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Evaluation of Power Line Carrier Technologies for Plug-In Electric Vehicle Communications

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ABSTRACT

In support of the Society of Automotive Engineers (SAE) efforts to develop standard means of communication with plug-in electric vehicles (PEVs), EPRI conducted an evaluation of several power line carrier (PLC) technologies. Evaluation of the technologies was based on a test plan developed in the SAE Hybrid Task Force. Direct PEV communication enables signaling of grid conditions to the PEV allowing for remote, intelligent management of vehicle charging. The interface can also support the use of off-board AC to DC power conversion (DC charging) by providing a means of controlling external power electronics from the vehicle.

Keywords
Power line carrier
Plug-in electric vehicle
Electric vehicle supply equipment
Smart charging

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1
INTRODUCTION

In support of efforts by the Society of Automotive Engineers to develop recommended practices for plug-in electric vehicle (PEV) communication, EPRI performed laboratory evaluation of several power line carrier (PLC) technologies. This effort was conducted in parallel with similar evaluation work conducted by Argonne National Lab. The results of these evaluations were used by SAE in selecting a PLC technology that met minimum requirements established within the SAE effort.

2
SAE RECOMMENDED PRACTICES BACKGROUND

The Society of Automotives Engineers (SAE) has developed a number of recommended practices related to charging of plug-in electric vehicles (PEVs) and has defined separate task forces for various aspects of this work. These task forces are further divided into sub-committees which address specific documents containing recommended practices for PEV charging.

The conductive charging interface was defined within the SAE J1772 Hybrid Task Force. This recommended practice covers the physical layout of the charging plug and receptacle as well as a simple signaling method using a single wire to communicate the ampacity of the EVSE to the PEV and to allow the PEV to signal the EVSE when it is connected and ready to accept charge.

Efforts related to communications were organized under the oversight of the Hybrid J2836, J2847, J2931 and J2953 Task Force which defined 19 documents as listed in Table 2-1. These added communication capabilities were designed to enable such features as smart management of PEV charging, control of an off-board vehicle charger, and local communication of the PEV state.

Table 2-1
Overview of SAE Standards Documents Related to PEVs

	Use Cases	Requirements	Protocol
Utility Programs	J2836-1	J2847-1	J2931-1 Basis
DC Charging	J2836-2	J2847-2	J2931-2 FSK
Reverse Power Flow	J2836-3	J2847-3	J2931-3 NB OFDM
Diagnostics	J2836-4	J2847-4	J2931-4 WB OFDM
Customer to PEV and HAN/NAN	J2836-5	J2847-5	J2931-5 Telematics
Wireless Power Flow	J2836-6	J2847-6	J2931-6 DSRC (RFID?)
			J2931-7 Security

Work on these 19 documents is being carried out by 10 sub-committees:

- Each of the J2836/J2847 document pairings have a sub-committee
- Documents J2931-1, -2, -3, and -4 share a common sub-committee
- Document J2931-5 has a sub-committee
- Document J2931-6 has a sub-committee
- Document J2931-7 has a sub-committee

The J2931-1, -2, -3, -4 sub-committee was tasked with defining the protocol and communication technology needed to support the use cases and requirements as defined in the J2836-1/J2847-1 and J2836-2/J2847-2 pairings[1]. Since the format of the cordset and J1772 connector was already defined, there was no opportunity to add additional conductors or pins to carry this added communication. Wireless communications such as ZigBee or Wi-Fi were ruled out due to the necessity of associating a particular vehicle with a particular physical EVSE.

The sub-committee's focus turned to power line communication (PLC) technologies. A PLC system operates by modulating data onto an existing power line or wire. A variety of PLC technologies have been on the market, serving as a "last mile" communications links from substation to customer in Europe, and providing home networking over existing in-wall power lines. In order to contain the communications signal between the EVSE and the PEV, the sub-committee decided to inject the PLC signal on the Pilot wire, which is only carried from the EVSE to the PEV.

The J2931-1, -2, -3, -4 sub-committee also developed a set of requirements for the communication link in the cordset. A test plan [1] was then developed to evaluate the ability of the candidate PLC technologies to meet those requirements.

[1] Only the SAE J2836/J2847 -1 and -2 committees were active during the period that the J2931 sub-committee defined the PLC requirements.

3

REQUIREMENTS FOR COMMUNICATION

The SAE J2931-1, -2, -3, -4 sub-committee defined a set of requirements for the PEV communication link which are detailed in this section.

The requirements were developed around two primary functions for the communications link:

- Provision for utility communications to the PEV (as defined in J2836-1/J2847-1)
- Control of an off-board DC charger (as defined in J2836-2/J2847-2)

These two functions drive a varied set of requirements: Utility communications require a wide bandwidth to support communications security but can tolerate longer latency (10s of seconds to minutes); DC charger control requires latency in the 10s of milliseconds but can be carried out with very simple, short data packets and relatively low data bandwidth. This variation was captured by defining requirements for utility and DC charge control communications independently. The selected PLC technology must be able to support these disparate functions over a single communications interface.

The requirements are tabulated under seven general heading categories:

- General Application Requirements (see Table 3-1); overarching requirements of the interface
- General Communication Requirements (see Table 3-2); requirements that are shared by utility and DC charge control interfaces
- Utility Communication Requirements (see Table 3-3); requirements unique to utility communication
- DC Charger Control Communication Requirements (see Table 3-4); requirements unique to DC charger control communications
- Reliability Requirements (see Table 3-5); requirements for link reliability
- Performance Requirements (see Table 3-6)
- Security Requirements (see Table 3-7)

Each requirement was assigned a priority:

- Basic – this is a basic requirement that all interfaces must implement
- Optional – this is a requirement that is optional
- TBD – to be determined; the committee chose not to define a priority for this property

Table 3-1
General Application Requirements

Requirement ID	Requirement	Reference	Priority
RD.App.1	Support basic Utility or service provider use cases	J2836/1	Basic
RD.App.2	Support basic Utility or service provider messages	J2847/1, SE2.0, ISO15118	Basic
RD.App.3	If DC Charging is provided, then Support off board charger use cases	J2836/2	Basic
RD.App.4	If DC Charging is provided, then Support DC messages	J2847/2, ISO15118	Basic
RD.App.5	Support Reverse Energy Flow use cases	J2836/3	TBD
RD.App.6	Support Reverse Energy Flow messages	J2847/3	TBD
RD.App.7	Support Diagnostics use cases	J2836/4	TBD
RD.App.8	Support Diagnostic messages	J2847/4	TBD
RD.App.9	Support Customer and HAN use cases	J2836/5	Optional
RD.App.10	Support Customer and HAN messages	J2847/5	Optional
RD.App.11	Utility messages and DC will use as many common components/software layers as possible and still comply with basic requirements to minimize cost		Basic
RD.App.12	Interoperate with all EVSE and EV	J2853/1, J2953/2	Basic
RD.App.13	Communication solution must not interfere with operation of existing legacy devices compliant with the current (2010) release of J1772™.	J1772	Basic
RD.App.14	Support for Multiple EUMDs, EVSE's, and ESIs on the same physical network (transformer)		Basic
RD.App.15	Support public and residential charging		Basic

Table 3-2
General Communication Requirements

Requirement ID	Requirement	Reference	Priority
RD.Comm.1	The DC and Utility or service provider messages shall use the same channel or media between the EV and EVSE to minimize cost based on the different requirements		TBD
RD.Comm.2	Meet Industry EMC and Radiated RF Standards		Basic
RD.Comm.3	Full compliance with SAE licensing terms - RANZ preferred (ref is Patent Release Form-2003.pdf)		Basic
RD.Comm.4	Solution shall be automotive-qualified	AEC-Q100 for ICs and AEC-Q101 for discrete semis	Basic
RD.Comm.5	Solution shall demonstrate technological maturity proven in other general contexts.		Basic
RD.Comm.6	Technology available in 2011 (Superseded)		
RD.Comm.7	Global acceptance is desired		Optional
RD.Comm.8	Solution shall be available from multiple vendors		Basic
RD.Comm.9	Length of Cordset is defined as in SAE J1772™, with an assumed typical value of 25 feet (applies to mains or pilot communication)		Basic
RD.Comm.10	Solution shall be an international standard i.e., IEEE		Basic
RD.Comm.11	Resulting standard shall select one medium and one PLC technology for communication over the cordset		Basic

Table 3-3
Utility Communication Requirements

Requirement ID	Requirement	Reference	Priority
RD.UtilComm.1	Provide correct association with the EV, ESI and sub meter in the same physical electrical circuit		Basic
RD.UtilComm.2	False association shall not occur from two or more twisted EVSE cordsets		Basic
RD.UtilComm.3	MAC/PHY throughput shall be 100 kbps or greater	S252[2] - OpenSG_Comm-PLC-HAN-Throughput-Analysis.pptx	Basic
RD.UtilComm.4	The Utility or service provider message latency is 15 minutes max.		Basic
RD.UtilComm.5	Use IPV6/HTTP1.1 and XML per SE2.0		
RD.UtilComm.6	Minimum distance over which communication capability shall be maintained without intermediary devices independent of the communications medium minimum distance for utility or service provider communications is 40 meters if using AC mains for communication minimum distance for utility or service provider communication if using the J1772™ Pilot wire shall be based on the maximum cable length allowed by SAE J1772™	40 meters for PLC operating over the mains, 25 feet (7.62 meters) for PLC operating over the pilot wire.	Basic

[2] Work Area for J2931/1 - Power Line Carrier Communications for Plug-in Electric Vehicles (10-5-10 Presentations) http://www.sae.org/servlets/works/postDiscussion.do?comtID=TEVHYB&docID=J2931/1&resourceID=190623&inputPage=showAll

Table 3-4
DC Charger Control Communications Requirements

Requirement ID	Requirement	Reference	Priority
RD.DCComm.1	Application Data (payload) rate is 6 Kbps or greater concurrently (full-duplex)		Basic
RD.DCComm.2	Round trip message Latency is 25ms max		Basic
RD.DCComm.3	Minimum distance over which communication capability must be maintained without intermediary devices independent of the communications medium is defined by SAE J1772™	Cordset length is 25 feet (7.62 meters)	Basic
RD.DCComm.4	Not used		
RD.DCComm.5	Not used		
RD.DCComm.6	If utility messages and DC charge control are combined, then QoS mechanism must be capable of prioritizing packets and the latency requirements provided in RD.DCComm.2 and RD.UtilComm.2 must be met		

Table 3-5
Reliability Requirements

Requirement ID	Requirement	Reference	Priority
RD.RelComm.1	There shall be no excessive impairment or degradation to the consumer network e.g., Multimedia distribution. Initial requirement set to 10% reduction in bandwidth maximum between two nodes on the consumer network		Basic
RD.RelComm.2	Communication shall not susceptible to noise and transmissions caused by crosstalk (4-sigma value of 99.4%) from other conductors in the cordset, or from another twisted cordset		Basic
RD.RelComm.3	The technology chosen shall not cause interference to signals that may be on other conductors in the cordset, or another twisted cordset		Basic
RD.RelComm.4	Co-exist with all current physical network interfaces operating on the medium		Basic
RD.RelComm.5	Co-exist with future physical interfaces not present in the market or in development		TBD
RD.RelComm.6	Co-exist with neighbor networks without substantial throughput degradation on consumer network or HAN		Basic

Table 3-5 (Continued)
Reliability Requirements

Requirement ID	Requirement	Reference	Priority
RD.RelComm.7	The HAN shall provide connectivity to 99% of the nodes in homes		Basic
RD.RelComm.8	The communication technology shall implement mitigation methods to deal with all common interferers found in home networks (Wired or Wireless), including hairdryers, holiday lights, high frequency switching power supplies, and microwave ovens.		Basic
RD.RelComm.9	Network traffic in the Utility HAN or Consumer Network will not cause degradation of DC messages throughput and latency below the requirements.		
RD.RelComm.10	Interoperability requirements as defined by SAE must interoperate with following technologies: TBD		TBD

Table 3-6
Performance Requirements

Requirement ID	Requirement	Reference	Priority
RD.Perf.1	The time to indicate to the consumer that communications has successfully established shall be <10s		Basic
RD.Perf.2	Except in the case of DC charging, the PEV shall receive charge if no communications can be established. In the event no communications can be established, the PEV may not qualify for certain PEV rate programs		Basic

Table 3-7
Security Requirements

Requirement ID	Requirement	Reference	Priority
RD.Sec.1	Utility or service provider messages will comply with NIST security requirements	SE2	Basic
RD.Sec.2	DC messages will comply with automotive security requirements (DC messages will comply with automotive requirements in J2847/2)		Basic
RD.Sec.3	DC messages will use same security as Utility or service provider Messages		TBD

4

REQUIREMENTS BASED TESTING

The communications requirements developed by the J2931-1, -2, -3, -4 sub-committee cover a broad scope. EPRI along with other committee members worked to develop a test plan to support the requirements. Not all requirements were testable within the more focused scope and purpose of the test plan. The test plan was intended to verify the critical technical requirements such as data rate, latency, range, noise susceptibility, coexistence, and interference.

The test plan was designed to evaluate standards, not individual products. To that end, a variety of vendor implementations of the underlying communications standards were sought for testing. Due to the relative newness and immaturity of the standards, the vendor implementations were a work-in-progress during the testing process. Testing was conducted on development platforms, not production-qualified products. The vendors provided several firmware updates during the testing process.

Some requirements were designated Non-Testable, not because a technical limitation in the development of a test, rather the designation was based on whether testing was in the scope of the test plan (as agreed by the SAE committee). In some cases requirements were designated non-testable if the requirement was non-quantitative or could be verified by design, specification, or inspection. In other cases tests were designated non-testable if they were product-specific and vendor-specific attributes, and not representative of the general characteristics of the technology and underlying standards.

Application Tests

These tests verify the ability of the communications links to support the Application requirements. The primary function of the communications link is to deliver the application messages in a timely manner (as measured by data rate and latency), and with reliability and repeatability.

Requirement ID	Requirement	Reference	Priority
RD.App.12	Interoperate with all EVSE and EV	J2853/1, J2953/2	Basic
RD.App.13	Communication solution must not interfere with operation of existing legacy devices compliant with the current (2010) release of J1772™.	J1772	Basic

The interface must interoperate with all EVSEs and PEVs, and not interfere with operation of existing legacy devices compliant with the current release of SAE J1772™.

These requirements were tested by the Pilot Signal Impairment Test (6.5.4 in the test plan [1]). This test verifies that the rise time, fall time, and duty cycle of the PWM signal on the Pilot [2] are not impaired or caused to be out of specification because of the PLC communication signal or coupling.

DC + SE2 – Common Communication Tests

These tests verify the communication requirements that have been categorized as common requirements. These can be system level or cross-cutting requirements.

Requirement ID	Requirement	Reference	Priority
RD.Comm.1	The DC and Utility or service provider messages shall use the same channel or media between the EV and EVSE to minimize cost based on the different requirements		TBD
RD.DCComm.6	If utility messages and DC charge control are combined, then QoS mechanism must be capable of prioritizing packets and the latency requirements provided in RD.DCComm.2 and RD.UtilComm.2 must be met		
RD.RelComm.9	Network traffic in the Utility HAN or Consumer Network will not cause degradation of DC messages throughput and latency below the requirements.		

These requirements were tested by the Shared Network Tests (Section 6.4.4 in the test plan). They provide concurrent data (stimulus) that verify the range of specific requirements for DC and Utility messages. These tests verified that the channel or media under test could support both message types simultaneously while meeting all requirements for both message types individually. QoS (Quality of Service – message prioritization) is used to give DC messages priority over Utility messages.

Cordset Distance Requirements

Requirement ID	Requirement	Reference	Priority
RD.Comm.9	Length of Cordset is defined as in SAE J1772™, with an assumed typical value of 25 feet (applies to mains or pilot communication)		Basic
RD.UtilComm.6	Minimum distance over which communication capability shall be maintained without intermediary devices independent of the communications medium minimum distance for utility or service provider communications is 40 meters if using AC mains for communication minimum distance for utility or service provider communication if using the J1772™ Pilot wire shall be based on the maximum cable length allowed by SAE J1772™	40 meters for PLC operating over the mains, 25 feet (7.62 meters) for PLC operating over the pilot wire.	Basic
RD.DCComm.3	Minimum distance over which communication capability must be maintained without intermediary devices independent of the communications medium is defined by SAE J1772™	Cordset length is 25 feet (7.62 meters)	Basic

These requirements were tested by the Communications Distance Test (Section 6.5.3 in the test plan). Tests were conducted with 25 foot (7.62 meters) of J1772™ cordset cable.

Communications Test: SEP 2.0 – Utility/HAN and DC Charging

For Utility/HAN communication, these tests verified the communication requirements that were categorized as related to communicating messages between the PEV and the HAN, EUMD, ESI, or other utility server or service point.

For the DC Charging use case, these tests verified the communication requirements between the EVSE and the PEV supporting the charging function.

Requirement ID	Requirement	Reference	Priority
RD.UtilComm.3	MAC/PHY throughput shall be 100 kbps or greater	S252[3] - OpenSG_Comm-PLC-HAN-Throughput-Analysis.pptx	Basic
RD.UtilComm.4	The Utility or service provider message latency is 15 minutes max.		Basic
RD.DCComm.1	Application Data (payload) rate is 6 Kbps or greater concurrently (full-duplex)		Basic
RD.DCComm.2	Round trip message Latency is 25ms max		Basic

These requirements were tested with the Throughput Tests and Latency Tests (Sections 6.1.1 and 6.1.2 in the test plan).

Association

Requirement ID	Requirement	Reference	Priority
RD.UtilComm.1	Provide correct association with the EV, ESI and sub meter in the same physical electrical circuit		Basic
RD.UtilComm.2	False association shall not occur from two or more twisted EVSE cordsets		Basic

These requirements were tested with the Association Tests (Sections 6.5.1 in the test plan).

[3] Work Area for J2931/1 - Power Line Carrier Communications for Plug-in Electric Vehicles (10-5-10 Presentations)
http://www.sae.org/servlets/works/postDiscussion.do?comtID=TEVHYB&docID=J2931/1&resourceID=190623&inputPage=showAll

Reliability Tests

These tests verified the requirements that were categorized as related to the reliability of the communications system. These tests were designed around selected worst-case scenarios, and did not attempt to address all possible cases.

Requirement ID	Requirement	Reference	Priority
RD.RelComm.1	There shall be no excessive impairment or degradation to the consumer network e.g., Multimedia distribution. Initial requirement set to 10% reduction in bandwidth maximum between two nodes on the consumer network[4]		Basic
RD.RelComm.2	Communication shall not susceptible to noise and transmissions caused by crosstalk (4-sigma value of 99.4%) from other conductors in the cordset, or from another twisted cordset		Basic
RD.RelComm.3	The technology chosen shall not cause interference to signals that may be on other conductors in the cordset, or another twisted cordset		Basic
RD.RelComm.4	Co-exist with all current physical network interfaces operating on the medium		Basic
RD.RelComm.6	Co-exist with neighbor networks without substantial throughput degradation on consumer network or HAN		Basic
RD.RelComm.8	The communication technology shall implement mitigation methods to deal with all common interferers found in home networks (Wired or Wireless), including hairdryers, holiday lights, high frequency switching power supplies, and microwave ovens.		Basic

Tests that verified the EV communication did not cause impairment or degradation to the consumer network were contained in Consumer PLC Susceptibility Tests (Test Plan Section 6.4.3).

Tests that verified the communication was not susceptible to crosstalk from similar or different PLC communication technologies coupled between nearby or twisted cordsets was accomplished in the Twisted Cordset Crosstalk Test (Section 6.2.1) and the Cordset Internal Crosstalk Test (Section 6.2.2).

Coexistence with other PLC communications systems on the medium was tested in the Self-Coexistence Test, and Coexistence with Consumer PLC Test, and (Test Plan Section 6.3.1-2).

Coexistence testing with Prime and LonWorks was originally planned, but not done because suitable devices were not available.

[4] The concern over energy devices using HomePlug GreenPHY affecting users of HomePlug AV was addressed by the HomePlug Alliance through the implementation of Dynamic Bandwidth Control (DBC) into the HomePlug GreenPHY specification.

Tests to verify the communications systems were able to operate with common interference signals found on the power line was done with the Mains Interference Test. (section 6.4.1) and the Coupled Cordset Interference Test (Section 6.4.2).

Performance Tests

Requirement ID	Requirement	Reference	Priority
RD.Perf.1	The time to indicate to the consumer that communications has successfully established shall be <10s		Basic

The Charge Initiation Response Test (Section 6.5.2) verified that the communication system could initiate a connection within the 10 second timeframe that was established as reasonable.

Non-Testable

The following requirements were either non-quantitative, verified by inspection or specification, or out of scope of the agreed test plan.

Requirement ID	Requirement	Reference	Priority
RD.App.1	Support basic Utility or service provider use cases	J2836/1	Basic
RD.App.2	Support basic Utility or service provider messages	J2847/1, SE2.0, ISO15118	Basic
RD.App.5	Support Reverse Energy Flow use cases	J2836/3	TBD
RD.App.6	Support Reverse Energy Flow messages	J2847/3	TBD
RD.App.7	Support Diagnostics use cases	J2836/4	TBD
RD.App.8	Support Diagnostic messages	J2847/4	TBD
RD.App.9	Support Customer and HAN use cases	J2836/5	Optional
RD.App.10	Support Customer and HAN messages	J2847/5	Optional
RD.App.11	Utility messages and DC will use as many common components/software layers as possible and still comply with basic requirements to minimize cost		Basic
RD.App.14	Support for Multiple EUMDs, EVSE's, and ESIs on the same physical network (transformer)		Basic
RD.App.15	Support public and residential charging		Basic
Requirement ID	Requirement	Reference	Priority
RD.App.3	If DC Charging is provided, then Support off board charger use cases	J2836/2	Basic
RD.App.4	If DC Charging is provided, then Support DC messages	J2847/2, ISO15118	Basic

Requirement ID	Requirement	Reference	Priority
RD.App.3	If DC Charging is provided, then Support off board charger use cases	J2836/2	Basic
RD.App.4	If DC Charging is provided, then Support DC messages	J2847/2, ISO15118	Basic

Requirement ID	Requirement	Reference	Priority
RD.Comm.2	Meet Industry EMC and Radiated RF Standards [5]		Basic
RD.Comm.3	Full compliance with SAE licensing terms - RANZ preferred (ref is Patent Release Form-2003.pdf)		Basic
RD.Comm.4	Solution shall be automotive-qualified	AEC-Q100 for ICs and AEC-Q101 for discrete semis	Basic
RD.Comm.5	Solution shall demonstrate technological maturity proven in other general contexts.		Basic
RD.Comm.7	Global acceptance is desired		Optional
RD.Comm.8	Solution shall be available from multiple vendors		Basic
RD.Comm.10	Solution shall be an international standard i.e., IEEE		Basic
RD.Comm.11	Resulting standard shall select one medium and one PLC technology for communication over the cordset		Basic
RD.UtilComm.5	Use IPV6/HTTP1.1 and XML per SE2.0		

Requirement ID	Requirement	Reference	Priority
RD.RelComm.5	Co-exist with future physical interfaces not present in the market or in development		TBD
RD.RelComm.7	The HAN shall provide connectivity to 99% of the nodes in homes		Basic
RD.RelComm.10	Interoperability requirements as defined by SAE must interoperate with following technologies: TBD		TBD

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[5] EMC testing was out of scope for the initial test plan because testing was conducted on development systems rather than production-ready products. For product design, specifications will call for EMC Compliance testing to be conducted according to standard industry procedures for the specific applicable standards. (For example J1775, or Ford EMC Standards).

Requirement ID	Requirement	Reference	Priority
RD.Perf.2	Except in the case of DC charging, the PEV shall receive charge if no communications can be established. In the event no communications can be established, the PEV may not qualify for certain PEV rate programs.[6]		Basic

The following requirements were either non-quantitative, or verified by inspection or specification.

