 and PRIME.

Sidebar: Issues impacting G3 performance and reliability

Through extensive field testing worldwide, TI has identified numerous issues that can impact signal G3 performance and reliability, including:

- Asymmetric channel performance: Uplink and downlink behavior can be completely different over the same physical medium. For example, a frequency that carries the uplink signal may not necessarily perform as well for the downlink.

- Local interference: Interference from electrical devices in homes can have a significant impact on signal performance. In Japan, for example, the water heater in homes introduced significant noise issues that needed to be addressed.
- Crossing the transformer: The coupler on low-voltage transformers presents noise challenges that must be specifically addressed.
- Topology: Networking between the grid to the home and from home to home must account for different channel characteristics.

For more information

Find out more about TI's power line communication (PLC) tools, software and technology:

- TI Smart Grid portfolio overview: **www.ti.com/smartgrid**
- Texas Instruments PLC technology: **www.ti.com/plc-lp**
- TI Smart Grid solutions guide: **www.ti.com/plc-wp**
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