Introduction

Power line communication (PLC) is a communication technology that sends data over existing power cables. This technology can send both power and data between PLC nodes in a half-duplex manner. Combining power and data over the same lines allows PLC technology to eliminate the need for additional wires to interconnect devices. PLC offers a cost-effective communication media for a wide range of applications in environments that otherwise might be too expensive to network. As a communications technology, PLC can be divided into two categories:

- Broadband PLC is appropriate for high-speed broadband network connections such as to the Internet. It generally operates at higher frequencies (1.8–250 MHz), high data rates (up to 100s of Mbps) and is used in shorter-range applications.

- Narrowband PLC is useful for applications requiring narrowband control or low-bandwidth data collection where low cost and high reliability are essential. It generally operates at lower frequencies (3–500 kHz), lower data rates (up to 100s of kbps), and has longer range (up to several kilometers), which can be extended using repeaters.

Depending upon the underlying power line characteristic, PLC can be further classified as PLC over AC power lines and PLC over DC power lines.

Many utilities around the world have chosen narrowband PLC over AC lines for their smart grid projects. By monitoring electricity usage based on time of day and even by device or application, utility companies can provide pricing structures that give consumers incentives to adjust their energy consumption, thus reducing peak-load and avoiding the need to construct new power plants.

The popularity of PLC adoption in smart grid applications has led to significant focus on PLC over
AC power lines. However, narrowband PLC over DC lines is also gaining ground in home networking, lighting and solar applications as well as in transportation vehicles (electronic controls in airplanes, automobiles and trains). The use of PLC in these applications reduces wiring complexity, weight, and ultimately cost of communications.

In this article we focus on the use of PLC over DC power lines and present a reference design that can help customers adopt PLC over DC power lines quickly and effectively.

One common question asked by system integrators is how to compare PLC over DC versus low-power wireless technology. While both PLC over DC and low-power wireless do not require new wire installation, with PLC, the connection is maintained even underground, through walls, and around corners. The communication channel is owned by the operator or utility, so the risks of sharing bandwidth are eliminated. PLC has no line-of-sight limitation and is not affected by weather.

**Flexibility in DC PLC solutions**

Developing an effective PLC solution has its challenges. Typically power lines are noisy and require a robust system architecture to ensure data reliability. Each end application and operating environment is different, thereby requiring a flexible design able to accommodate a wide variety of conditions. System designers need a flexible platform that enables them to optimize designs to the particular requirements of each application, and allows designs to adapt to new standards and market opportunities as they arise. In this way, intellectual property can be reused across multiple applications to accelerate development and speed time-to-market while expanding market opportunities.

A key part to achieving flexibility is a modular architecture in terms of hardware and software. Breaking down complex PLC systems into a number of independent subsystems allows developers to change one aspect of a design (such as the modulation scheme or network protocol used) without having to completely redesign the entire system. Some examples of the various possibilities include:

- **Modulation scheme**: Flexibility at the hardware and software levels enables developers to implement the most efficient modulation scheme for a particular application. For example, several modulation schemes are available for narrowband communications, including spread-frequency shift key (S-FSK) and orthogonal frequency-division multiplexing (OFDM) modulation.

- **Communication protocols**: For purposes of interoperability, devices may need to be compliant to a particular protocol standard. By utilizing a flexible platform, developers easily can implement
popular PLC standards - including S-FSK (IEC61334), PRIME and G3 or implement a custom protocol that meets their application’s specific requirements.

For narrowband DC PLC applications there is little in the way of existing standards, and in many applications the network is self-contained. In these circumstances, a simpler communication protocol stack can be used. An example of this kind of simpler, proprietary protocol stack is TI’s PLC-Lite (Figure 1). This stack is particularly suitable for cost-sensitive environments and applications where the complexities of G3 and PRIME are not required, while still requiring a robust communications channel.