Requirement ID	Requirement	Reference	Priority
RD.Sec.1	Utility or service provider messages will comply with NIST security requirements	SE2	Basic
RD.Sec.2	DC messages will comply with automotive security requirements (DC messages will comply with automotive requirements in J2847/2)		Basic
RD.Sec.3	DC messages will use same security as Utility or service provider Messages		TBD

[6] This requirement is out of scope for this test plan. The expected behavior is a function of the EVSE, and not related to the communications technology.

5
OVERVIEW OF THE TESTED COMMUNICATION TECHNOLOGIES

The design of the test plan was intended to verify that the candidate communication technologies were able meet the requirements specified in the SAE J2931-1 document. The tests were based on verifying the performance of the communications standards, not specific vendor products.

The two standards that were identified as candidates during the development of the test plan were HomePlug GreenPHY [3] and G3 [4].

During the testing process, attempts were made to obtain devices from multiple vendors that were representative of the two standards, but only one vendor of each standard was able to provide working development systems during the timeframe of the testing.

Mains and Pilot communication

The HomePlug GreenPHY and G3 standards were originally designed to operate over power line conductors, but were capable of operating over any type of wire. Some earlier versions of the PLC standards required a power waveform on the wire to synchronize the communication, but the versions tested were able to self-synchronize. The PLC systems operated normally over unpowered or DC powered conductors.

The test plan included tests for coupling the PLC communications signals over both the mains (L1 and L2 in J1772) as well as the pilot wire. During the process of completing the testing, the SAE Hybrid Committee decided to focus exclusively on carrying the PLC signal on the pilot, and testing on the mains was de-emphasized.

Devices and vendors of the test platforms

Broadband PLC: HomePlug GreenPHY

For HomePlug GreenPHY, the vendor was Qualcomm-Atheros [5]. HomePlug GreenPHY operates in the frequency range of 2 MHz to 28 MHz using orthogonal frequency domain modulation (OFDM).

During the testing, three different platforms were used for testing:

- An off-the-shelf retail product (the Netgear XAV-2001) was loaded with special firmware to operate in a mode that duplicated most of the behavior of HomePlug GreenPHY. In the factory configuration, the XAV-2001 can only communicate over the powerline (mains). The stock units were modified to make the PLC signal available on a coax cable for coupling to the cordset Pilot conductor (see Figure 5-1).
- The PL-15 development platform was used for tests involving association between the EV and EVSE (see Figure 5-2).

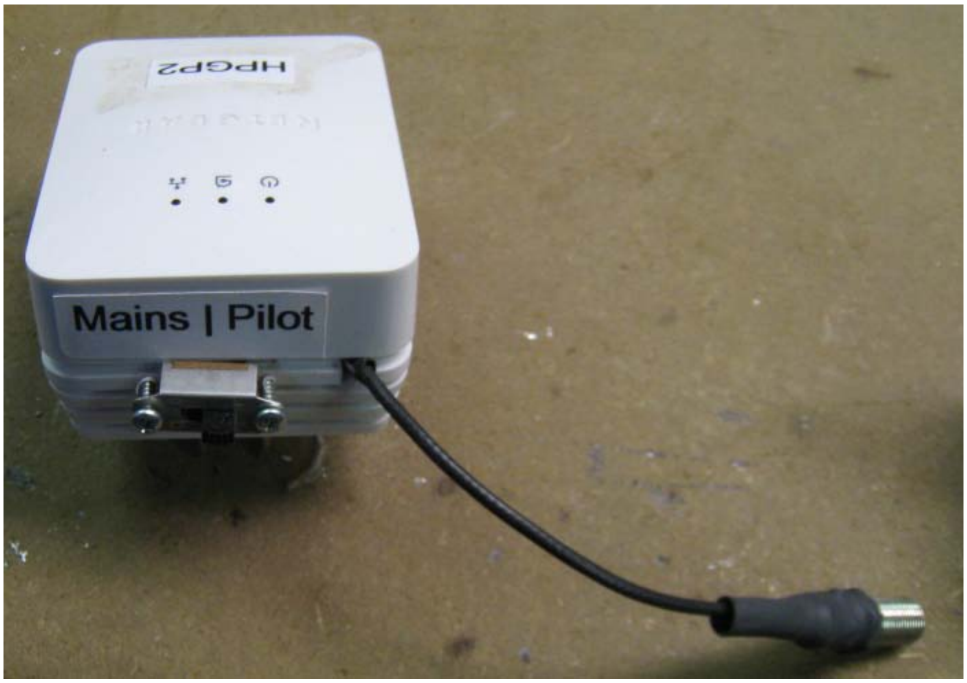

Figure 5-1
Netgear XAV-2001 HomePlug module

Figure 5-2
Qualcomm-Atheros PL-15 Development Platform

- The PL-16 development platform became available late in the testing process (see Figure 5-3). It is based on new silicon (The QCA7000 chip) that fully implements all aspects of the HomePlug GreenPHY standard.

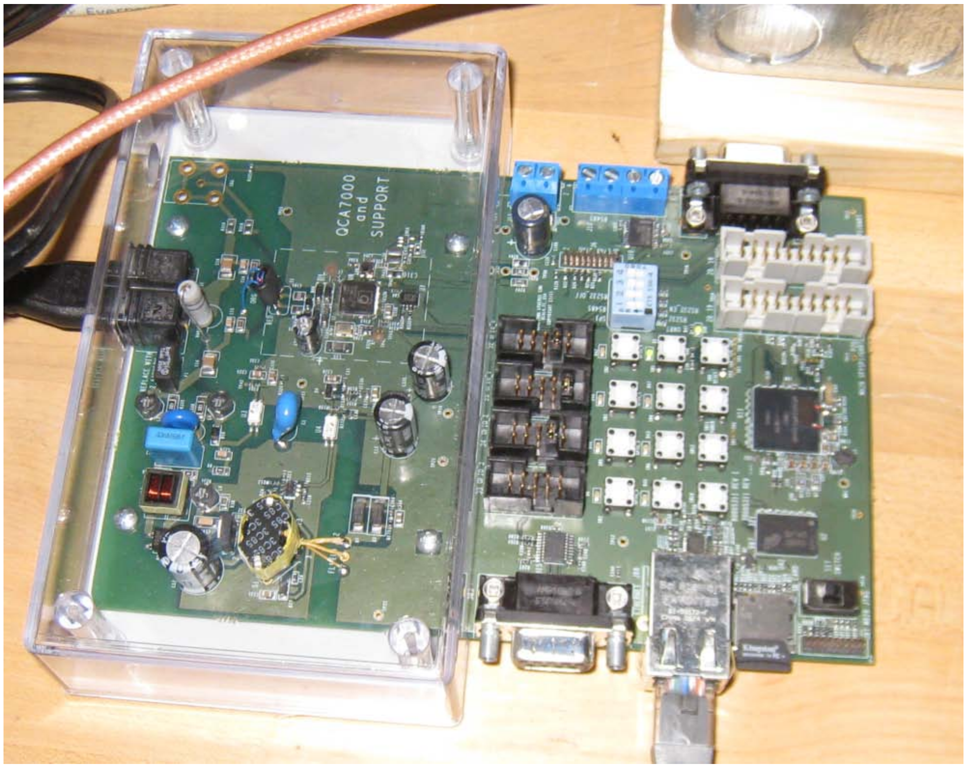

Figure 5-3
Qualcomm-Atheros PL-16 platform

Narrowband PLC: G3

For the G3 standard, the vendor was Maxim Integrated [6]. The development platforms were named “Laguna” (see Figure 5-4) and “Tahoe-2” (see Figure 5-5). They are based on the MAX2992 modem IC.

The G3 systems that were tested operate in the FCC band within the frequency range of 160 KHz to 478 KHz. (G3 systems operate in different frequency bands in other regulatory domains, such as Europe).

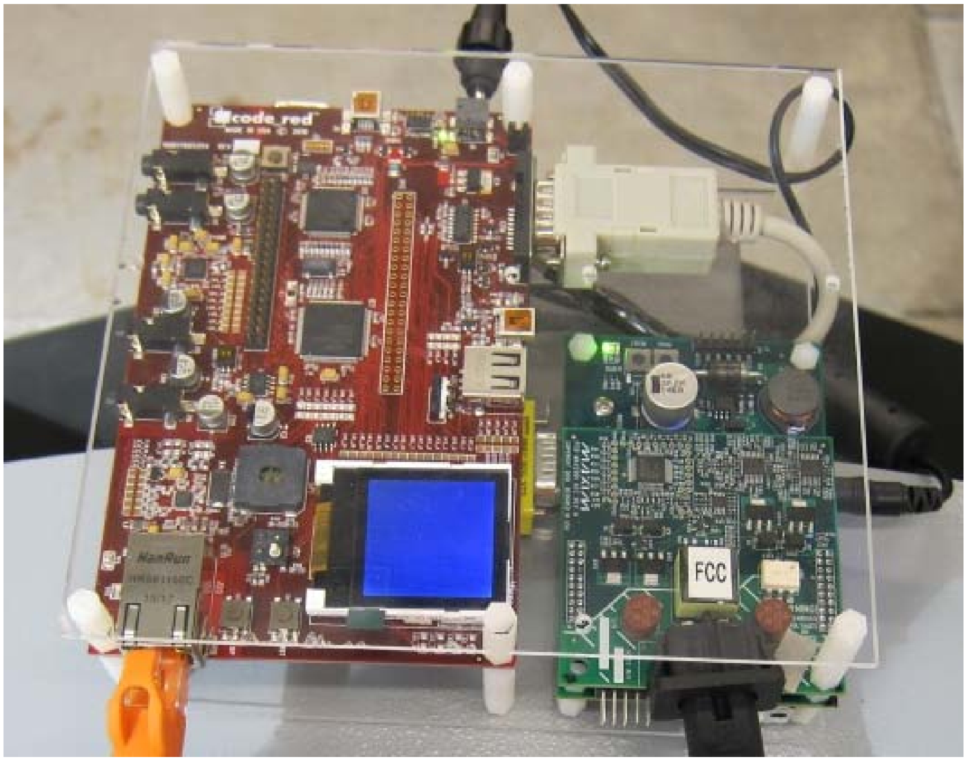

Figure 5-4
Maxim G3 "Laguna" modem with Code Red host processor

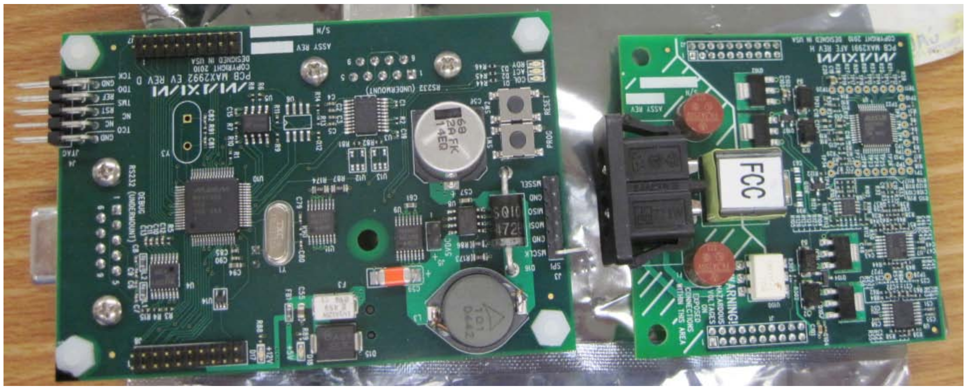

Figure 5-5
Maxim MAX2292 Modem

6
LAB SETUP FOR TESTING

The testing was performed with two EVSE units with J1772 Cordsets. The Device Under Test (DUT) was one of the communications systems being tested which consisted of two or more communicating nodes.

The baseline setup was one DUT node connected to the J1772 connector, and the other DUT node terminated at an EVSE (Figure 6-1). The PEV receptacle will be mounted in a box with the mains and pilot conductors brought out to terminal strips. Circuitry necessary to emulate the vehicle on-board interface will be present in the breakout box. The EVSE will be functional and able to generate the pilot PWM signal and voltages. The EVSE will also contain accessible connection points for the mains and pilot line signals used for connection to the DUT node. The actual lab setup is shown in Figure 6-2.

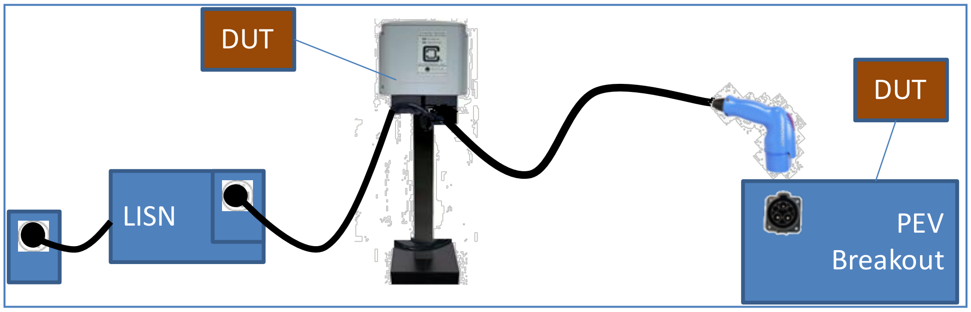

Figure 6-1
Logical Lab Setup (one EVSE)

Figure 6-2
Lab Setup

7 SUMMARY OF INDIVIDUAL TEST RESULTS

The complete test report was presented to the SAE Hybrid Committee, and is available as "S375 - EPRI Test Report (V2d-ext).docx" [7]. The following section highlights the relevant results.

Pilot Signal Impairment Tests

This test verifies that the communication system does not interfere with the operation of the pilot signal as specified in requirements RD.App.12 and RD.App.13. The pilot signal must conform to the requirements of J1772 with or without the PLC communications system connected.

Devices tested:

- QCA PL-16 (HPGP 18V on pilot),
- QCA PL-16 (HPGP 1V on pilot),
- Maxim Tahoe2++ (G3 2.82V on pilot)

Results

No measureable changes to the 1 KHz square wave amplitude were measured with any PLC coupling, so these results are not captured.

No changes in voltage, duty cycle, or square wave rise/fall time sufficient to impair EVSE/EV system operation were noted.

There was a small but measurable increase in rise and fall times of the square wave due to the loading of the PLC coupling circuit. The J1772 standard does not specify a limit for the rise and fall time on the pilot wire. The rise and fall time limits are measured at the square wave generator, prior to a 1K resistor that drives the pilot wire.

Figure 7-1shows the Pilot waveform with the 1Vpp PLC signal imposed on it. The oscilloscope timebase is set so that a less than ½ cycle of the 1KHz PWM signal is visible (showing in the high state).

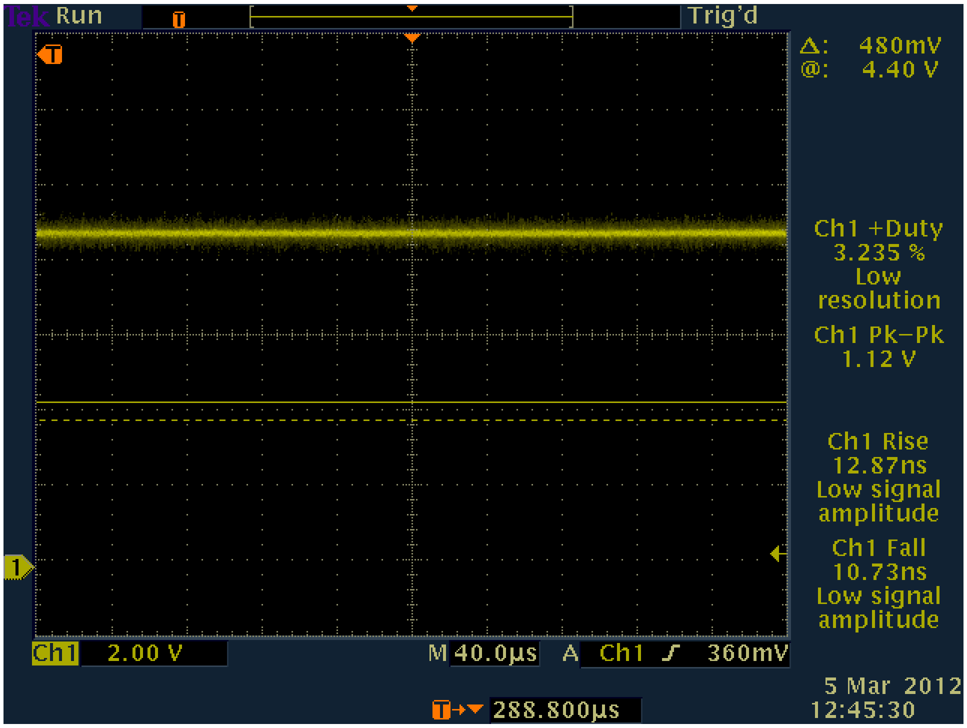

Figure 7-1
Pilot signal level - PL-16

Shared Network Tests

These tests verified that the communication system could concurrently support the DC Charging application and the Utility communication application as specified in requirements RD.Comm.1 and RD.DCComm.6.

Devices tested:

- Netgear XAV2001 (HPGP 18V on pilot),
- QCA PL-16 (HPGP 18V and 1V on pilot),
- Maxim Tahoe2++ (G3)

Shared Network tests were limited to testing the ability of a technology to support two simultaneous applications over one communications link. Tests regarding sharing with different technologies were covered under Coexistence.

Setup for HPGP Pilot Shared Network Test

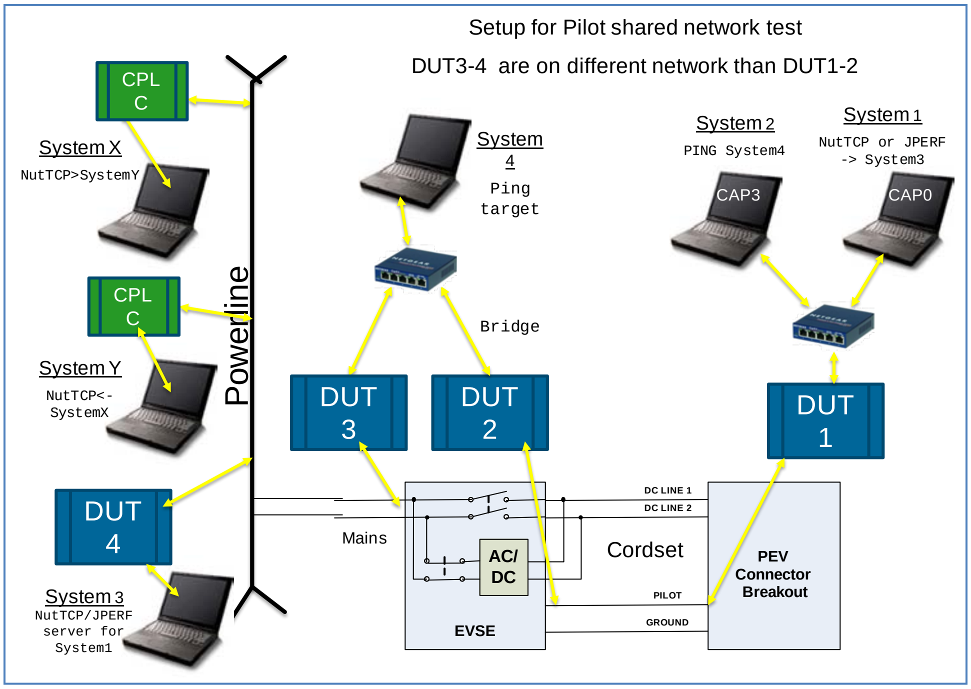

Figure 7-2
Setup for HPGP Shared Network Test on Pilot

The Test Plan (section 6.4.4.1) called for shared network tests to measure latency on a shared network carrying 100kbps utility traffic. These results are presented here. Other tests with different scenarios are presented in the appendix of the SAE Test Report [7].

Results

Results presented here are for Shared Network Tests, focusing on carrying two applications over the same interface using the Pilot wire. Coexistence and Susceptibility with respect to interactions with consumer networks are addressed under the Coexistence Tests.

HomePlug GreenPHY - While DC Messages are sharing the link with utility data at 100Kbps (TCP or UDP), DC latency is typically 6mS and does not exceed 15mS. This is below the upper limit of 25mS. At 100Kbps, utility message have 0% packet loss. This meets the SAE requirement.

G3 - Round Trip latency for DC Messages was 50mS to 250mS, which exceeds the upper limit of 25mS. Utility message throughput is 15-30Kbps, below the lower limit of 100Kbps. The performance is below the limits, regardless of whether the link is supporting one at a time, or if they are shared simultaneously. This does not meet the SAE requirement.

More detailed test results from the shared network tests are presented in “APPENDIX A Shared Network Tests”.

Distance Tests

These tests verified that the system could support the distances specified in requirements RD.Comm.9, RD.UtilComm.6, and RD.DCComm.3. A 25 foot cordset length is specified as the minimum.

Devices tested:

- Netgear XAV2001 (HPGP 18V on pilot),
- QCA PL-16 (HPGP 1V on pilot),
- Maxim Tahoe2++ (G3 2.82V on pilot)

All tests were conducted using 25 foot cordset on the EVSE's.

Given the link margins and interference rejection demonstrated in other tests, there is no reason to doubt that communications are possible over distances larger than any practical cordset length.

Results

HPGP **–** Met SAE requirement.

G3 – Met SAE requirement.

Association Tests

These tests verified that a correct association could be established between multiple PEVs and EVSEs in the same vicinity sharing the same power source. The requirements for association were specified in RD.UtilComm.1, RD.UtilComm.2, and RD.UtilComm.12.

Coupling of the PLC signals through the mains could potentially cause incorrect association. The HomePlug GreenPHY standard incorporates a mechanism called SLAC (Signal Level Attenuation Characterization), which determines the directly connected EVSE by comparing signal amplitudes.

The G3 standard does not support a technique for verifying association; it was not possible to conduct any association tests on G3.

Devices tested:

- QCA PL-15

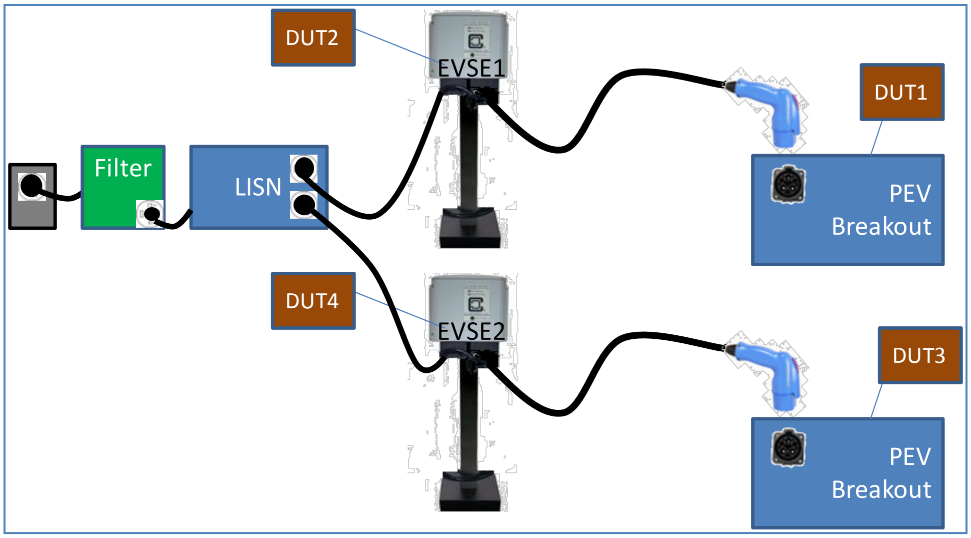

Figure 7-3
HPGP Association Testing – Basic Setup

Results

Passing results were obtained from all test cases (see Figure 7-4).

HPGP – Met SAE requirement.

G3 – Functionality Not Supported

SLAC from single EV

	J1772™ State		Connected		RSSI		
Test #	EVSE 1	EVSE 2	PEV 1	PEV 2	EVSE 1	EVSE 2	Comments
1	B	A	Y	N	20	32	Pass
2	A	B	Y	N	37	20	Pass
3	B	B	Y	Y	37	20	Pass
4	B	B	Y	Y	20	32	Pass
5	B	A	N	Y	20	37	Pass
6	A	B	N	Y	30	20	Pass
7	B	B	Y	Y	30	20	Pass
8	B	B	Y	Y	20	38	Pass
9	B	A	Y	N	20	33	Pass
10	A	B	Y	N	37	20	Pass
11	B	B	Y	Y	37	20	Pass
12	B	B	Y	Y	20	38	Pass
13	B	A	N	Y	20	33	Pass
14	A	B	N	Y	35	20	Pass
15	B	B	Y	Y	35	20	Pass
16	B	B	Y	Y	20	36	Pass

Tested with 0.470nf Coupling cap

Connected pair
Another connected pair
Unconnected

SLAC initiated

Concurrent SLAC, Multi-EV

	J1772™	Connected	RSSI		
Test #	EVSE	PEV	EVSE 1	EVSE 2	Comments
17	1	1	15	37	Pass
	2	2	37	17	Pass
18	2	1	38	16	Pass
	1	2	16	36	Pass
19 (Twisted)	1	1	15	34	Pass
	2	2	35	16	Pass
20 (Twisted)	2	1	37	15	Pass
	1	2	15	35	Pass

Tested with 1.5nf coupling cap

Figure 7-4
Results from Association Tests

Throughput Tests:

This test verified that the communication standard could meet the requirements for data throughput requirements specified in RD.UtilComm.3 (100Kbps) and RD.DCComm.1 (6Kbps).

The throughput measurement reference point is not consistently defined. On one hand, RD.UtilComm.3 references MAC/PHY throughput. However, the test plan specifies TCP/IP throughput to enable a common reference point among differing communications platforms and technologies. Without the use of a higher layer reference such as TCP/IP, throughput measurements must be made by vendor-specific tools which make direct comparisons impossible.

Given that utility communications (Smart Energy) messages typically use larger packets (>1024 bytes), the difference is a few percent. (Figure 7-5)

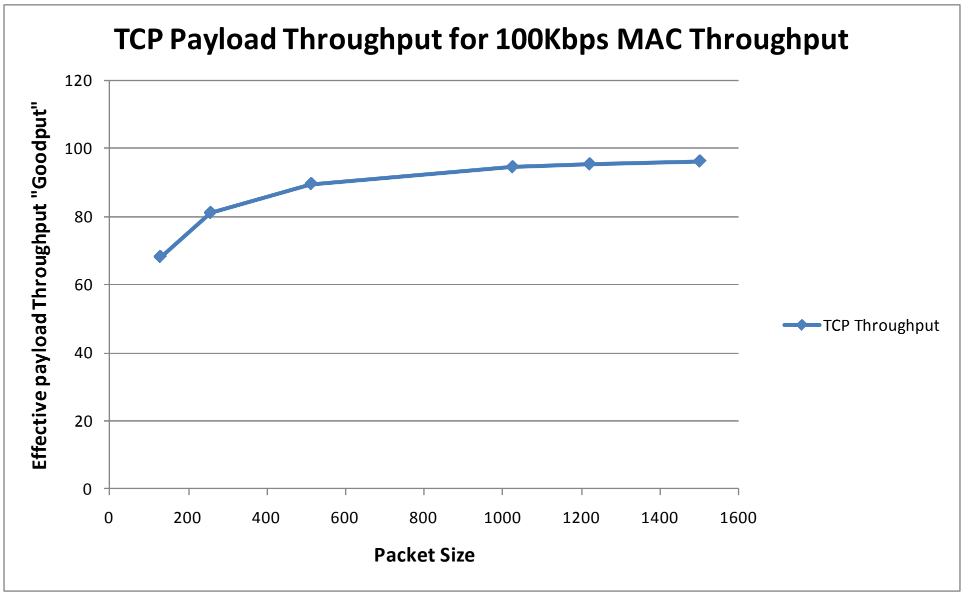

Figure 7-5
Conversion between MAC and TCP/IP throughput based on packet size

Devices tested:

- QCA PL-16 (HPGP 18V on pilot),
- QCA PL-16 (HPGP 1V on pilot),
- Maxim Tahoe2++ (G3 2.82V on pilot)
- Maxim Tahoe2++ (G3 1V on pilot)

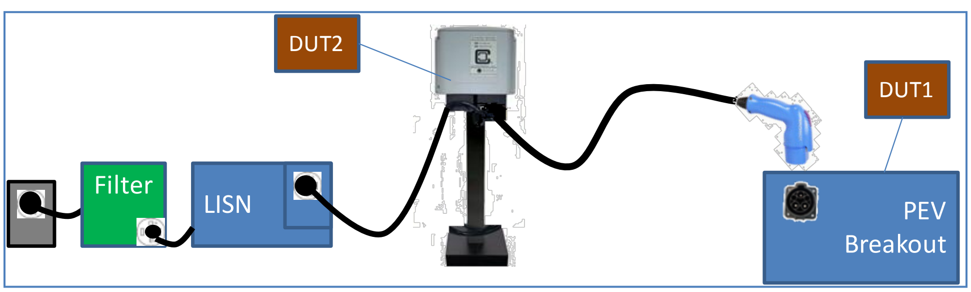

Figure 7-6
Throughput Test Setup

Data

HPGP (PL-16 1V) on Pilot:

TCP Throughput: 4358.25 Kbits/sec

Average of 6 runs from PL16_Pilot Int-82ohm_6afe.xlsx ; XLSX data from raw data in PL16_Pilot Int-82ohm_6afe\ jperf- throughput 128K buffer client.txt)

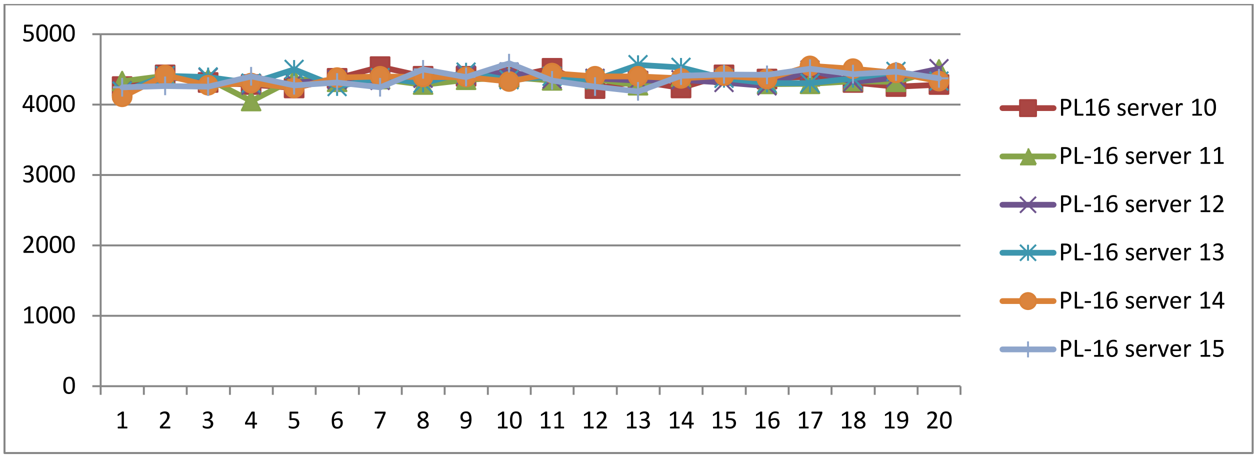

Figure 7-7
PL-16 Throughput Measurement (X-axis -Time in Seconds)

G3 (2V) on Pilot:

(From MaximG3_Tahoe2_2-29-12.xlsx)

TCP Throughput (average)

Default buffers (Code Red Board)		40.38634	Kbps
1K buffers Tahoe2++		18.04	Kbps
1K buffers Tahoe2++		18.04	Kbps
256b buffers Tahoe2++		3.9	Kbps

Figure 7-8
Throughput versus Buffer Size

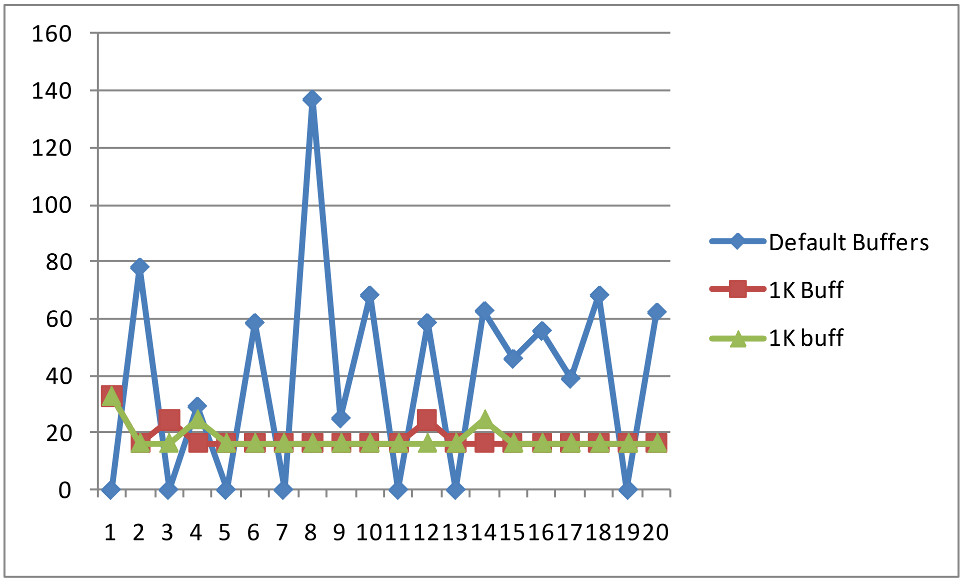

Figure 7-9
G3 TCP Performance (X-axis – Time in Seconds)

Note: The vendor indicated that TCP is known to be problematic for these test platforms. Alternative testing was performed using UDP.

UDP Rate	Delivered UDP,	%loss
25	23.3	6.7
50	30.3	39
100	35.1	69

Figure 7-10
G3 Tahoe2++ UDP Summary Results

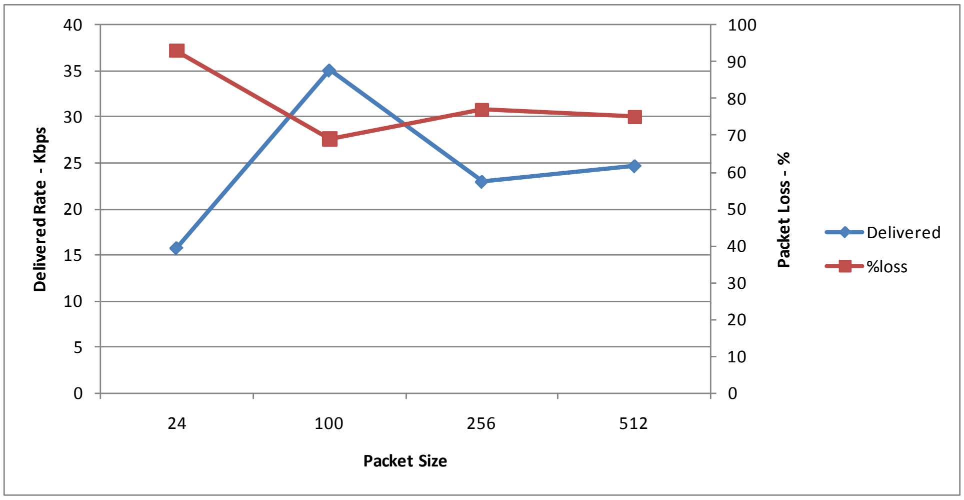

Figure 7-11
G3 Tahoe2++ UDP Throughput versus Packet Size

Observing the optimum performance at 100 byte packet size, an additional set of tests were run to see how different source UDP rates would perform:

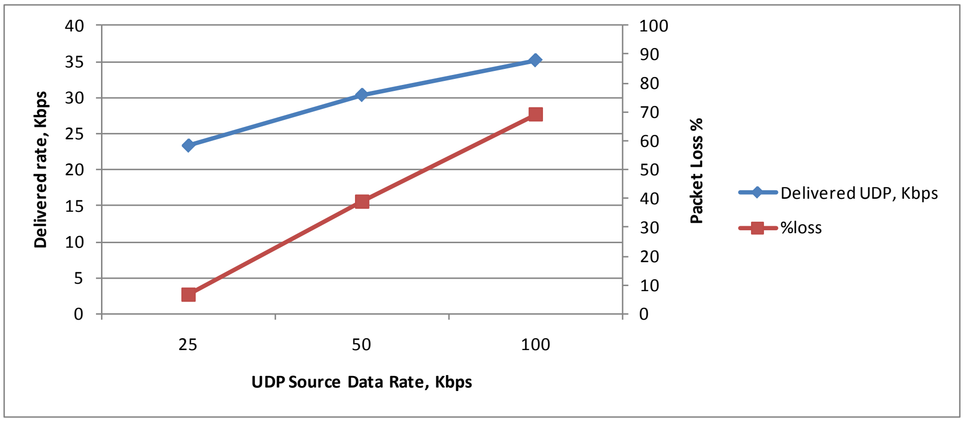

Figure 7-12
G3 Tahoe2++ UDP throughput, delivered vs. source rate with 100 byte packets

A maximum rate of 35Kbps UDP throughput is seen when attempting 100Kbps, but at that rate there is a 70% packet loss. When sourcing 25Kbps, the packet loss is 6.7%.

G3 (1V) on Pilot:

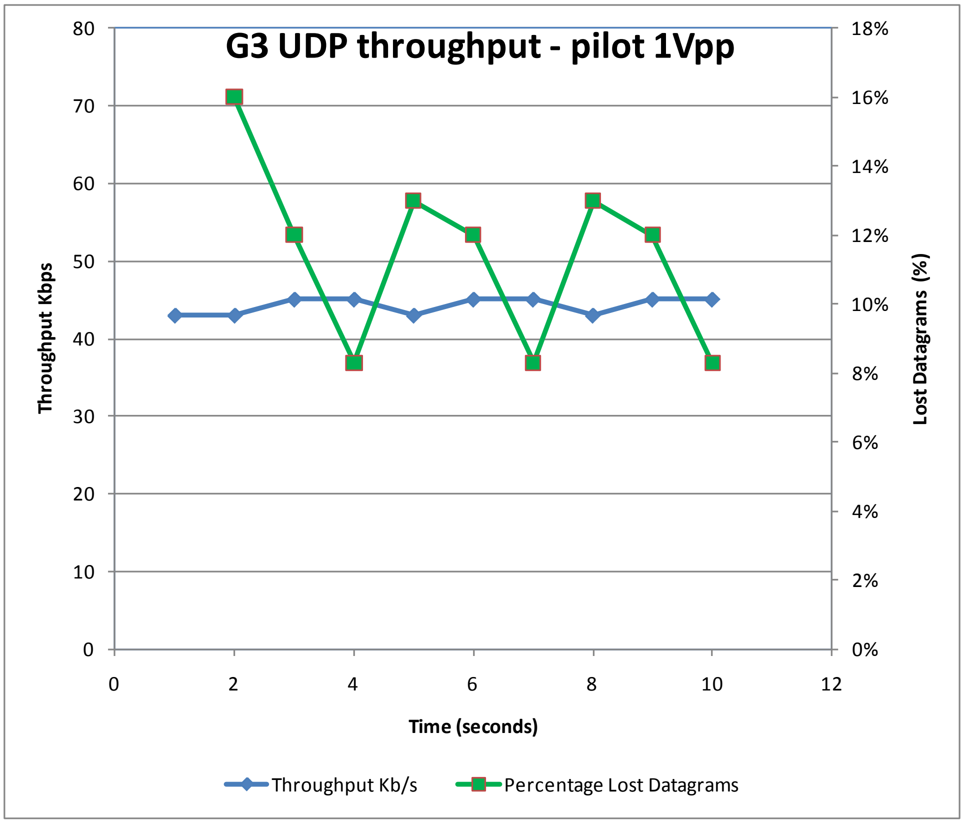

Figure 7-13
G3 Throughput, Pilot, 1V P-P

Changing the signal level does not significantly change the results.

A variety of tests were attempted with the G3 platform, varying parameters in an attempt to find any combination that could provide throughput that meet the requirement of 100Kbps.

Results

HomePlug GreenPHY - A consistent throughput of 4Mbps was measured. This meets the SAE requirement.

G3 - Results varied depending on parameters, and UDP vs TCP, but measured results were always below the lower SAE utility data rate limit of 100Kbps. This does not meet the SAE requirement.

Latency Tests

This test verified that the round-trip latency of packet communications met the requirements specified in RD.UtilComm.4 (15 minutes) and RD.DCComm.2 (25mS).

Devices tested:

- QCA PL-16 (HPGP 18V on pilot),
- QCA PL-16 (HPGP 1V on pilot),
- Maxim Tahoe2++ (G3 2.82V on pilot)

Data

HPGP (1V) on Pilot (PL-16):

7.04 ms average for packets smaller than 900 bytes.

8.64 ms average for all packet sizes between 16 and 1024 bytes.

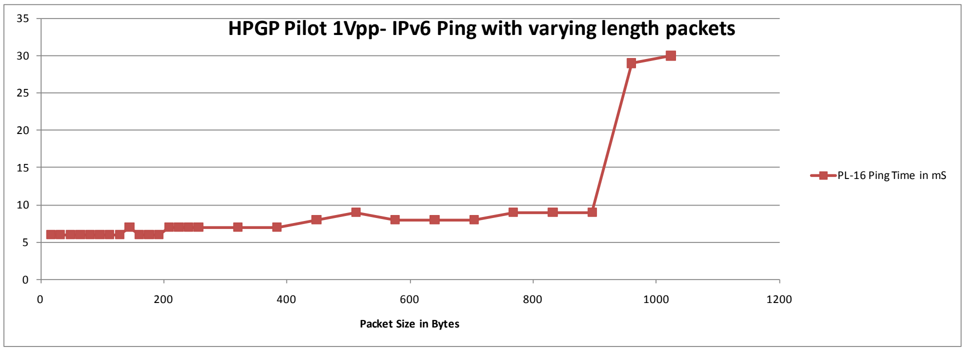

Figure 7-14
PL-16 Ping Latency

G3 (2V) on Pilot

From file “MaximG3_Tahoe2_2-29-12.xlsx”. Due to the relatively low data rate, latency is proportional to packet size. Since the G3 modems implemented an asynchronous serial host interface, which also added latency, the time for communicating the data over the serial host interface was subtracted out of the lower trace.

46.0 ms best case latency (for 32 byte packet)

122.4 ms average for packets smaller than 900 bytes

138.32 ms average for all packet sizes between 16 and 1024 bytes

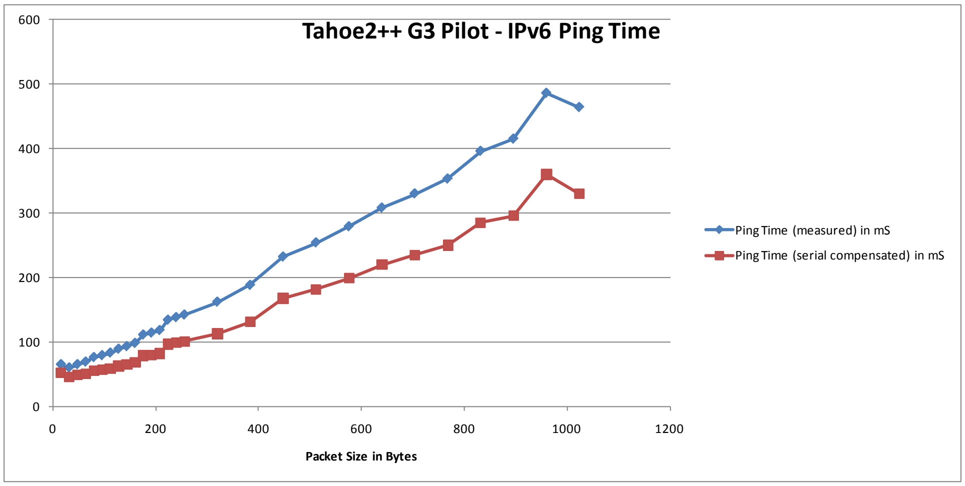

Figure 7-15
G3 (Tahoe2++) Ping Latency

Results

HomePlug GreenPHY - Passes with an average latency under 10ms. No explanation was available for the increase in ping latency for packet over approximately 900 bytes. This meets the SAE requirement.

G3 - Fails with an average latency over 100mS. It exceeds the 25mS limit for any packet size tested. This does not meet the SAE requirement.

Crosstalk Tests

The crosstalk tests were designed to verify two types of requirements as specified in RD.RelComm.2 and RD.RelComm.3. One requirement was that the signal was not susceptible to crosstalk from other cordsets or signals on other conductors in the cordset. The other requirement was that the communications signal would not cause harmful interference networks operating on other cordsets or conductors in the cordset.

The tests were conducted in two configurations: 1) using two cordsets twisted together, and 2) using a single cordset and testing internal crosstalk between conductors.

Devices tested:

- QCA PL-16 (HPGP 18V on pilot),
- QCA PL-16 (HPGP 1V on pilot),
- Maxim Tahoe2++ (G3 2.82V on pilot)

Twisted Cordset Crosstalk

The purpose of this test was to determine if there was enough coupling from twisted cordsets to affect communications.

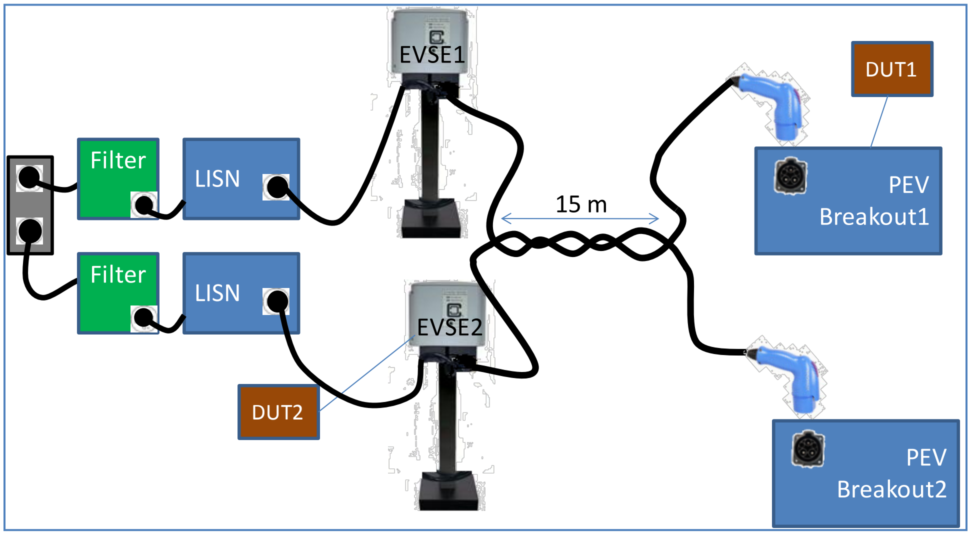

Figure 7-16
Logical Setup for Twisted Cordset Test

Data

HomePlug GreenPHY - 1Vpp

One node was coupled to the pilot of one cordset, while the other node was connected at the EVSE of the 2nd cordset with the cordset cables twisted together over their length (see Figure 7-17).

With both EVSEs in State B (vehicle connected but not ready to accept energy – main AC contactor open in EVSE) there was insufficient coupling to make a connection.

Putting one EVSE into State C (vehicle ready to accept energy – main AC contactor closed), there was insufficient coupling to make a connection.

Putting both EVSEs into state C, there was insufficient coupling to make a connection.