PLC-Lite is the perfect solution for a simple light bulb or wall switch within a building network where only a few kilobits per second is required. PLC-Lite offers a maximum data rate of 21 Kbps and supports both full-band and half-band modes. It was been designed to provide added robustness to certain types of interference, including narrowband interference that can affect G3 links. PLC-Lite contains a simple carrier sense multiple access and collision avoidance (CSMA/CA) media access control (MAC) layer, which can integrate with any application-specific stack.

Because of the simplicity and lower data rate, PLC-Lite can be implemented at a substantially lower cost per link. It also offers tremendous flexibility and allows developers to customize channel links outside the constraints of an industry standard. A complete set of features are summarized in Figure 2.

**Figure 1. Comparison of PLC communication protocols**

<table>
<thead>
<tr>
<th>Standard</th>
<th>Technology</th>
<th>Band Occupied</th>
<th>Data Rate Range</th>
<th>Target TI Processor</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1</td>
<td>SFSK</td>
<td>60–76 kHz</td>
<td>1.2–2.4 kbps</td>
<td>F28027</td>
</tr>
<tr>
<td>PRIME</td>
<td>OFDM</td>
<td>42–90 kHz</td>
<td>21–120 kbps</td>
<td>F28069</td>
</tr>
<tr>
<td>ERDF G3</td>
<td>OFDM</td>
<td>35–90 kHz</td>
<td>5.6–45 kbps (6–72 kbps)*</td>
<td>F28069</td>
</tr>
<tr>
<td>P1901.2/ G3 FCC</td>
<td>OFDM</td>
<td>35–450 kHz</td>
<td>34–234 Kbps (37–590 kbps)*</td>
<td>F28M35x</td>
</tr>
<tr>
<td>PLC-Lite (TI Proprietary)</td>
<td>OFDM</td>
<td>42–90 kHz</td>
<td>2.4–21 kbps</td>
<td>F28036/ F28027</td>
</tr>
</tbody>
</table>

*Without overhead.
Interfacing to the power lines in a system present another set of design challenges that needs to be addressed for a DC PLC implementation. Some specific problem areas include:

- impedance control for multiple nodes support;
- filtering of PLC from any switching power supply; and
- power line coupling protection circuitry for reliable AC-coupling

**Multiple nodes support**

To be effective, most DC PLC implementations want to support a large number (10s -100s) of nodes connected through a single power line bus. In order for the transmissions to reach all nodes without significant attenuation, the key requirement is a familiar one:

\[
\text{Source Impedance} \ll \text{Load Impedance} \quad \text{(Equation 1)}
\]

We can illustrate how this is achieved in a reference design. For the following analysis, assume that the PLC-Lite modulation frequency is approximately 40 KHz. The source impedance of a PLC node is then calculated (Equation 2).
\[ \frac{1}{2\pi f_c} = \frac{1}{2\pi(40000)(0.000022)} = 0.18 \Omega \]

(Equation 2)

where

\[ c = C_6 = 22 \, \mu F \] (Figure 3)

Assume that the load impedance of a given receiver node as seen by the transmitter node is approximately 30 Ohm. As multiple nodes are added, this load impedance is reduced as the loads are seen as a parallel combination of impedances. For example, if there are nine nodes on the system, then the total load impedance, as seen by one transmitter node, is calculated as shown in Equation 2.

For example take two cases. In one there is one transmitter (master) node and four receiver (slave) nodes. In the other there is one master node and nine slave nodes. The requirement for the source impedance as calculated in Equation 2 changes based on the number of slave nodes.

- 9 (receivers) + 1 (transmitter) = 10 PLC nodes, load impedance = 30/10 = 3 Ohms
4 (receivers) + 1 (transmitter) = 5 PLC nodes, load impedance = 30/5 = 6 Ohms

Figure 4. Test result with 1 transmitter, no receivers

Figure 5. Test result with 1 transmitter, 4 receivers
As seen in Figures 4 – 5, there is an insignificant change in amplitude of the modulation signal as more slaves are added. In the previous setup, the DC line is probed (AC coupled) to the oscilloscope. The oscilloscope is triggered when an external switch on the PLC node is pressed, which then generates a PLC communication burst.