Figure 7-17
Setup for HPGP Twisted Cordset Crosstalk

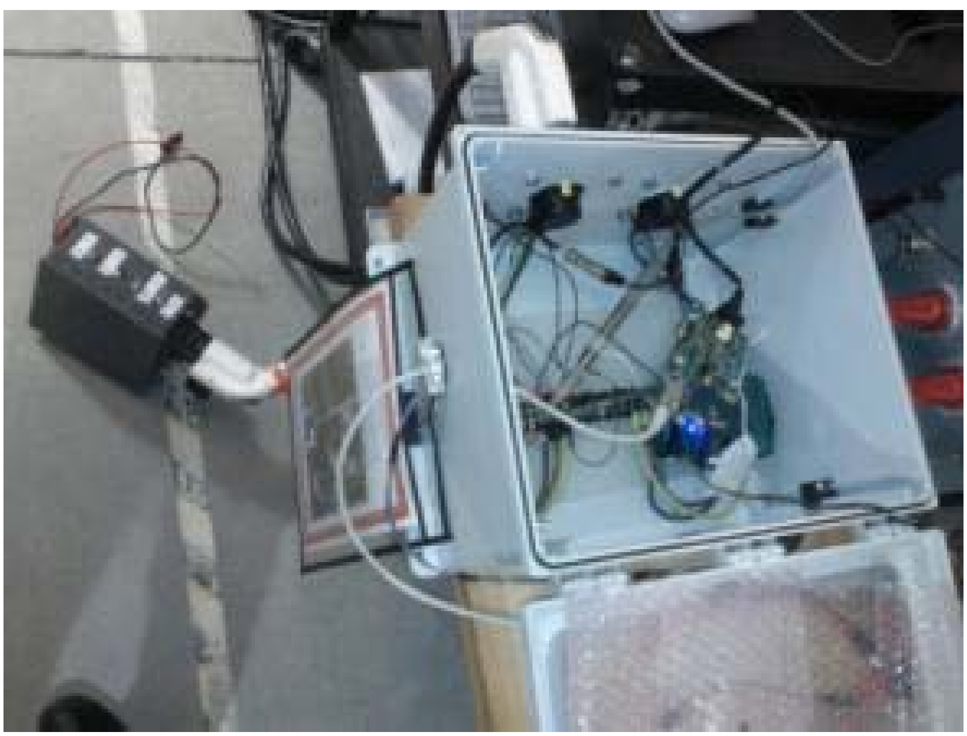

Figure 7-18
Setup for G3 Twisted Cordset Crosstalk

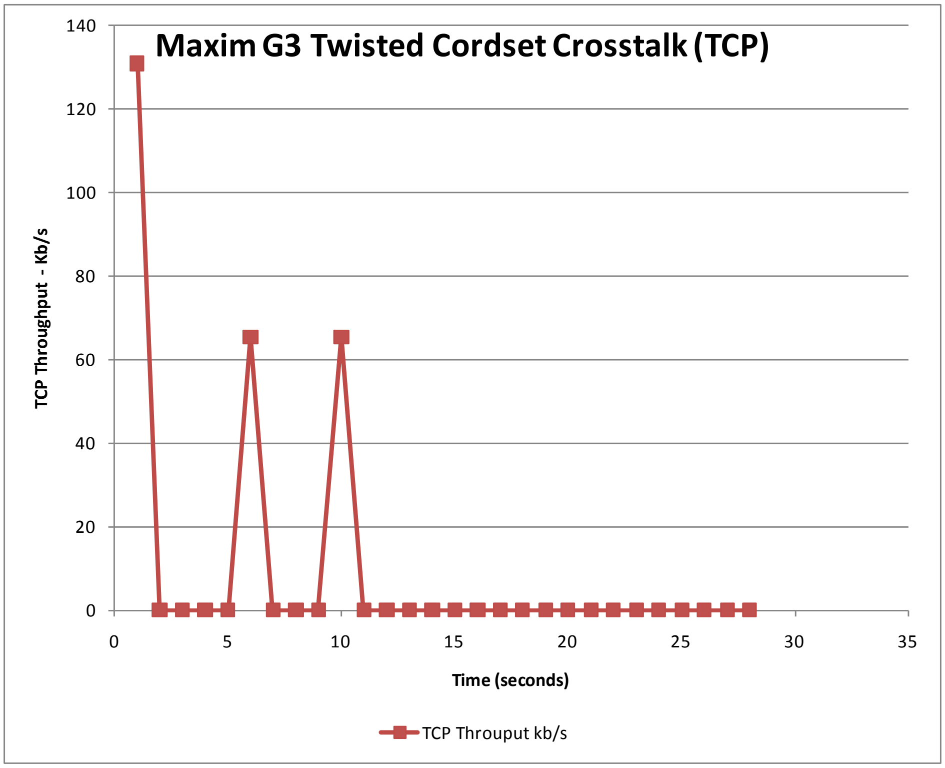

Figure 7-19
G3 Crosstalk TCP Communication

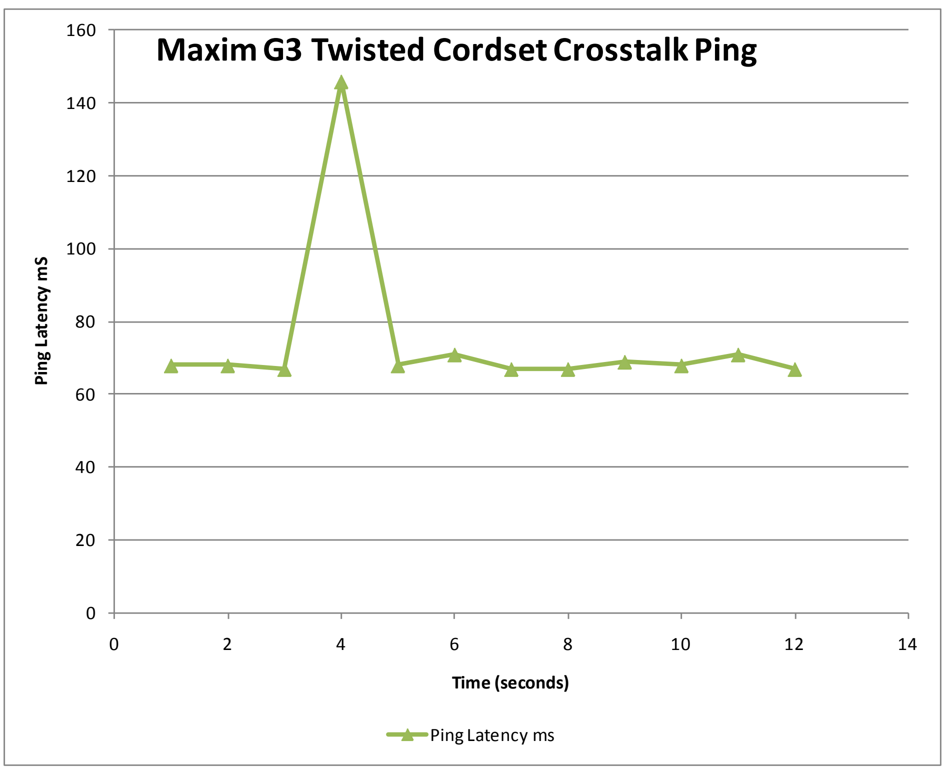

Figure 7-20
G3 Twisted Cordset Crosstalk (Ping)

With G3, a usable connection could be established using only the crosstalk between two twisted cordsets, although performance was reduced compared to a direct connection over a single cordset.

Cordset Internal Crosstalk Test

In the internal crosstalk tests, the communications signals on the mains coupled to the pilot and vice versa. The result was a sharing of bandwidth in a similar matter as with coexistence tests, where different networks share the same medium.

HomePlug GreenPHY - 1Vpp

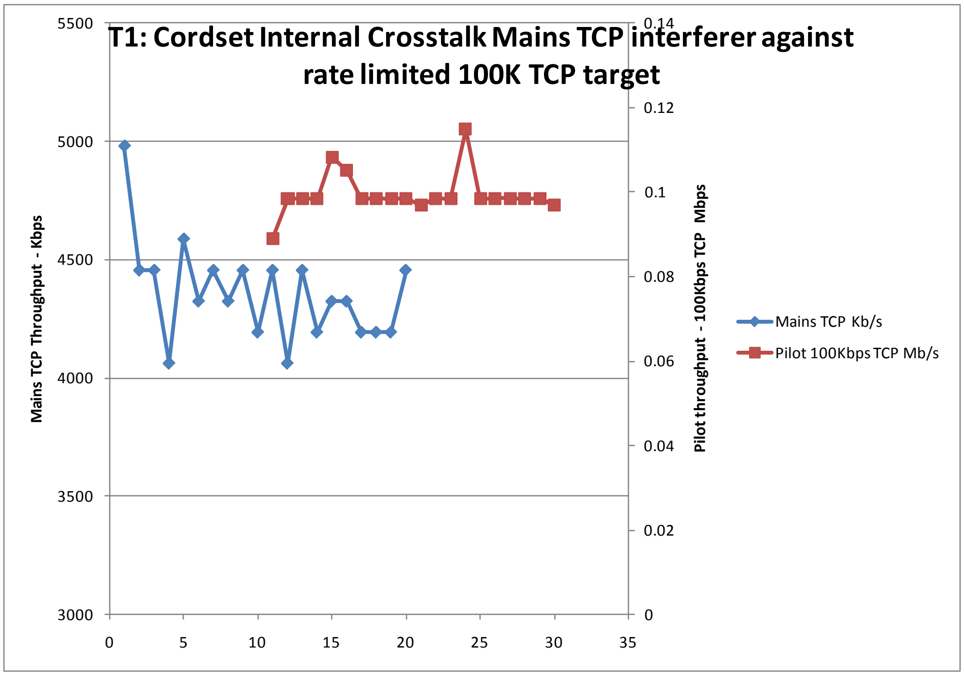

Figure 7-21
Cordset Internal Crosstalk – Pilot 100K TCP affected by unlimited TCP on Mains

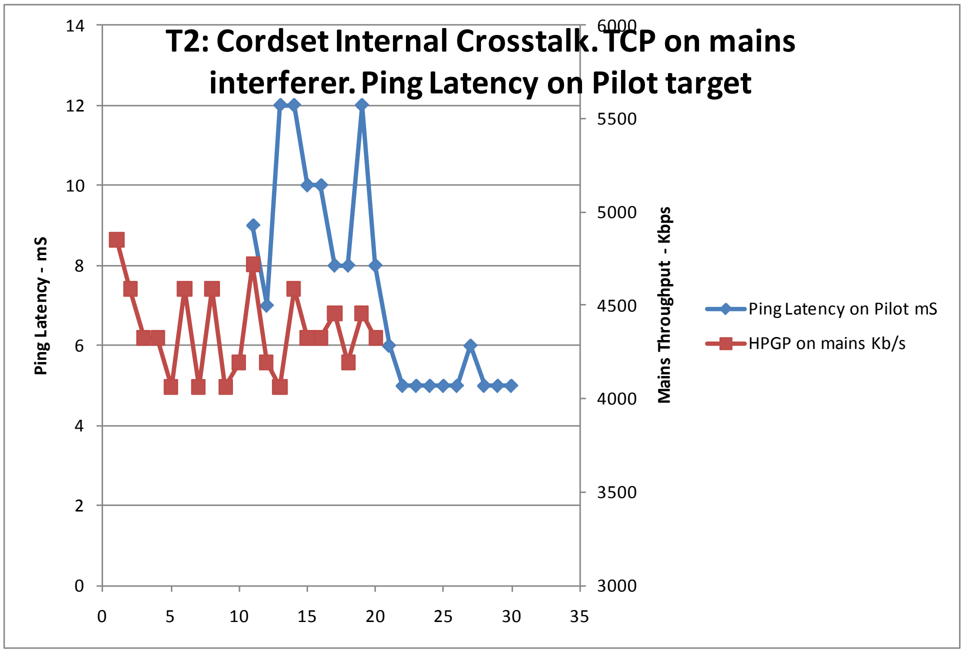

Figure 7-22
Cordset Internal Crosstalk – Pilot Ping Latency affected by full rate TCP on Mains

Interpretation:

In T1, the 100Kbps TCP throughput (representing utility messages on cordset) was not affected by full rate TCP on mains.

In T2, the Ping Latency (representing DC messages on the cordset) was somewhat affected, but did not exceed test limits for round trip latency while full rate TCP on mains was running.

In T1 and T2, the cordset signal did not adversely affect the TCP throughput of the signal on the mains.

G3:

The following graph shows test results for a TCP test running on the mains, and after 15 seconds a separate pair of modems start a ping test running on the pilot. The two G3 systems should have been able to coexist despite any internal coupling of their signals.

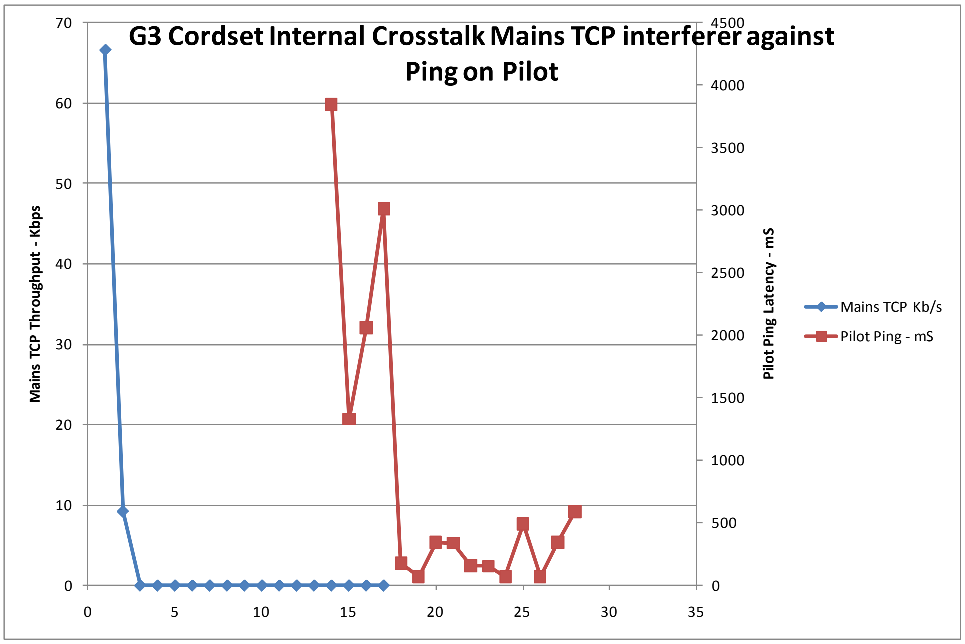

Figure 7-23
G3 Pilot Latency with interfering G3 on Mains

Interpretation: The TCP flow on mains had the typical wide variation seen on G3. During the run of the competing Ping, it stopped entirely, and was not able to re-establish any measured throughput. The Ping latency during the competing TCP flow was much larger, and dropped to more typical values when the ping was running alone (after the TCP flow stopped).

We were unable to get two simultaneous TCP flows to run concurrently. This could be interpreted as an issue with respect to “RD.RelComm.3: The technology chosen shall not cause interference to signals that may be on other conductors in the cordset, or another twisted cordset”. Attempting to run G3 TCP on the cordset, or even Pings on the cordset link, definitely affected any G3 signal present on the mains. G3 signals on the mains are present in many parts of the world where G3 is used for AMI communications.

Results

Twisted Cordset Tests:

HomePlug GreenPHY: There was no coupling of HPGP in the twisted cordset test. This indicates there is not a substantial coupling between twisted cordsets.

G3: A usable connection could be established using only the crosstalk between two twisted cordsets, although performance was reduced compared to a direct connection over a single cordset. This indicated that there was substantial coupling between twisted cordsets.

Cordset Internal Crosstalk Tests:

HomePlug GreenPHY: A test of 100Kbps TCP throughput (representing utility messages on cordset) was not affected by full rate TCP on mains. A test of the Ping Latency (representing DC messages on the cordset) was somewhat affected, but the values do not exceed test limits for round trip latency while full rate TCP on mains was running. In both tests, the cordset signal (representing the EV and EVSE) did not adversely affect the TCP throughput of the signal on the mains (representing a possible home network using HomePlug). Although coupling exists, there was no degradation of throughput to the point where other test limits (latency and throughput) were not met.

G3: It was not possible to maintain two simultaneous TCP flows, or a TCP flow with Pings between a coupled G3 system on the pilot and the mains. Coupling existed, and the systems were not able to operate within test limits in the coupled case.

Coexistence Tests

Coexistence tests verified the systems' ability to coexist with other communications signals on the same medium (wire). These tests verified RD.RelComm.4, RD.RelComm.6, and RD.RelComm.1. There were two aspects to the testing. First, self-coexistence verified the system can coexist with another signal of the same type on the wire. Secondly, the systems was required to co-exist with different varieties of communications signals that could exist on the wire. Although many types of PLC systems exist, it was impossible to test all combinations, due to time and budget constraints, as well as limited equipment availability.

Coexistence testing focused on devices that actually exist, and have some market share (i.e. a possibility that devices would be found in homes and businesses where EVSEs will be deployed). For the HomePlug GreenPHY system, coexistence testing was conducted against HomePlug AV and HD-PLC devices. HomePlug AV is the most common device type. Wikipedia estimates that "millions of HomePlug AV devices ship each month" [8]. HD-PLC was competitor to HomePlug, but is not longer actively marketed.

Devices tested:

- QCA PL-16 (HPGP 1V on pilot) and HPAV (18V) on main
- QCA PL-16 (HPGP 7V on pilot) and HPAV (18V) on main (see appendix)
- Maxim Tahoe2++ (G3 1.4-1.6V on pilot) and Concerto on main

Data

Self Coexistence

This test verified the system was able to operate with another communications system of the same time on the same medium. As an example, an energy management HAN could form a separate HPGP network from the EV and EVSE and run on the power line. This test verified the ability to coexist with that separate network.

HomePlug GreenPHY:

Two logically unique networks share the same medium (different network IDs are used).

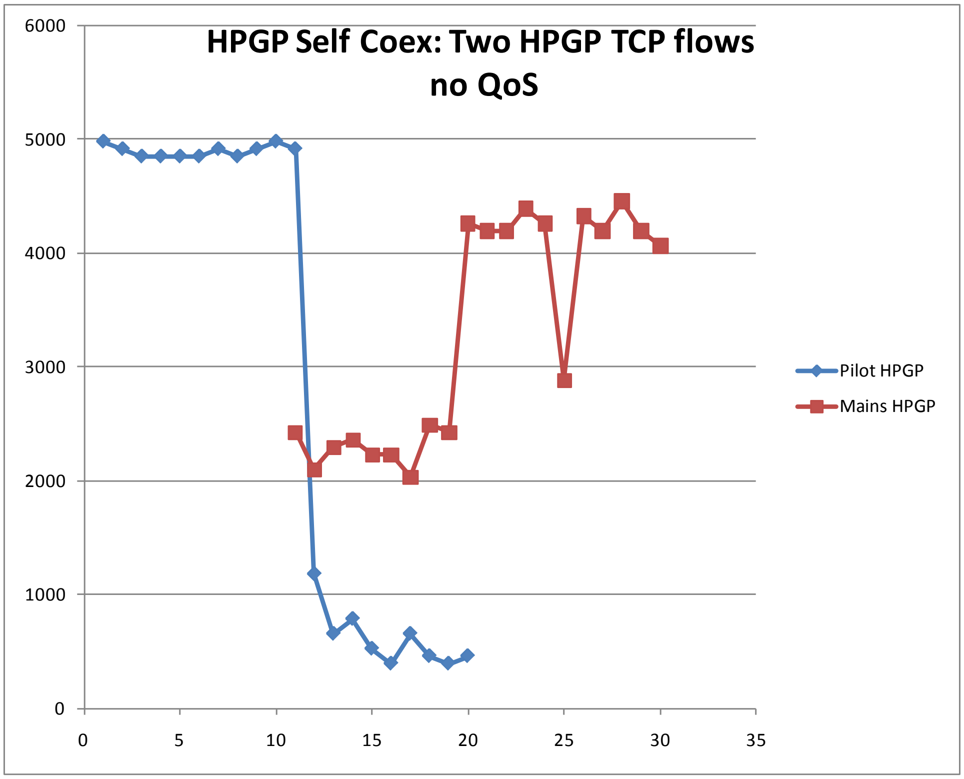

Figure 7-24
HPGP Self Coexistence – TCP on Each Network

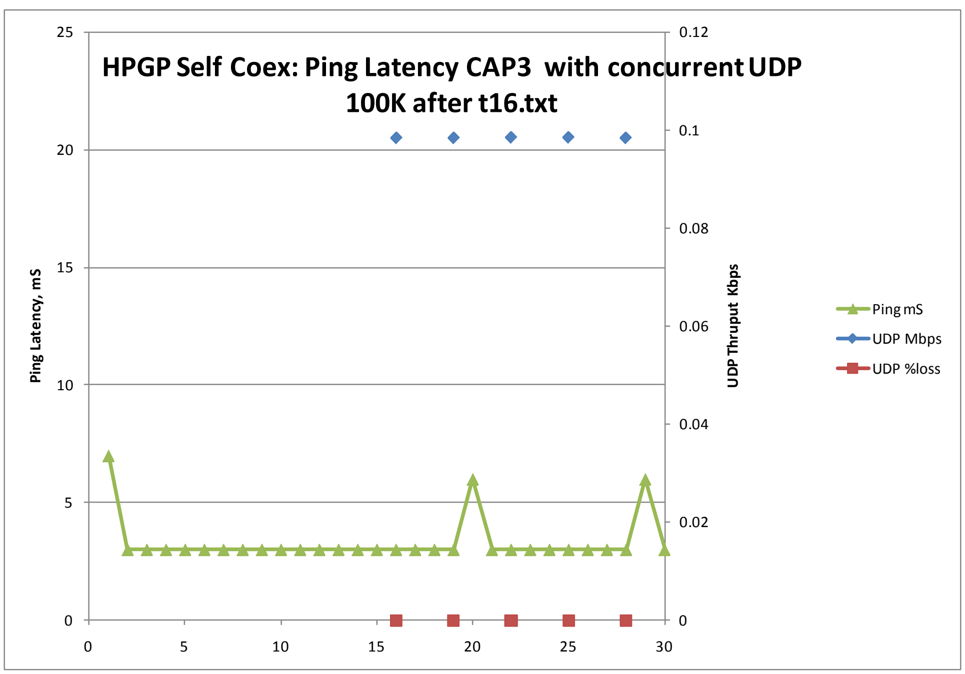

Figure 7-25
HPGP Self Coexistence - Ping on One Network and UDP on the Other

G3:

In this test, two different Maxim G3 platforms were used: Tahoe2 on mains, and CodeRed on the Pilot. The Tahoe2 link was set to a logically unique network ID (from 0x4221 to 0x4222).

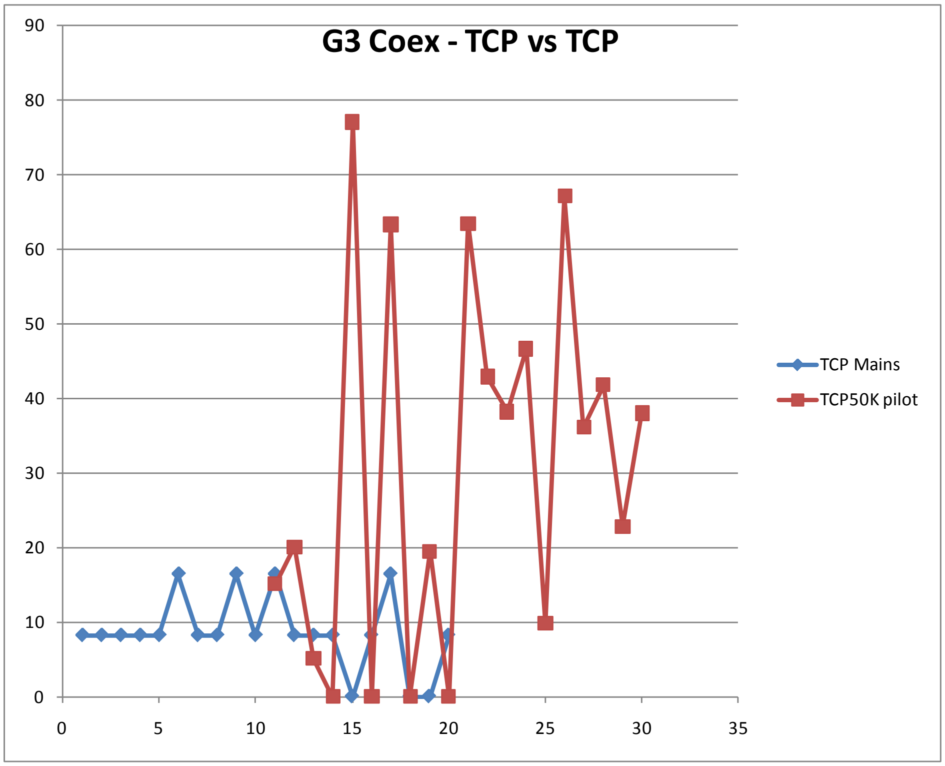

Figure 7-26
G3 Self Coexistence - TCP on Each Network (X-axis is time in seconds)

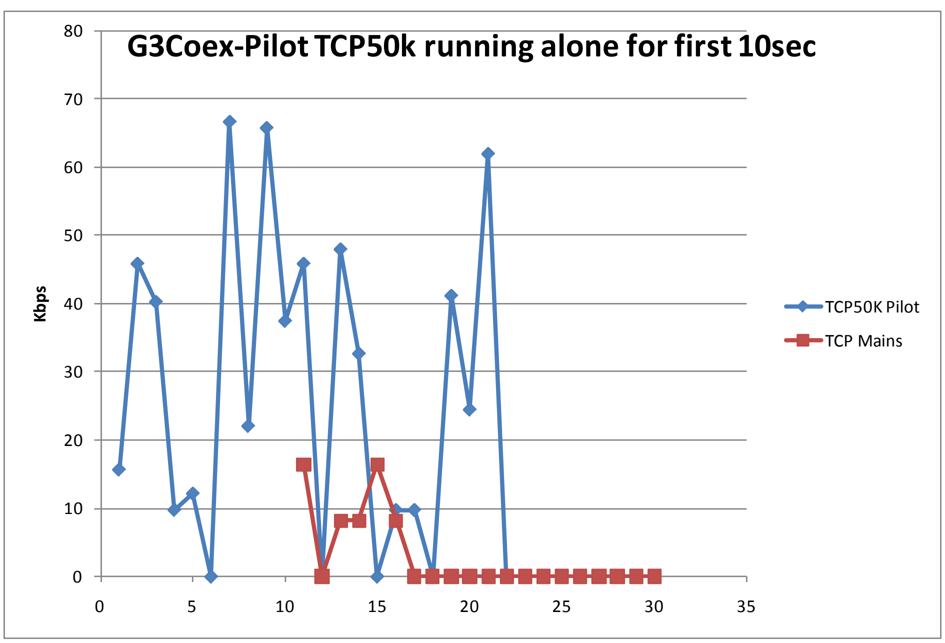

Figure 7-27
G3 Self Coexistence - TCP50K on pilot (X-axis is time in seconds)

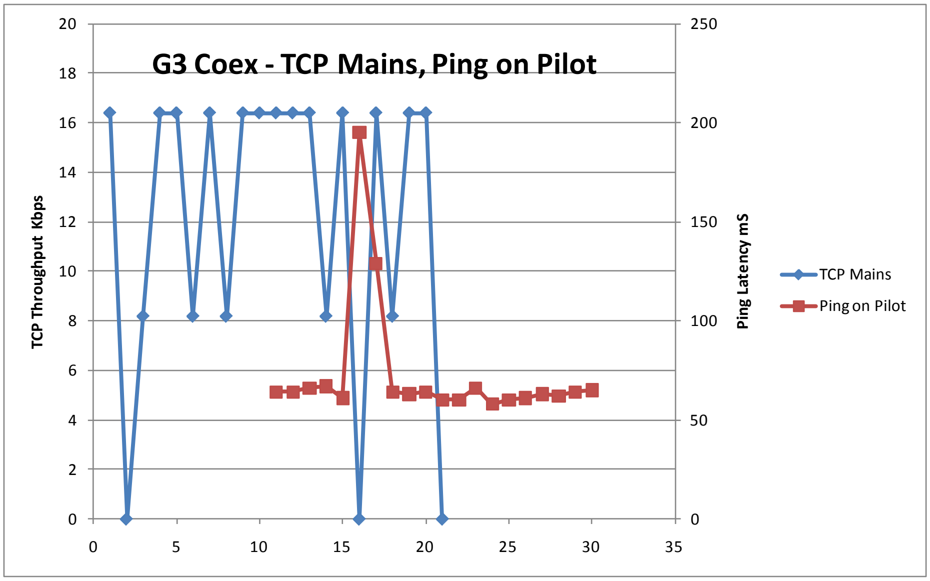

Figure 7-28
G3 Self Coexistence - TCP mains, Ping on Pilot

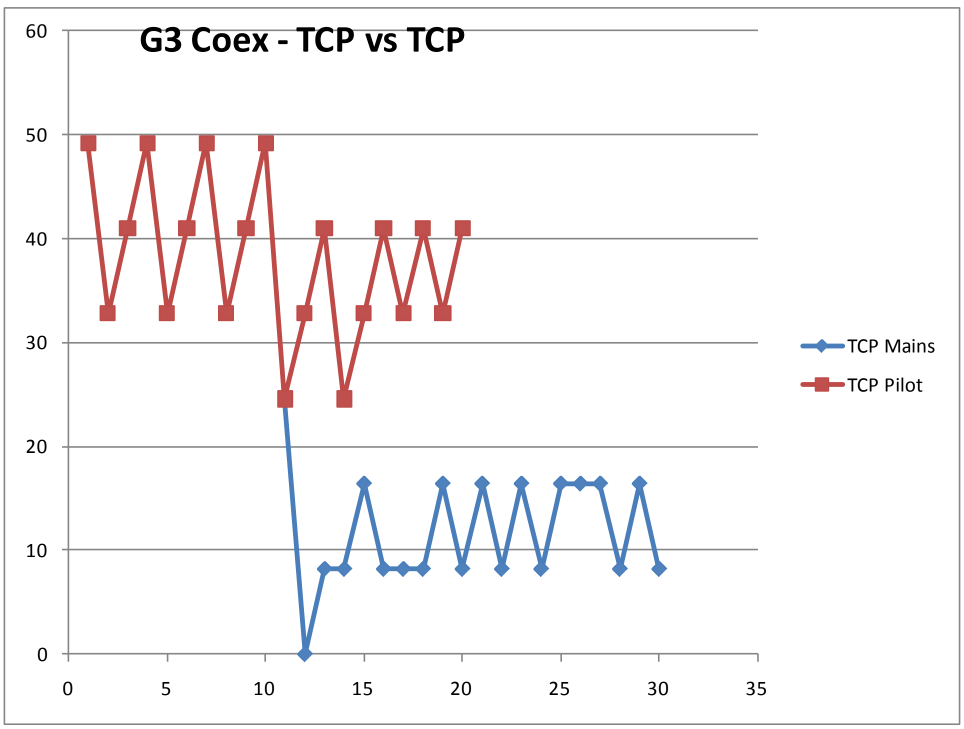

Figure 7-29
G3 Self Coexistence - TCP mains, TCP on Pilot

Consumer PLC Susceptibility

Cordset Communications does not adversely impact existing consumer PLC communications systems.

HomePlug GreenPHY: (Pilot injection of ~1Vpp)

HomePlug GreenPHY was tested against HomePlug AV as the consumer network.

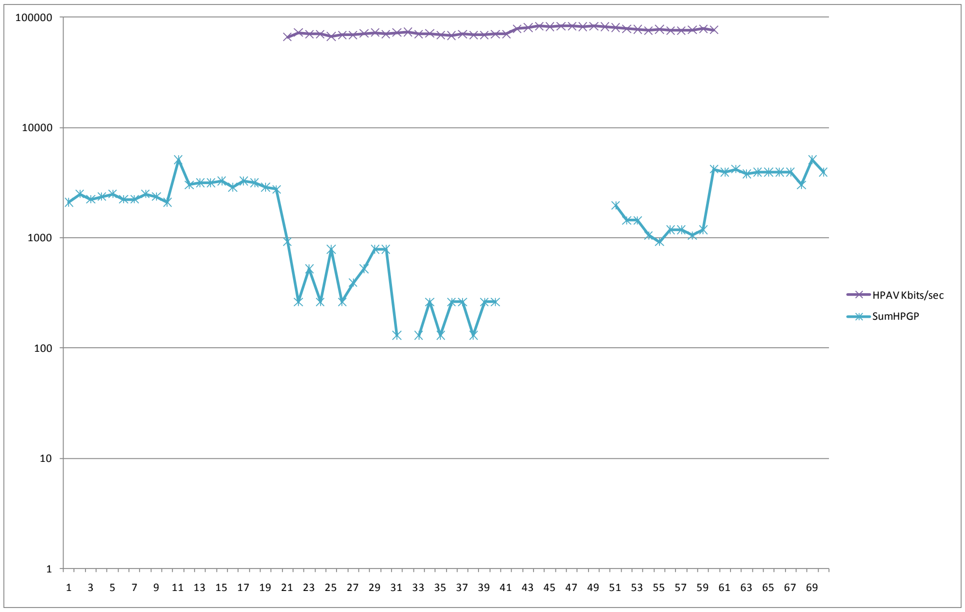

Figure 7-30
HPAV maximum rate TCP with competing HPGP

Fully loaded TCP over HPAV drops from around 80Mbps to 70Mbps when fully loaded HPGP from two nodes is competing.

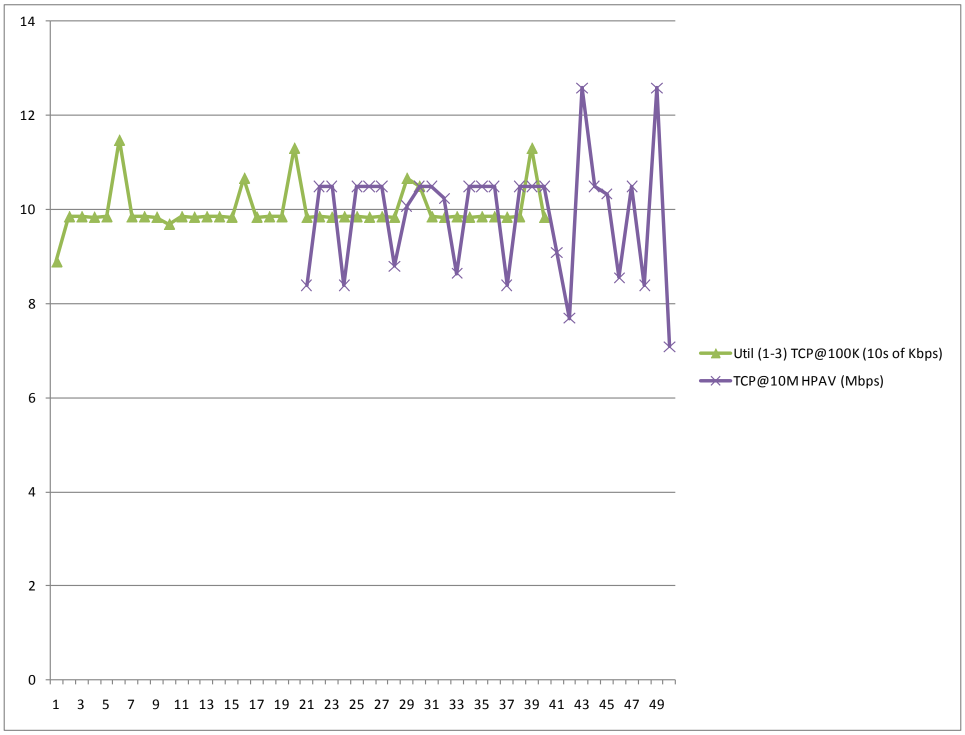

Figure 7-31
HPAV 10Mbps TCP with competing HPGP 100Kbps TCP

The test plan called for 10Mbps TCP over HomePlug AV (representing a video stream on the HPAV network) to operate concurrently with a 100 Kbps TCP stream on the HomePlug GreenPHY network (representing the EV to utility communication). Both networks operated within normal ranges. The HPAV throughput was not significantly affected by 100Kbps TCP over HPGP.

G3:

No "consumer" versions of G3 were available to test with. Results in Coexistence test results indicate G3 performance when sharing with other networks in the same band.

Coexistence with Consumer PLC (HomePlug AV)

This test verified that Consumer PLC networks would not have an adverse effect on the PEV / EVSE communication.

HomePlug GreenPHY: (Pilot injection of ~1Vpp)

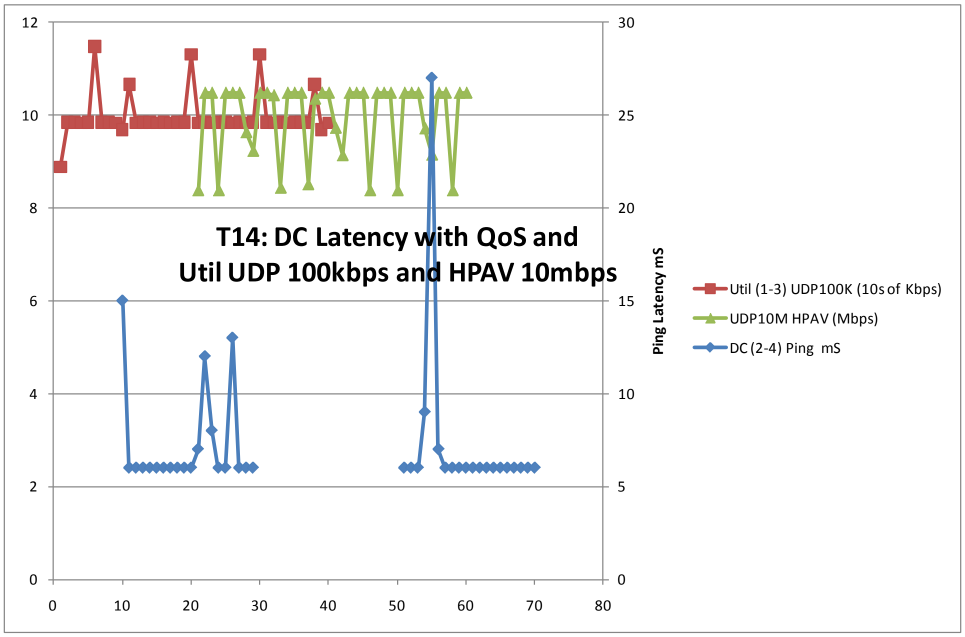

Figure 7-32
Consumer PLC Coexistence - HPAV Affect on HPGP Throughput and Latency (X-axis – Time in Seconds)

One outlying packet exceeded the 25ms latency limit specified by SAE.

The HomePlug standard includes QoS (Quality of Service) prioritization. The HomePlug GreenPHY specification also includes a mechanism called Dynamic Bandwidth Control (DBC), which prevents HomePlug GreenPHY devices from taking too much bandwidth away from HPAV.

No QoS	1035.4	HPGP during shared zone		73085.7	HPAV in shared zone	
T1	4351.4	HPGP alone		81789.1	HPAV alone	

Figure 7-33
HomePlug GreenPHY HPAV Coexistence with no QoS

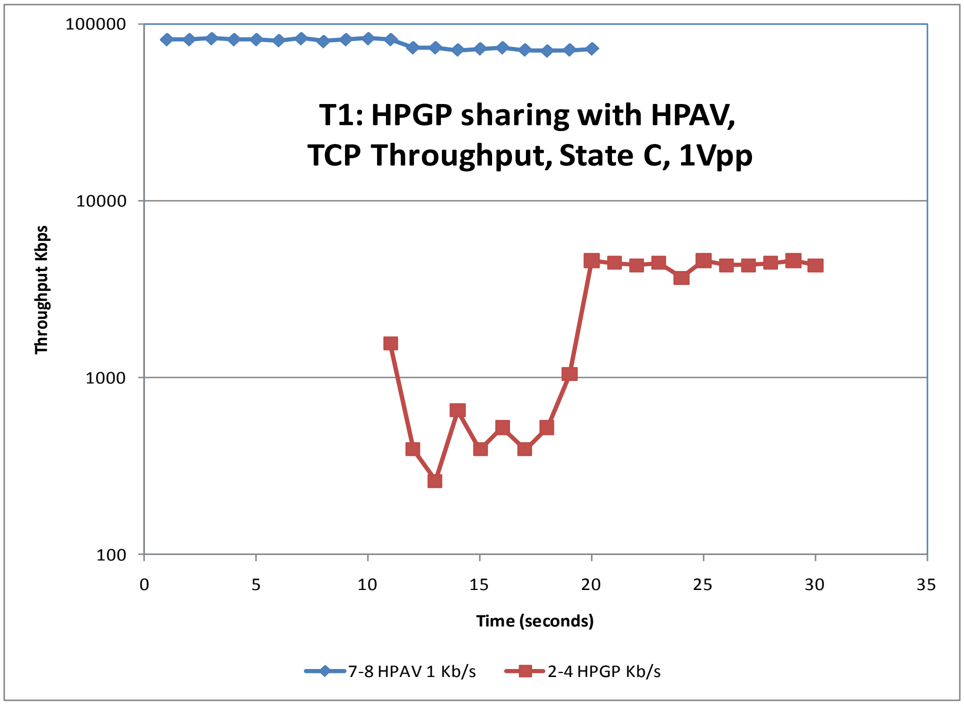

Figure 7-34
HPAV vs HPGP on Pilot 1Vpp No QoS

With QoS:	720.8	2-4 during shared zone			76126.5	HPAV in shared zone	
T4	4049.9	2-4 alone			82628	HPAV alone	

Figure 7-35
HomePlug GreenPHY HPAV Coexistence with QoS

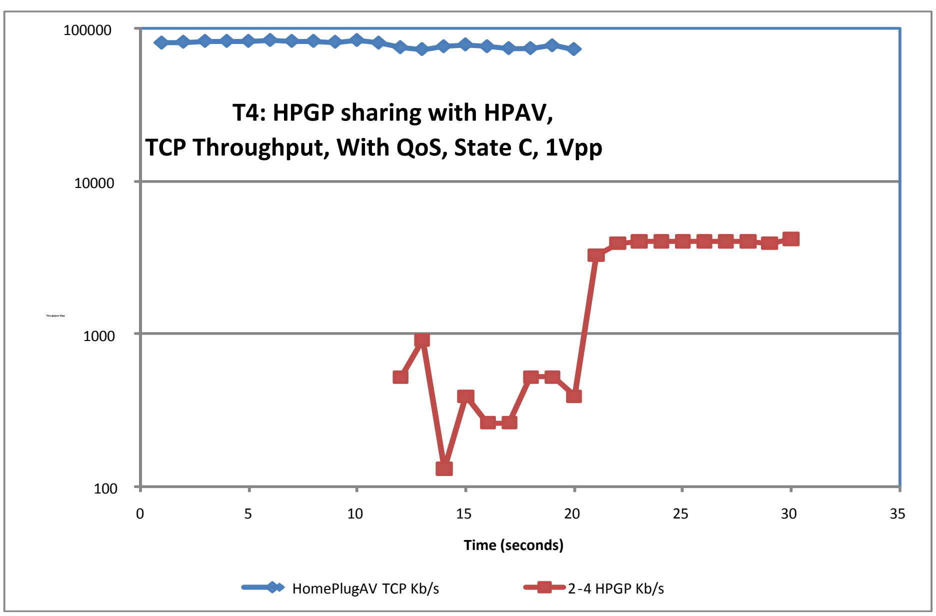

Figure 7-36
HPAV vs HPGP on pilot 1Vpp with QoS

Conclusion: Because of the limitation of DBC, the HPGP rate was not improved using QoS. The DBC effectively overrode the QoS to preserve HPAV throughput. This was not a concern for the PEV/ EVSE communication, since the throughput requirements were below the threshold for DBC.

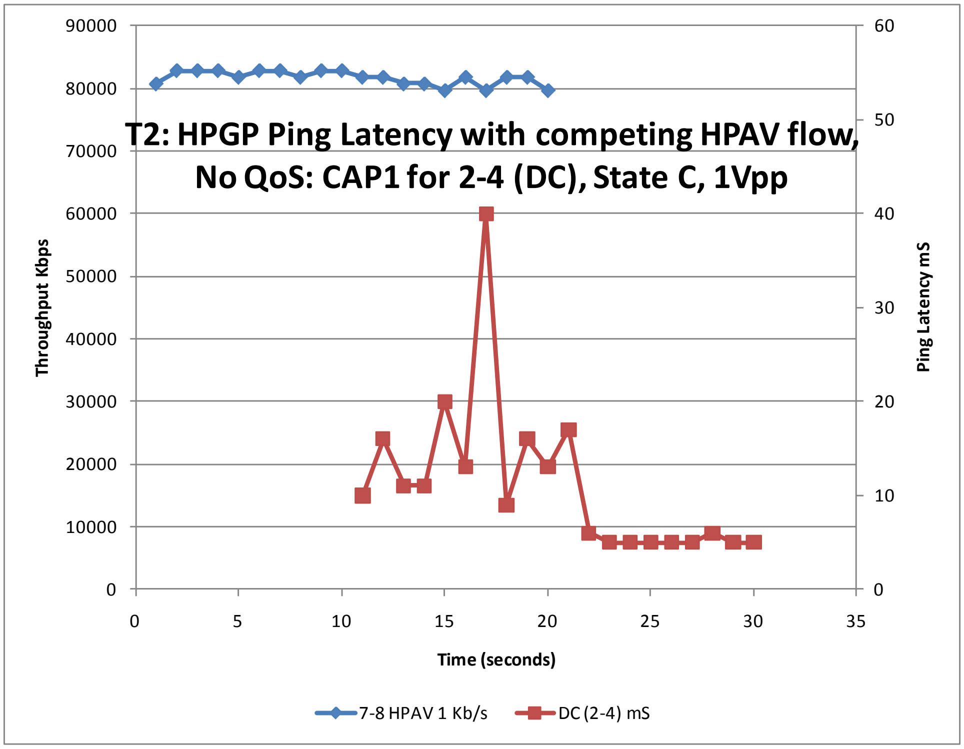

Figure 7-37
HPAV/HPGP Coexistence: HPGP Ping Latency, No QoS: CAP1 for 2-4 (DC), State C, 1Vpp

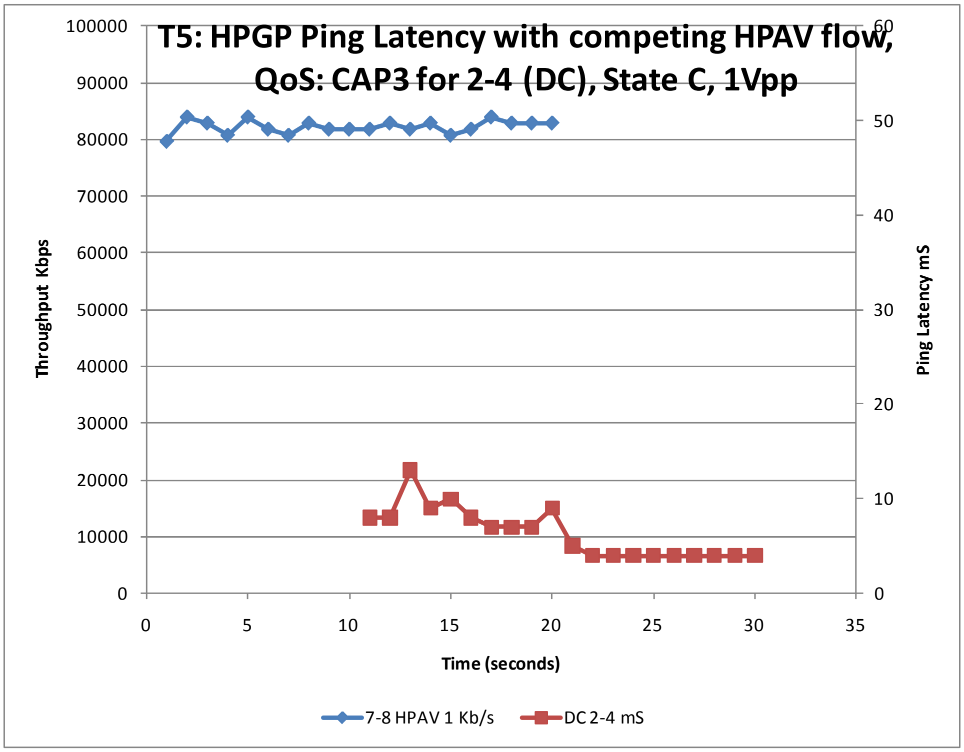

Figure 7-38
HPAV/HPGP Coexistence: HPGP Ping Latency, With QoS: CAP2 for 2-4 (DC), State C, 1Vpp

Conclusion: CAP3 QoS improved performance when HPGP was contending against HPAV. The maximum latency dropped from 40mS without QoS to 13mS with QoS enabled on HPGP. The DBC mechanism did not affect results, because the overall data rate of Pings was below the threshold for DBC.