**PLC filtering from any switching power supply**

Another challenge in the DC PLC design is that a PLC node has to use the DC supply to generate the local voltages (15V, 3.3V) as well as modulate the same DC supply. In such a scenario the DC/DC switching power supply interferes with the PLC modulation, if appropriate filtering is not incorporated.

![Figure 6. Power supply filtering circuitry](image)

As shown in Figure 6, a low-pass filter separates the PLC modulation signal from the switching regulator. The Fc of the low-pass filter is calculated based on the band occupied by the PLC modulation. As PLC Lite occupies 42 to 90 kHz, the Fc as per the low-pass filter comprises L = 360 µH (180 µH + 180 µH) and C of 1 µF.

\[
F_c = \frac{1}{\pi \times \sqrt{LC}} = \text{approximately } 17 \text{ kHz}
\]

**Equation 3  Power line coupling protection circuitry for reliable AC-coupling**

**Power line coupling protection circuitry for reliable AC-coupling**

A PLC analog front-end (AFE) can get subjected to surges on the DC power supply. Thus, it is important to design the AC-coupling stage such that the PLC node can function reliably in a harsh environment.
Figure 7. First stage AC-coupling
To ensure overall system reliability, the DC line is not directly AC-coupled to the AFE device. The line goes through a two-step AC-coupling process (Figures 7 - 8). In the first stage, the DC line is AC-coupled to an intermediary stage that has a TVS protection and, therefore, arrests voltage surges to 9.2 V for a peak surge current of 43.5 A. In this stage the common-mode is biased to the GND. In the second-stage AC-coupling, the data is AC-coupled to the AFE device with a DC bias of 7.5 V.

**Reference design**

The DC (24 V nominal) power-line communication (PLC) reference design is intended as an evaluation module for users to develop end-products for industrial applications leveraging the capability to deliver both power and communications over the same DC power line. The reference design provides a complete design guide for the hardware and firmware design of master and slave nodes in an extremely small (approximately 1-inch diameter) industrial form factor. The design files include schematics, bill of material, layer plots, Altium files, Gerber files, a complete software package with the application layer, and an easy-to-use graphical user interface (GUI).

The application layer addresses the slave nodes as well as the communication from the host processor such as the PC or Sitara™ ARM® MPU (Figure 9). The host processor communicates only to the master node through a USB-UART interface. The master node then communicates to the slave nodes through PLC. The easy-to-use GUI (Figure 10) is also included in the evaluation module (EVM) that runs on the host processor and provides address management as well as slave-node status monitoring and control by the user.

The reference design has been optimized from each slave node’s source-impedance perspective such that multiple slaves can be connected to the master. Protection circuitry has been added to the analog front-end (AFE) so that it can be reliably AC-coupled to the 24-V line. The reference design layout has been optimized to meet the AFE031 layout requirements for high-current traces.
Figure 9. Reference design system block diagram

Figure 10. GUI tool screenshot

Conclusion
In this article, we have reviewed how narrowband PLC over DC power lines can be an effective tool for networking in a variety of industrial applications. This approach leverages the successful use of PLC in AC power line applications in existing smart grid deployments. The wide range of operating conditions possible for PLC requires a flexible solution in both software and hardware. Interfacing to the DC power lines also requires careful design consideration to ensure the system is robust and scalable to many network nodes.

To address the design challenges and help a systems designer adopt the PLC over DC successfully in their application, Texas Instruments has released a DC PLC reference design[1] which is based on the TI analog front-end AFE031 as well as C2000 microcontroller[2]. The reference design comes with a complete set of hardware design files, firmware for the MCU, GUI-based application software as well as a very detailed documentation with lab test results. A systems designer can easily evaluate this platform as well as effectively build their end applications.

References

1. DC Power Line Communication (PLC) Reference Design, Texas Instruments
2. Download datasheets for the AFE031 and TMS320F28035