HomePlug GreenPHY Coexistence with Consumer PLC (HD-PLC)

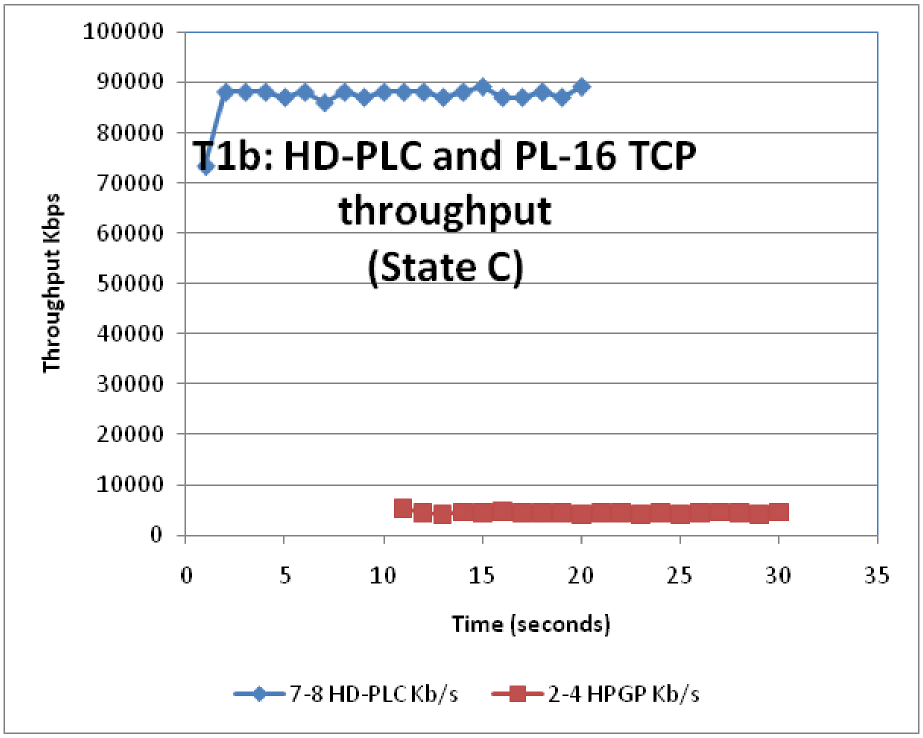

Figure 7-39
HD PLC competing with HPGP (TCP vs TCP)

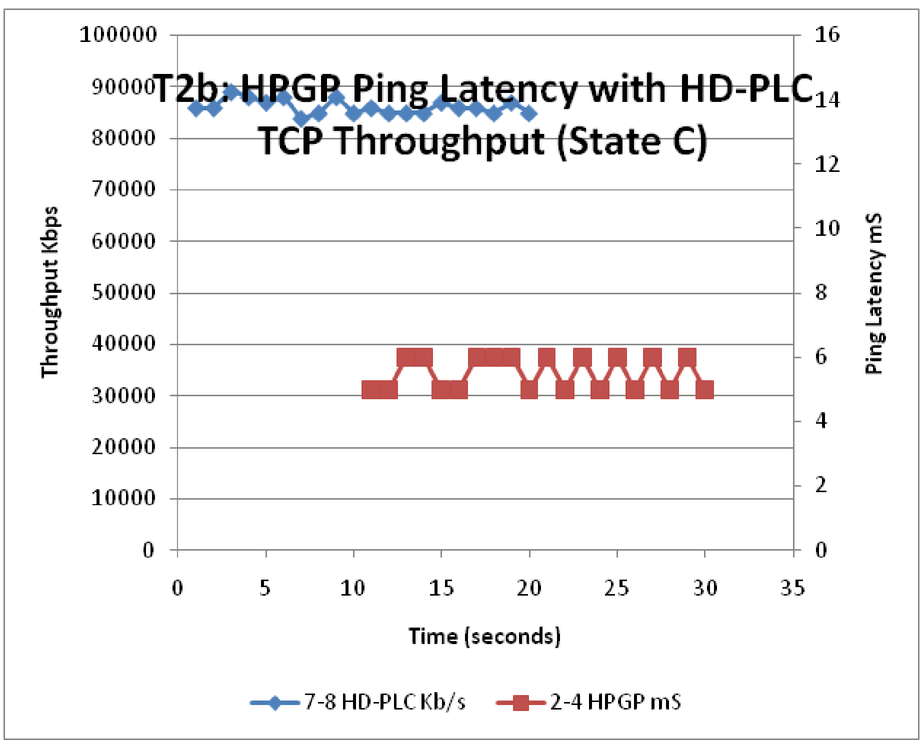

Figure 7-40
HD PLC competing with HPGP (TCP and HPGP Ping Latency)

Results

The HD-PLC prototypes did not cause appreciable degradation of throughput or latency of HPGP.

G3 Coexistence Test Using Tahoe2++ and TI Concerto

The only two different G3 platforms that were available were the Maxim and the TI Concerto. The Tahoe was run in normal G3 mode with IPv6 TCP and Ping.

The TI Concerto was run using vendor software's test mode because IP Drivers were not available.

The Tahoe system was run for 15 seconds alone. The Concerto system was then started and ran until the test run completed.

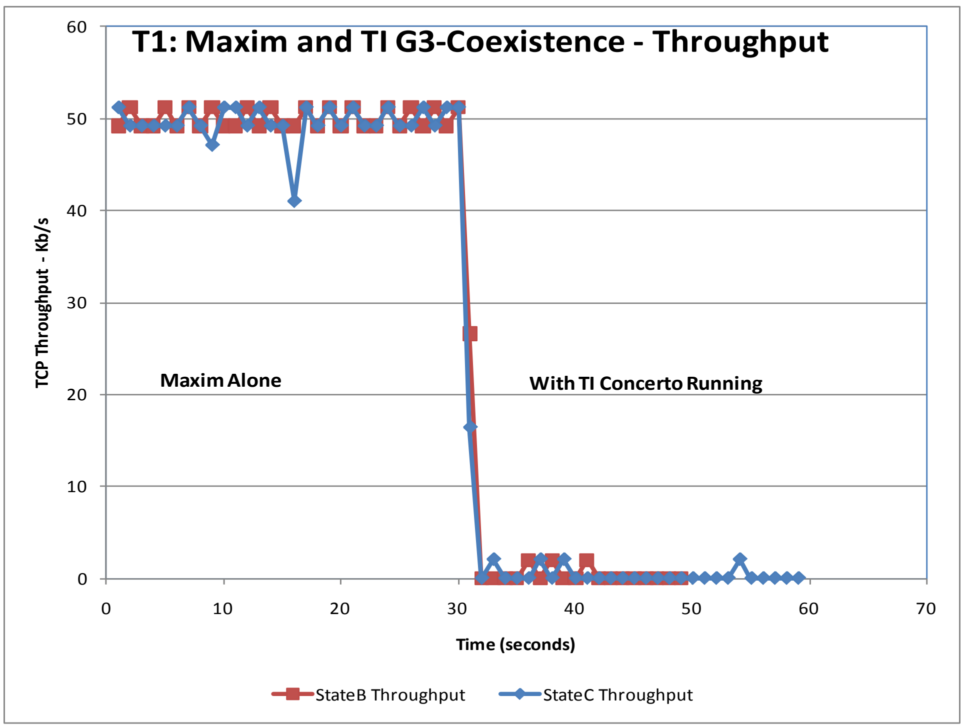

Figure 7-41
Maxim G3 Coexistence with TI Concerto - Throughput

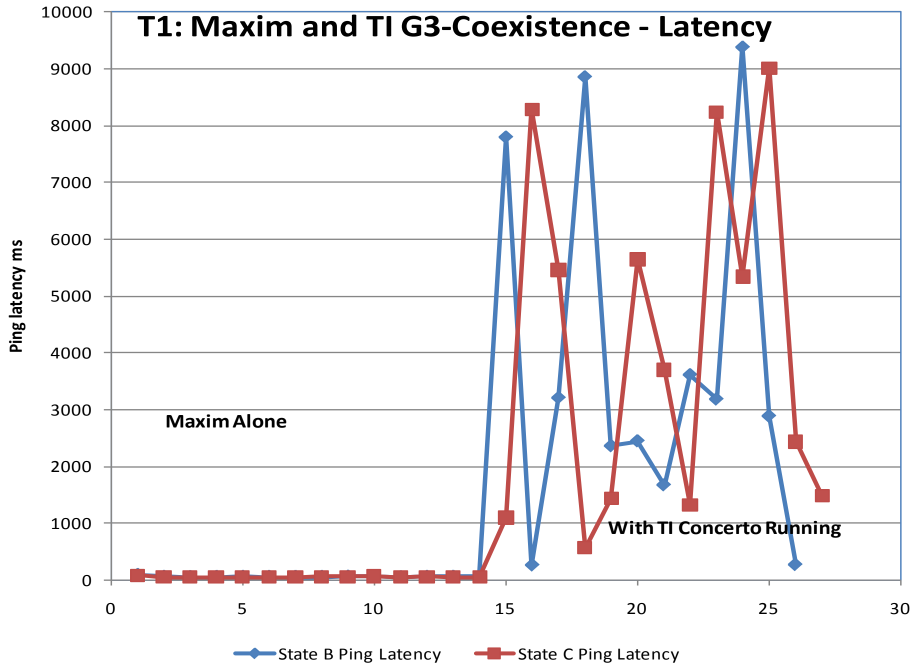

Figure 7-42
Maxim G3 coexistence with TI Concerto - Latency

Results

When both systems were operated concurrently, the TCP throughput dropped to nearly zero, and the ping latency increased dramatically. The G3 coexistence mechanism did not appear to provide equal, efficient sharing of the available resources on the medium.

Interference Tests

The interference tests verified the communication systems' ability to meet requirement RD.RelComm.8. The system was expected to be resilient in the presence of typical types of power line interference.

Devices tested:

- QCA PL-16 (HPGP 18V on pilot) (see appendix)
- QCA PL-16 (HPGP 1V on pilot)
- QCA PL-16 (HPGP 7V on pilot) (see appendix)
- Maxim Tahoe2++ (G3 2.82V on pilot)

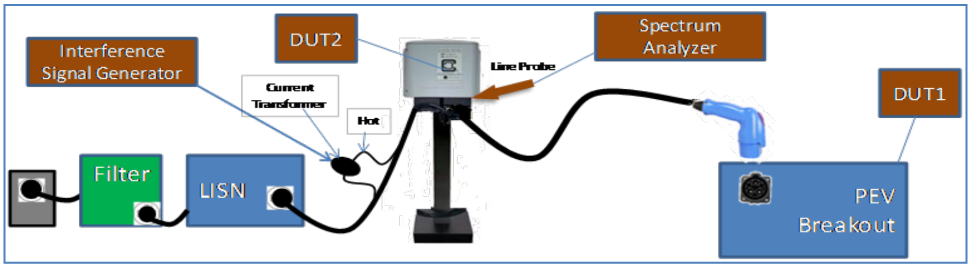

Figure 7-43
Set up for Interference Tests

The objective of these tests was to determine system resilience to interference from the power line. Interference was always injected on Mains with the measurement point on the mains or pilot, depending on type of PLC being tested.

The interference sources used were:

- White Noise – the typical source for interference testing
- DC Charger noise – actual noise waveform captured from an Eaton DC Fast Charger

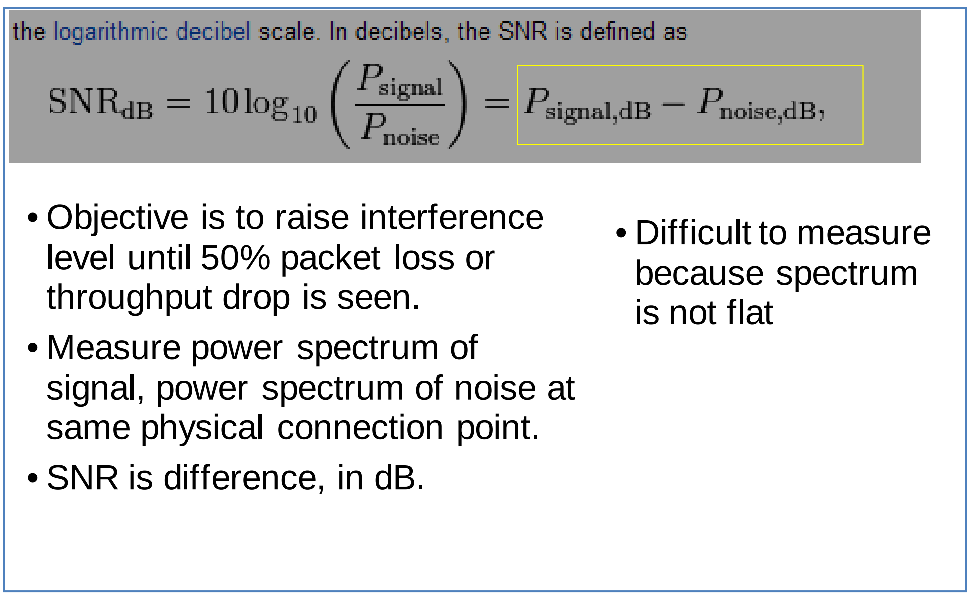

Figure 7-44
Measuring Signal to Noise Ratio

Data

There was no specific test limit for required signal to noise ratio. The tests involved raising interference levels until the communication was impaired, and measuring the Signal to Noise ratio at that point. There was no pass/fail criterion, so only relative comparisons were made.

Coupled Cordset Interference

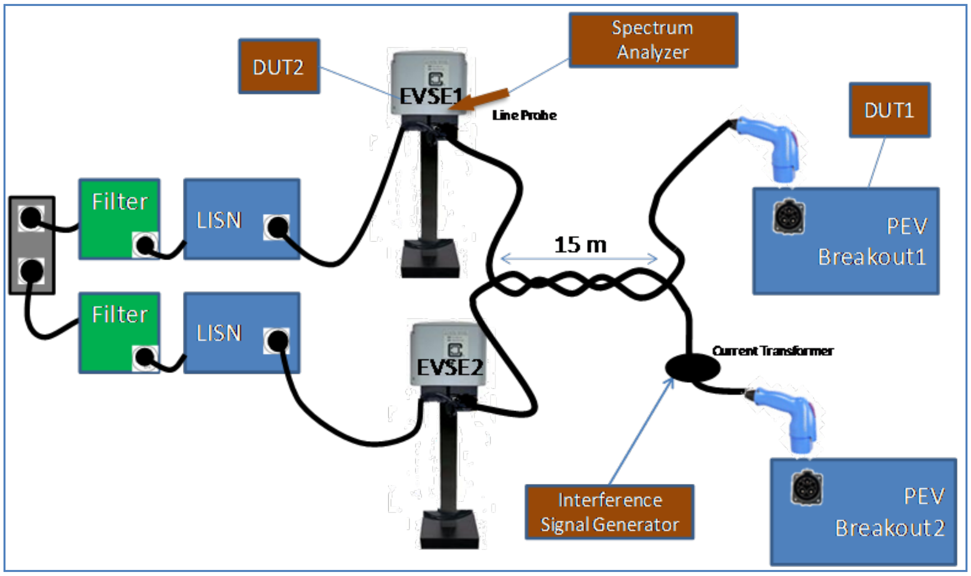

Figure 7-45
Diagram of Coupled Cordset Interference Test Setup

Noise was injected onto one cordset, which was twisted around the other. Impairment was measured on the pilot of the target cordset.

Results

HomePlug GreenPHY – with coupled cordset interference

Tested PEV1 with 1V PP HPGP on Pilot

The signal generator was unable to generate sufficient amplitude of induced noise in the twisted cordset to cause any measured impairment of performance on the pilot of the target cordset.

G3 – with coupled cordset interference

Wideband FM Noise was increased to the point where to following performance drop was seen.

At this point G3-PLC Power Spectral Density is -48.68dBm/Hz, and the noise PSD is -30.1dBm/Hz, giving a SNR of -18.58dB

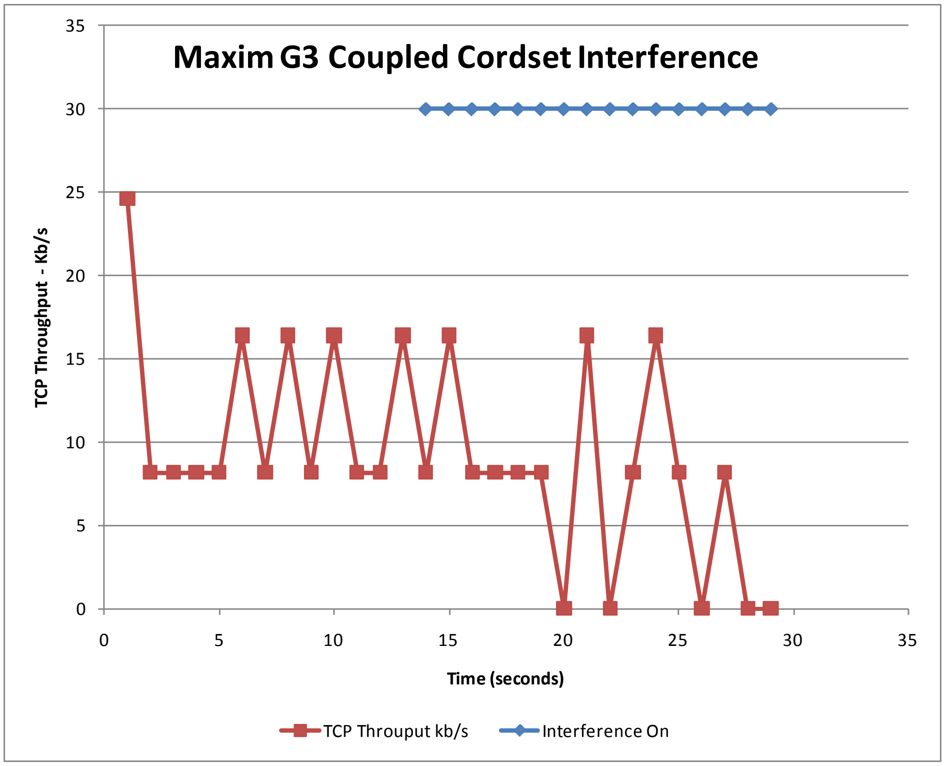

Figure 7-46
G3 Coupled Cordset Interference (TCP)

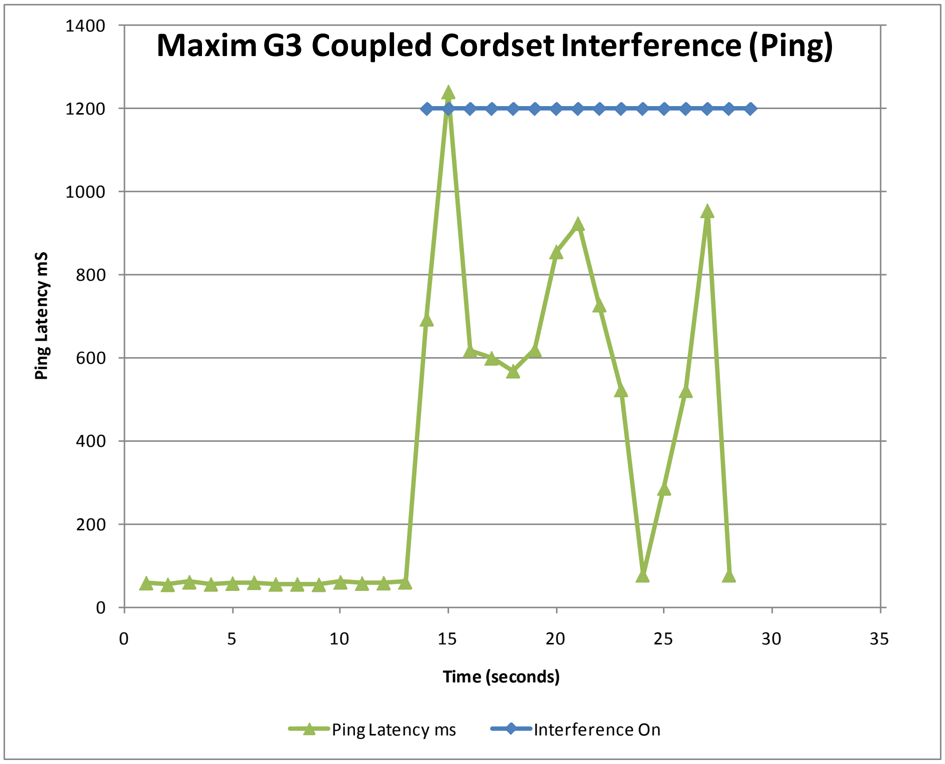

Figure 7-47
G3 Coupled Cordset Interference (Ping)

Conclusion: Neither technology was significantly affected by coupled noise. Although G3 was affected, the SNR was very good, with the noise over 18dB stronger than the signal.

DC Charger Noise Interference Tests

Noise Characterization

The noise signal was captured from an Eaton DC fast charger, and scaled to fit the sample rate and memory size of the arbitrary signal generator.

Initially, the signal was directly connected to the spectrum analyzer (through a 20dB attenuator) to characterize the signal. For the tests, the following conditions were used:

- The HPGP analyzer setup is: 15MHz center, Integration bandwidth 26Mhz, Span 30Mhz.
- The G3 analyzer setup is: 319Khz center, integration bandwidth 318 KHz, Span 400Khz
- The generator was set to 4V pp (relative to full scale output)
- In the HPGP band, the PSD was -70.63dBm/Hz (max hold, DC coupled, w 20dB Attn)
- (Noise spectrum in HPGP Band 4Vpp 20dB attn max hold_0001.png)
- In the G3 band, the PSD was -63.56dBm/Hz (max hold, DC coupled, w 20dB Attn)

(Noise spectrum in G3 Band 4Vpp 20dB DC max hold_0001.png)

DC charger noise was (-65.56 - -70.63) = 5.07dB stronger in G3 part of band, everything else being equal.

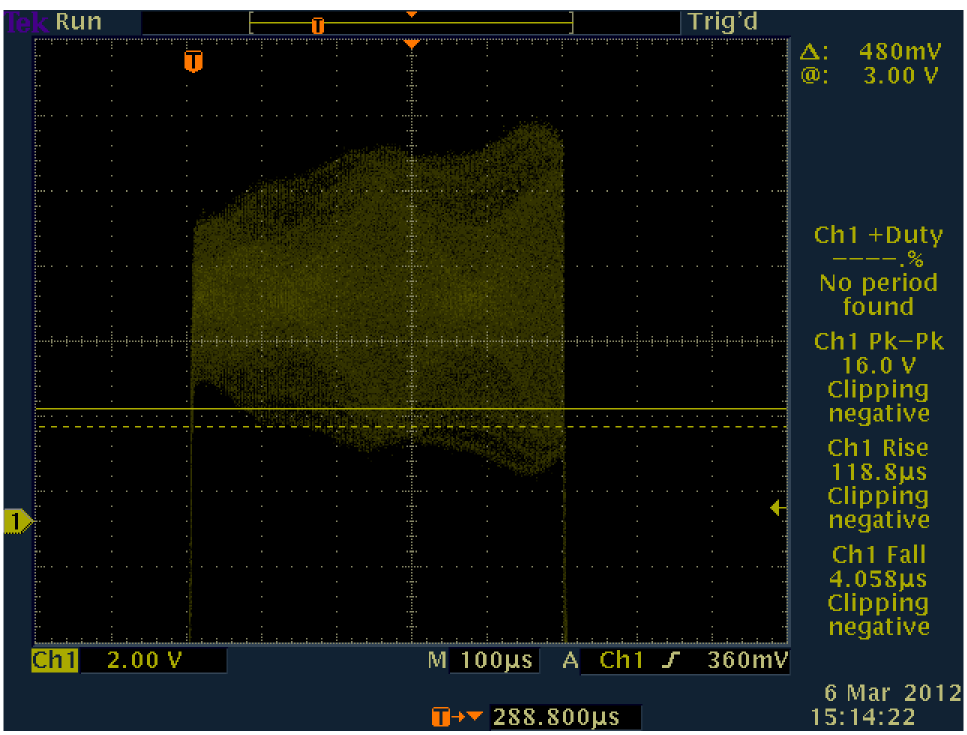

Figure 7-48
DC Noise on Pilot

Figure 7-49
DC Noise Test Setup – Radio Frequency Amplifier driving Current Transformer (CT) on Mains

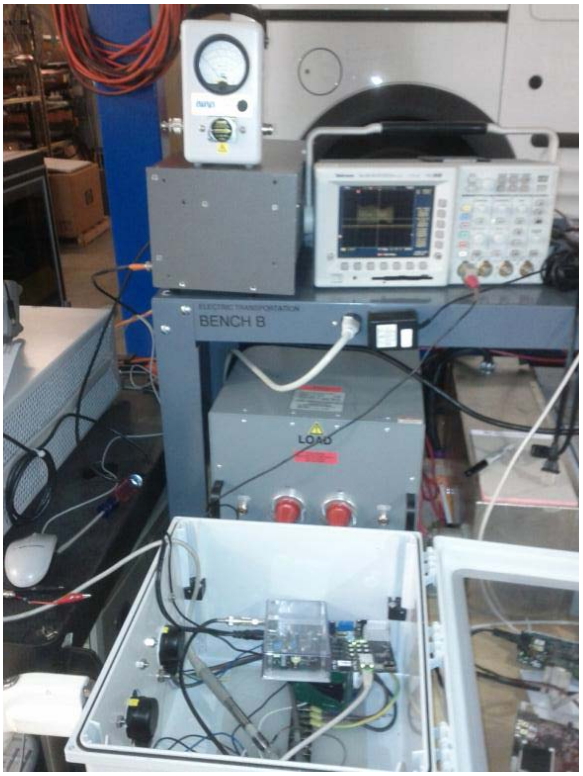

Figure 7-50
DC Noise Test Setup - PL-16 in EV Emulator

Results

HomePlug GreenPHY - with DC Charger Noise

Running DC noise at 2.1Vpp through AR RF power amplifier, induced into mains with current transformer. Level was increased to point where Jperf throughput was reduced to around 1mbps.

- Noise only -89.70dBm/Hz.
- PLC only -110.7dBm/Hz.

Measured Signal to Noise Ratio: -21dB

G3 - with DC Charger Noise

DC noise was passed through a radio frequency power amplifier and induced into the mains with a current transformer. Noise started at Time 10 (Figure 7-51).

- Level 7.5vpp into amplifier.
- Jperf 95% packet loss.
- Noise Only -85.30dBm/Hz. PLC Only 84.77dBm/Hz.

Measured Signal to Noise Ratio: 0.53dB

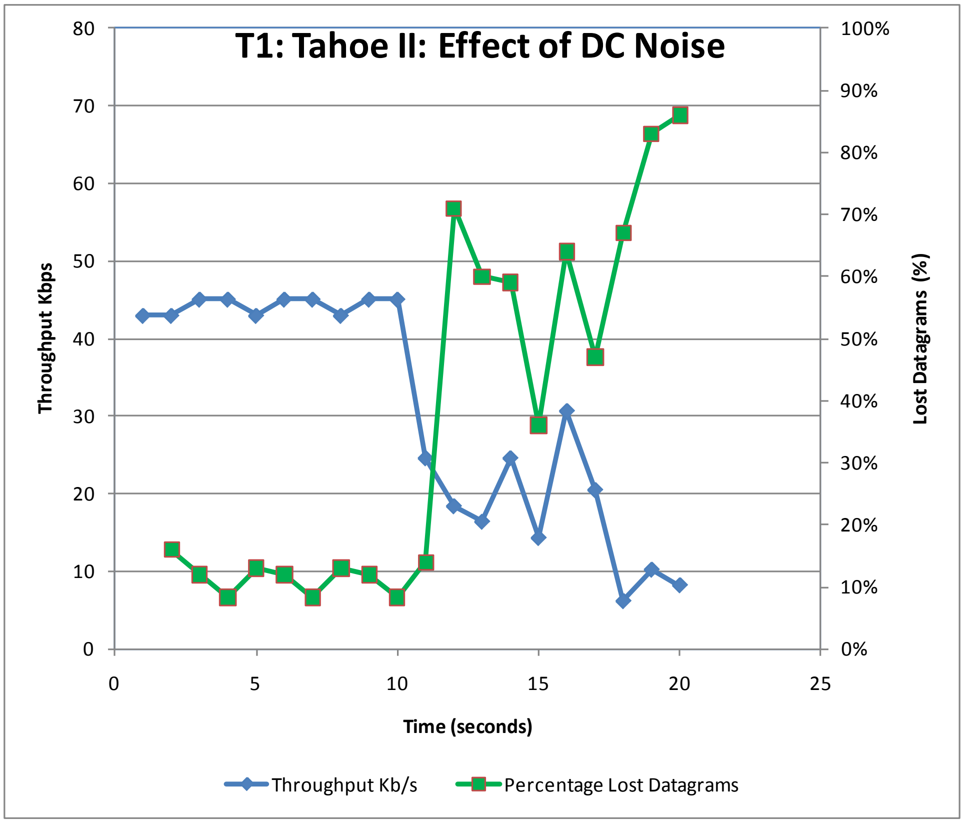

Figure 7-51
Tahoe2++ Throughput without/with DC Noise

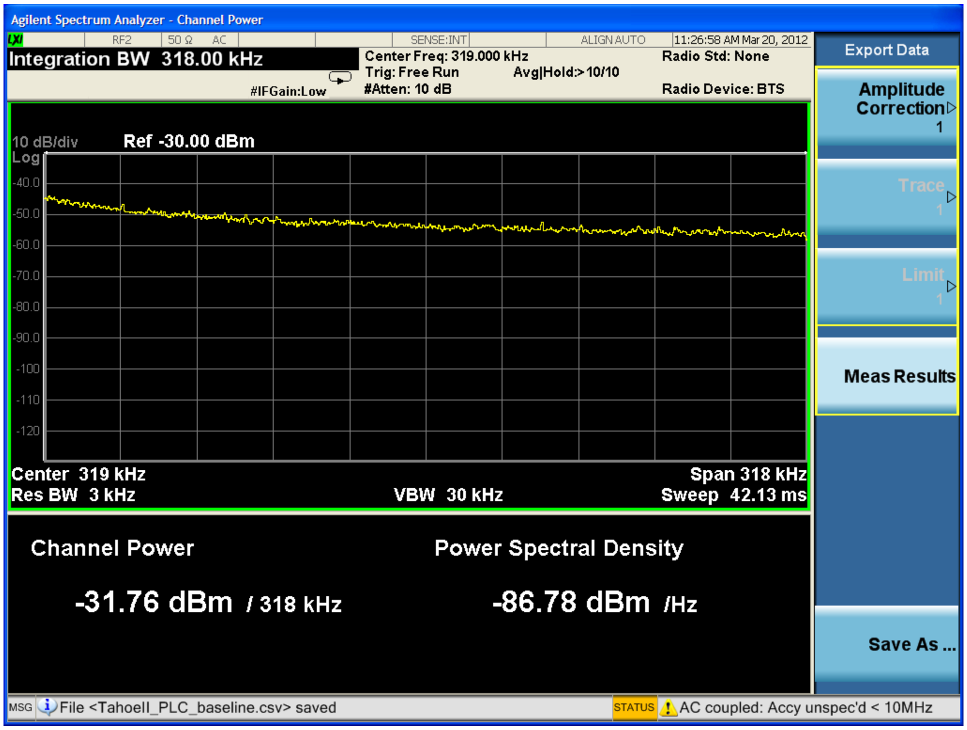

Figure 7-52
Tahoe2++ DC Noise Test - PLC only Baseline

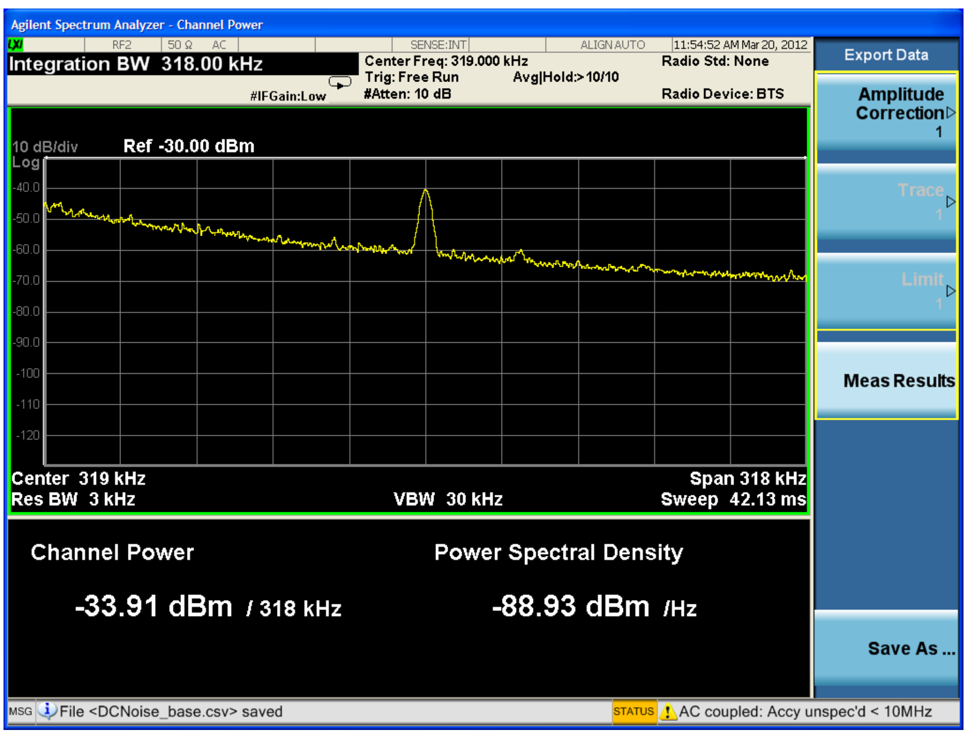

Figure 7-53
Tahoe2++ DC Noise Test - Noise Only

White Noise Interference Tests

White noise was injected on the pilot wire and raised in level until PLC communications ceased.

Results

HomePlug GreenPHY - with White Noise Interference

- PL16 on pilot 1Vpp levels
- White noise level raised to point of throughput impairment
- Noise only -81.5 dBm/Hz.
- PLC only PLC only -71.8 dBm/Hz.

  Signal to Noise Ratio: 9.7dB

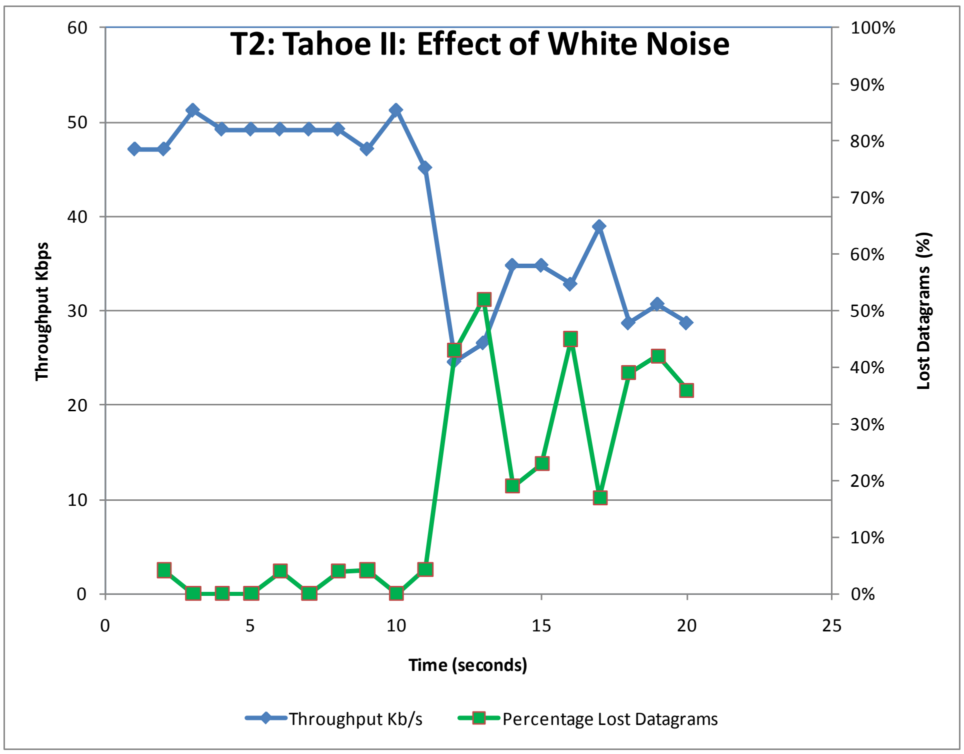

Figure 7-54
G3 Throughput with White Noise Starting at T=12 Seconds

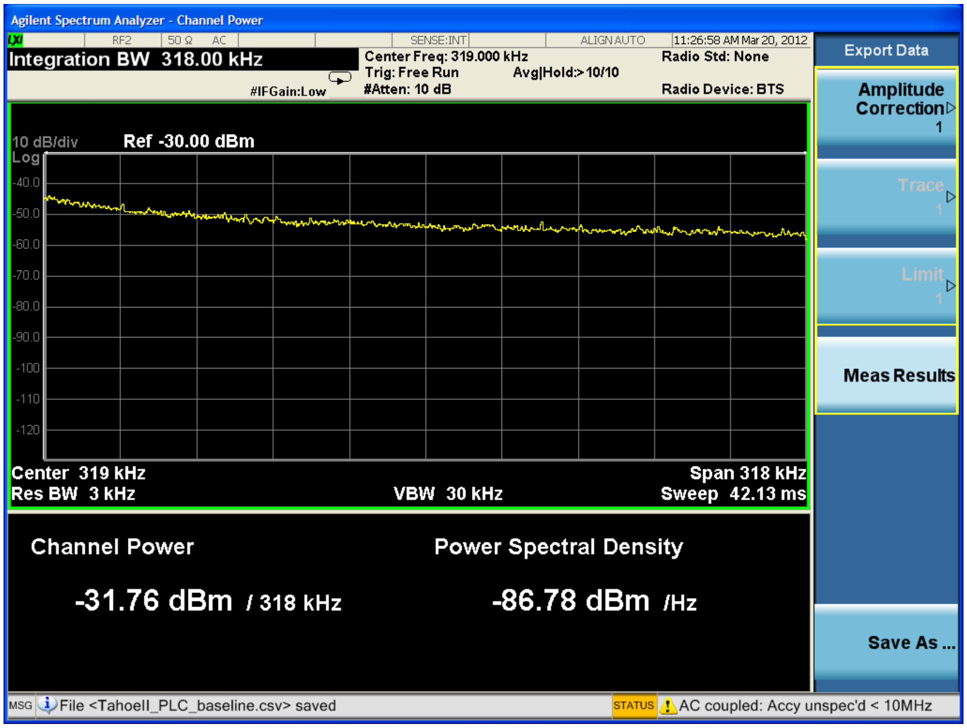

Figure 7-55
Tahoe2++ White Noise Test - PLC Only

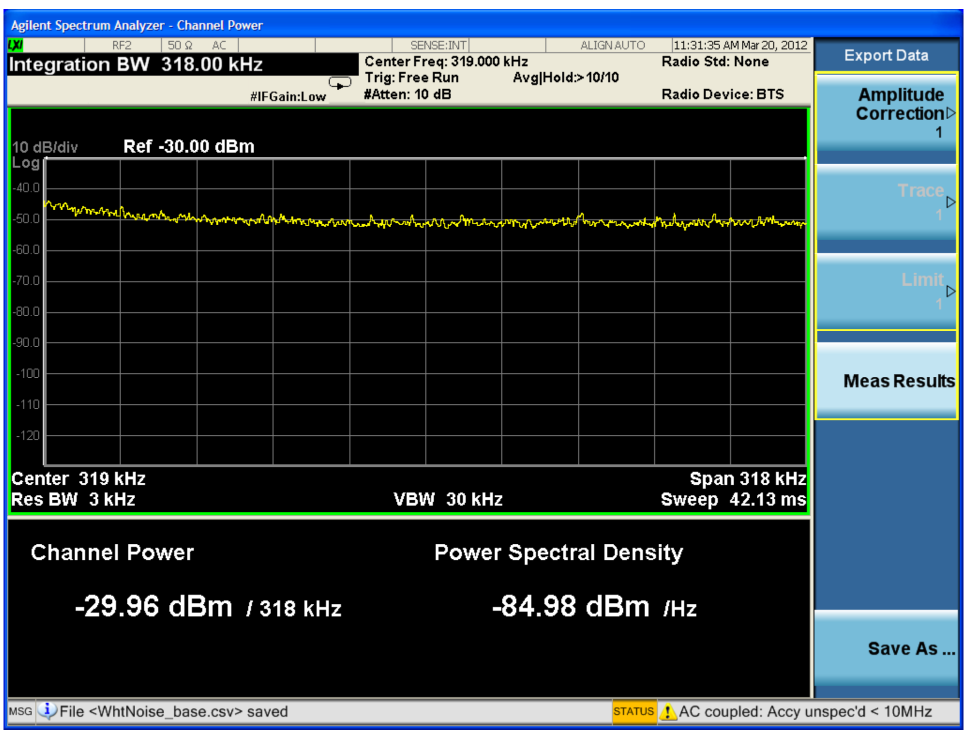

Figure 7-56
Tahoe2++ White Noise Test - White Noise Only

G3 - with White Noise Interference

- Signal PSD -86.78dBm/Hz
- Noise PSD -84.98dBm/Hz,

  Signal To Noise Ratio 1.75dB.

Performance Tests

This test verified that the systems could meet the requirement RD.Perf.1. It determined the time to establish communications, which was required to be less than 10 seconds.

Devices tested:

- QCA PL-16 (HPGP 1V on pilot),
- Netgear XAV2001 (HPGP 18V on pilot),
- Maxim Tahoe2++ (G3)

Results

Charge Initiation for HPGP on Pilot

Time to establish connection with PL-16 powered up	3 S
Time to establish connection with PL-16 powered off	29 S
Time to establish connection with Netgear powered off	8 S

Charge Initiation G3 on Pilot

Time to establish connection with Tahoe2++ powered up	10 S
Time to establish connection with Tahoe2++ powered off	74 S

The requirements do not specify whether the time is measured starting with the modems powered on, powered off, or in a sleep state. Both HomePlug GreenPHY and G3 failed to meet the SAE requirement time limit for the power-off initial condition when testing the development hardware platforms.

8
RESULTS SUMMARY AND FUTURE RESEARCH

Test Results Summary

Test	HPGP Result	HPGP Notes	G3 result	G3 Notes
Pilot Signal Impairment Tests	Pass	No changes in voltage, duty cycle, or square wave rise/fall time sufficient to impair EVSE/EV system operation were noted.	Pass	No changes in voltage, duty cycle, or square wave rise/fall time sufficient to impair EVSE/EV system operation were noted.
Shared Network Tests	Pass	While DC Messages are sharing the link with utility data at 100Kbps (TCP or UDP), DC latency is typically 6mS and does not exceed 15mS. This is below the upper limit of 25mS. At 100Kbps, utility message have 0% packet loss. This meets the SAE requirement.	Fail	Round Trip latency for DC Messages was 50mS to 250mS, which exceeds the upper limit of 25mS. Utility message throughput is 15-30Kbps, below the lower limit of 100Kbps. The performance is below the limits, regardless of whether the link is supporting one at a time, or if they are shared simultaneously. This does not meet the SAE requirement.
Distance Tests	Pass	All tests were conducted using 25 foot cordset on the EVSE's. Given the link margins and interference rejection demonstrated in other tests, there is no reason to doubt that communications are possible over distances larger than any practical cordset length.	Pass	All tests were conducted using 25 foot cordset on the EVSE's. Given the link margins and interference rejection demonstrated in other tests, there is no reason to doubt that communications are possible over distances larger than any practical cordset length.
Association Tests	Pass	16 combinations were tested - all passed	N/A	G3 does not support Association
Throughput Tests	Pass	A consistent throughput of 4Mbps was measured. This meets the SAE requirement.	Fail	Results varied depending on parameters, and UDP vs. TCP, but measured results were always below the lower SAE utility data rate limit of 100Kbps. This does not meet the SAE requirement.
Latency Tests	Pass	Passes with an average latency under 10ms. No explanation was available for the increase in ping latency for packet over approximately 900 bytes. This meets the SAE requirement.	Fail	Average latency over 100mS. It exceeds the 25mS limit for any packet size tested. This does not meet the SAE requirement.

Test	HPGP Result	HPGP Notes	G3 result	G3 Notes
Crosstalk Tests	Pass	There was no coupling of HPGP in the twisted cordset test. This indicates there is not a substantial coupling between twisted cordsets. For internal crosstalk, although coupling exists, there was coexistence. There was no degradation of throughput to the point where other test limits (latency and throughput) were not met	Fail	A usable connection could be established using only the crosstalk between two twisted cordsets, although performance was reduced compared to a direct connection over a single cordset. This indicated that there was substantial coupling between twisted cordsets. For internal crosstalk, it was not possible to maintain two simultaneous TCP flows or a TCP flow with Pings between a coupled G3 system on the pilot and the mains. Significant coupling existed, and the systems were not able to operate within test limits in the coupled case.
Self Coexistence	Pass	HPGP can share the wire with other networks of the same type, while continuing to meet throughput and latency requirements.	N/A	Since the standard does not meet throughput and latency requirements when operating alone, it still cannot meet them when sharing bandwidth.
Consumer PLC Susceptibility	Pass	This verifies that the EV network does not adversely affect a consumer (HomePlug AV) network. The test plan called for 10Mbps TCP over HomePlug AV (representing a video stream on the HPAV network) to operate concurrently with a 100 Kbps TCP stream on the HomePlug GreenPHY network (representing the EV to utility communication). Both networks operated within allowed limits. The HPAV throughput was not significantly affected by 100Kbps TCP over HPGP	N/A	There is no consumer version of G3 PLC
Coexistence with Consumer PLC (HomePlug AV)	Pass	This test verifies that a consumer PLC network (HomePlug AV) does not adversely affect the EV communication. Throughput and latency requirements for the EV were met during concurrent HPAV network operation	N/A	There is no consumer version of G3 PLC

Test	HPGP Result	HPGP Notes	G3 result	G3 Notes
HomePlug GreenPHY Coexistence with Consumer PLC (HD-PLC)	Pass	Although HD-PLC has not been adopted in the market, some prototypes were obtained for testing. The HD-PLC prototypes did not cause appreciable degradation of throughput or latency of HPGP.	N/A	HD-PLC coexistence applies only to HomePlug
G3 Coexistence Test Using Tahoe2++ and TI Concerto	N/A	G3 Coexistence test applies only to G3	Fail	Since the standard does not meet throughput and latency requirements when operating alone, it still cannot meet them when sharing bandwidth. However, testing of coexistence resulted in significant, additional degradation of performance.
Coupled Cordset Interference Tests	N/A	Pass/Fail criteria were not available. The signal generator was unable to generate sufficient amplitude of induced noise in the twisted cordset to cause any measured impairment of performance on the pilot of the target cordset.	N/A	Pass/Fail criteria were not available. Wideband FM Noise was increased to the point where to following performance drop was seen. At this point G3-PLC Power Spectral Density is -48.68dBm/Hz, and the noise PSD is -30.1dBm/Hz, giving a SNR of -18.58dB
DC Charger Noise Interference Tests	N/A	Pass/Fail criteria were not defined. Running DC noise at 2.1Vpp through AR RF power amplifier, induced into mains with current transformer. Level was increased to point where throughput was reduced to around 1mbps. The measured Signal to Noise Ratio was -21dB. (larger values below zero are better) (Noise only -89.70dBm/Hz. PLC only -110.7dBm/Hz)	N/A	Pass/Fail criteria were not defined. DC noise was passed through a radio frequency power amplifier and induced into the mains with a current transformer. At the point where a 95% packet loss was measured, the Signal to Noise Ratio was 0.53dB. (Noise Only -85.30dBm/Hz. PLC Only 84.77dBm/Hz)

Test	HPGP Result	HPGP Notes	G3 result	G3 Notes
White Noise Interference Tests	N/A	Pass/Fail criteria were not defined. At the point where the noise level caused throughput impairment, the measured Signal to Noise Ratio was -9.7dB. (Noise only -81.5 dBm/Hz. PLC only PLC only -71.8 dBm/Hz)	N/A	Pass/Fail criteria were not defined. At the point where the noise level caused throughput impairment, the measured Signal to Noise Ratio was 1.75dB. (Noise only-84.98dBm/Hz. PLC only PLC only --86.78dBm/Hz)
Performance Tests (initialization)	Fail	Using development boards, the time to boot and establish a link from power-on was 29 seconds, exceeding the 10 second limit. However, the time to boot and establish a link from power-on was 8 seconds for a commercial product (Netgear), so the development board support processor is the issue.	Fail	Using development boards, the time to boot and establish a link from power-on was 74 seconds, exceeding the 10 second limit. There are no "commercial products" for G3 currently available.

Future Research

In working with the electric transportation utility members, the need was expressed for a white paper that describes and documents the possible communications paths based on these newly developed SAE standards. This effort is currently under way and will provide an overview from the utility to the PEV for communications paths, protocols and implications of different means of establishing the utility to PEV/consumer link.

The white paper will include:

- Details of the interface from the PEV to the EVSE
  - Describe the features provided by the SAE interface.
  - Describe different types of charging and how they relate to and impact the communications interface.
- An update of current proposed SAE communications requirements
  - SAE continues to refine and rework the communications requirements based on recent progress on the standards. The white paper will provide an update on their current status.
- A top down description of smart charging communications
  - Provide an overview of the various means that utility information can be transmitted to PEVs
  - Identify pros and cons of the various implementation paths

- DC charger control and its relationship to the SEP 2.0 stack
  - Describe the relationship of the SEP 2.0 communications stack to the stack proposed for DC charging.
  - Provide a narrative on the possibility of integrated utility communications and DC charger control on a common stack. Identify potential hurdles to this integration.
- Descriptive scenarios for various smart charging applications
  - Discuss real world applications of smart charging giving consideration to the key elements of control and function
  - Identify where information resides, points of control, and the actors and their roles in various smart charging scenarios

9
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A

APPENDIX – PLC SHARED NETWORK TESTS

Shared Network test Setups

The shared network tests provided verification of the ability of a single communications link to support multiple applications (Utility and DC messages) simultaneously. It also provided data on coexistence. The test sequence developed provided both types of tests, in various combinations.

More challenging tests, above and beyond the test plan requirements, were run to increase understanding of the technology.

Note that the QoS capabilities used for Shared Network Tests were only available on HomePlug GreenPHY at the time of testing. The G3 standard and development platforms that were tested did not provide a QoS mechanism.

Originally, the Shared Network Test was implemented with DSCP tagging as shown in Figure A-1 - Shared Network Test Setup using DSCP because the HPGP control software only provided access to the QoS Classifier using this mechanism. The support of DSCP tagging in Windows proved to be incomplete, problematic, and varied between different versions of Windows.

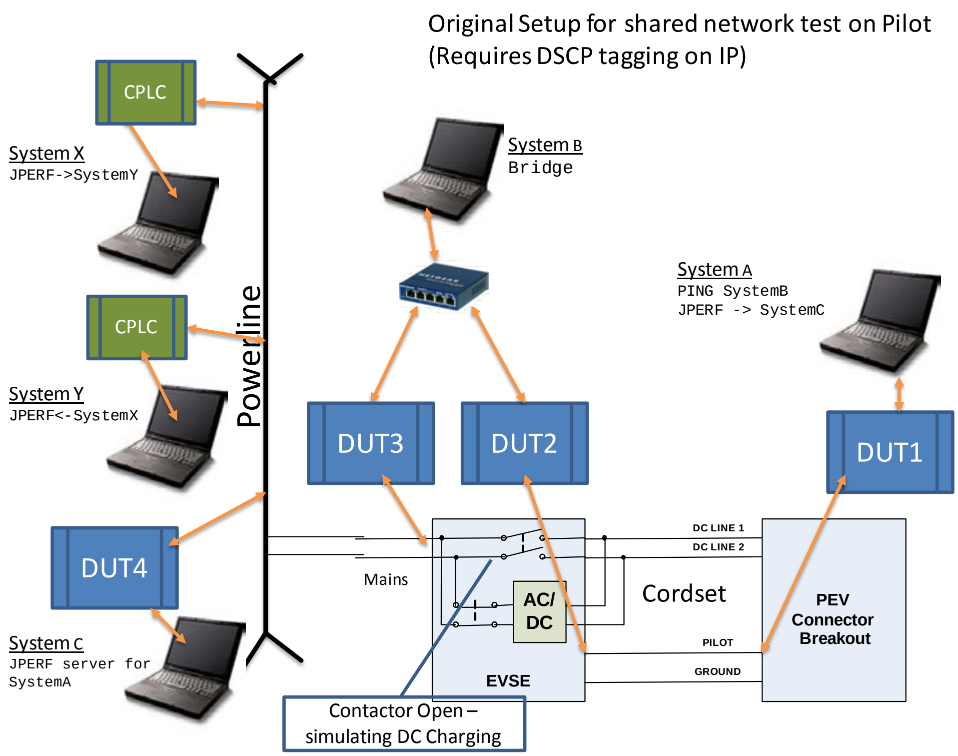

Figure A-1
Shared Network Test Setup using DSCP

After the test plan was created, new configuration files were developed that enabled QoS priorities to be set based on IP addresses. These were supported by the following setup. The setups in Figure A-2 and Figure A-3 were used with the IP-based QoS classifiers for the Shared Network Test. For the pilot test, two distinct logical networks were used for the pilot link between PEV to EVSE (supporting both DC and Utility messages) and the link from EVSE to HAN device (supporting only utility messages). The HPAV consumer network also shared the mains side of the EVSE.

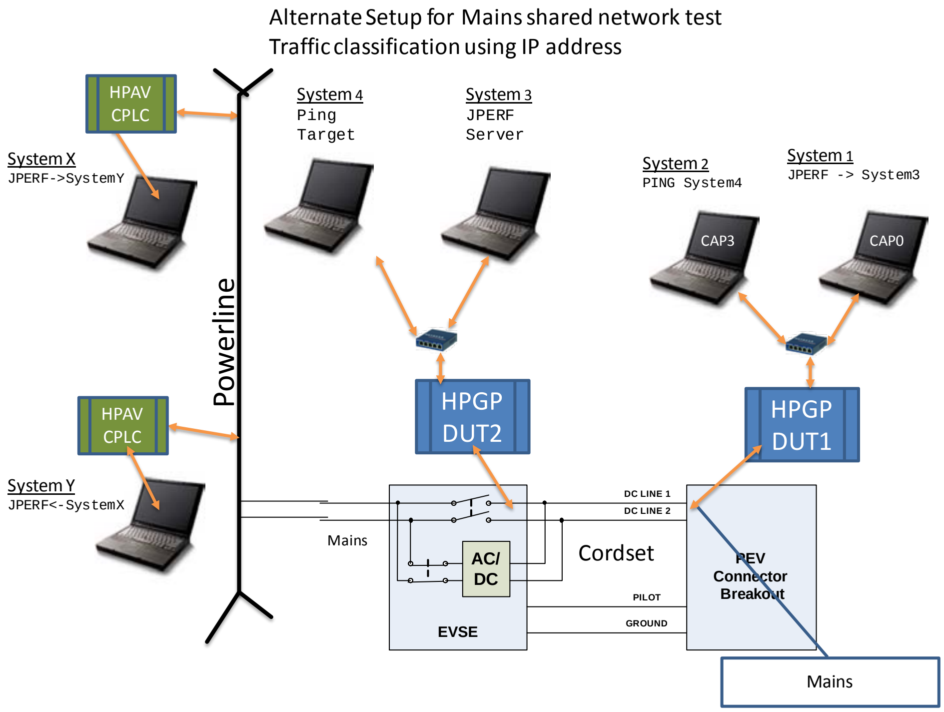

Figure A-2
Shared Network Test Setup using IP Addresses for QoS Priority (Mains)

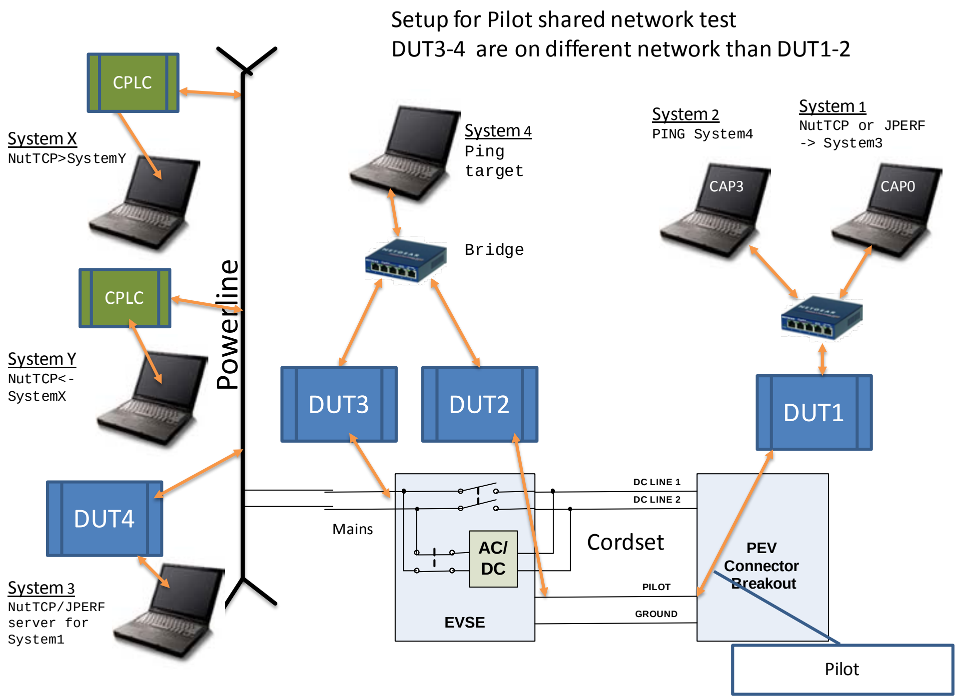

Figure A-3
Shared Network test setup using IP Addresses for QoS Priority (Pilot)

Shared network Test Results

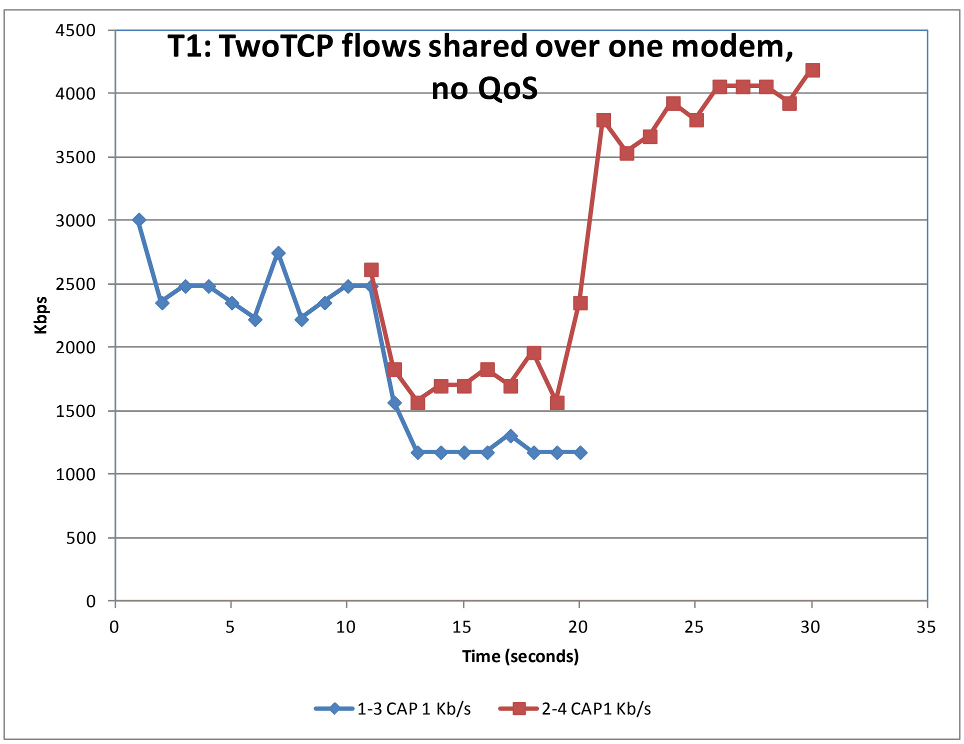

Figure A-4
Test 1: Two TCP flows shared over one modem, no QoS

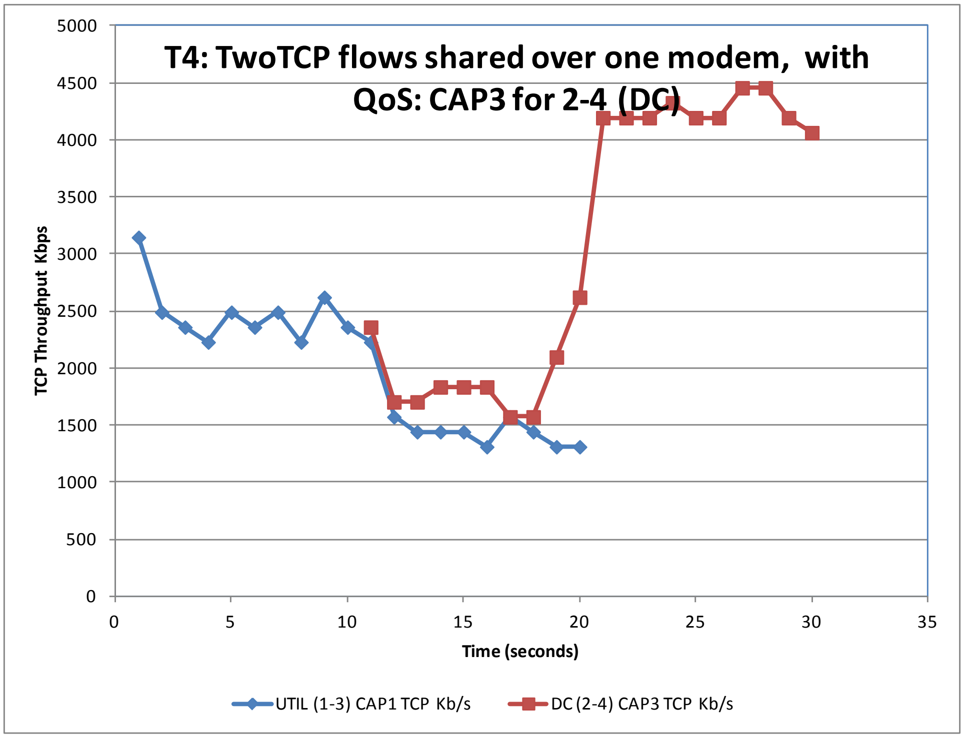

Figure A-5
Test 4: Two TCP flows shared over one modem, with Q0S: CAP3 for 2-4 (DC)

T1 and T4 show the QoS differentiation with two full rate TCP flows sharing a single modem. The results did not show a significant difference. In fact, the higher priority flow had lower throughput relative to the normal priority flow in T4 when QoS was enabled.

This effect was due to the PL-16 not implementing internal packet prioritization in its buffers. QoS was still achieved for on-wire contention prioritization with other modems, which is shown below.

The following two figures present results from an earlier version of the HomePlug GreenPHY development hardware where the modem implemented internal queue prioritization as well as on-wire contention prioritization.

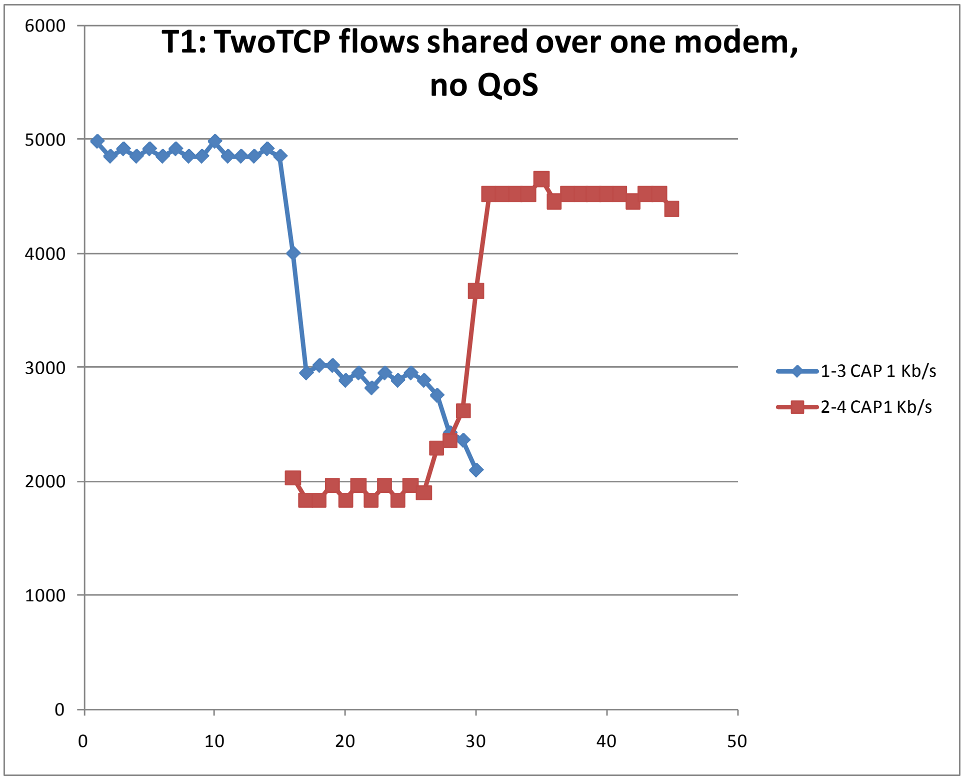

Figure A-6
Early Version of Test 1: Two TCP Flows Shared Over One Modem, No QoS

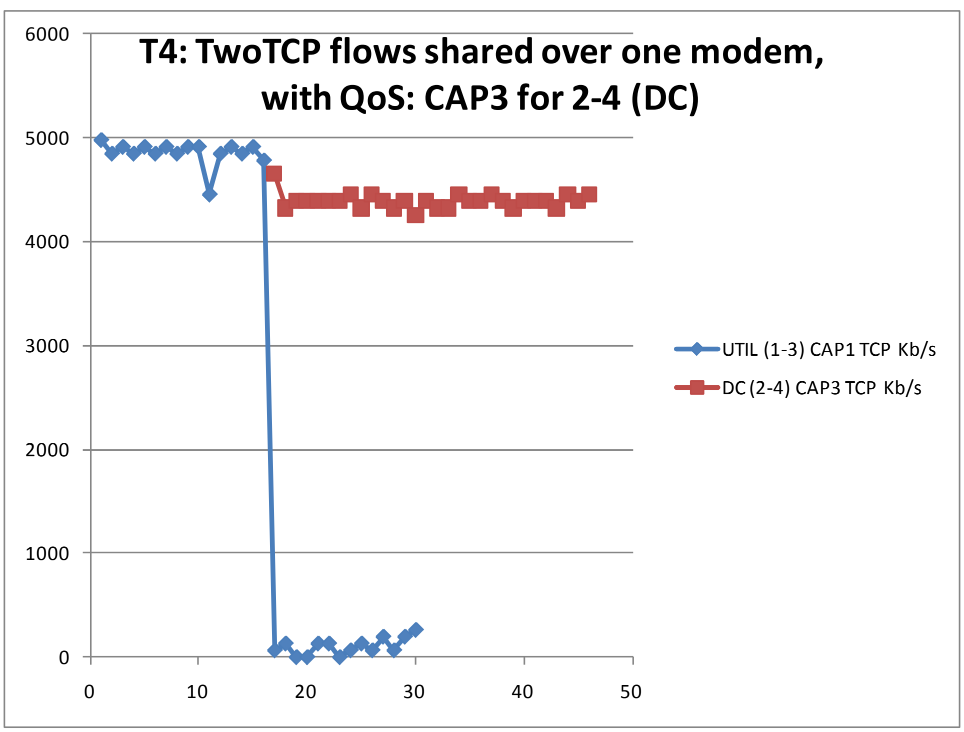

Figure A-7
Early Version of Test 4: Two TCP flows shared over one modem, with Q0S: CAP3 for 2-4 (DC)

Note the large change in the non-prioritized flow and minimal change in prioritized flow when two streams contend with QoS enabled.

T2 (No QoS) and T5 (with QoS) show the effect of a full rate TCP flow on the latency of a small-packet Ping flow sharing the same modem, with and without QoS (see Figure A-8 and A-9). Again, the lack of priority buffering in the PL-16 resulted in increass in latency when the ping packets were queued behind TCP packets, rather than being moved to the front of the transmit queue due to their QoS priority. Since the two flows were sharing the same modem, the on-wire QoS has no effect.

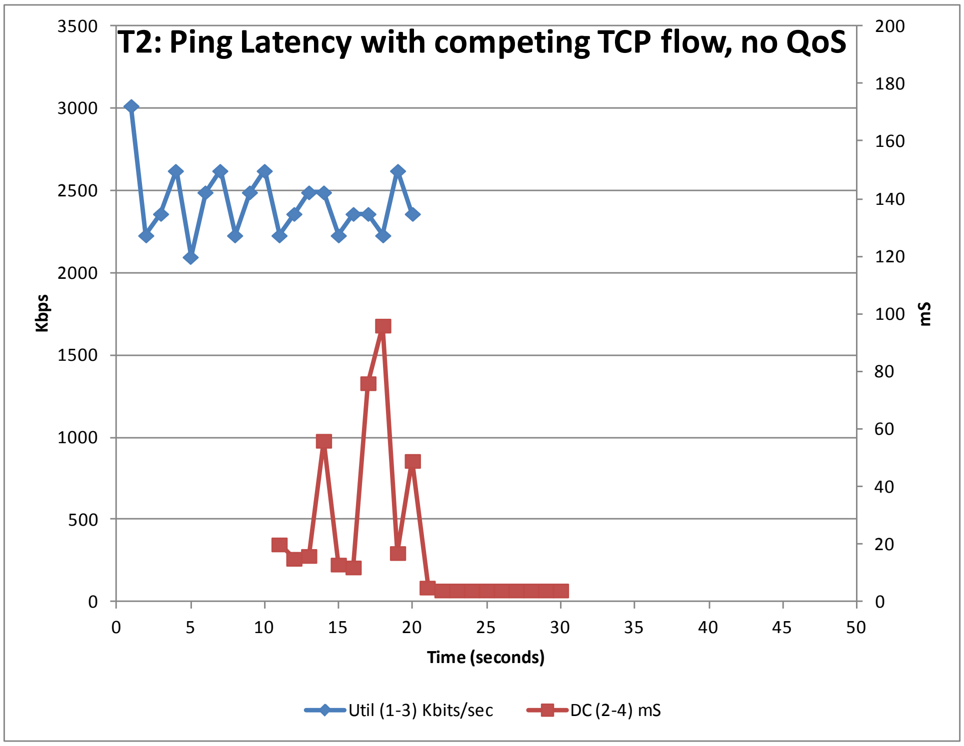

Figure A-8
Test 2: Ping Latency with Competing TCP Flow, No QoS

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