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APPLICATION NOTE 5356

Overcoming Smart Grid Communications Challenges with Orthogonal Frequency Division Multiplexing (OFDM) and IEEE 1901.2

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Abstract: While many questions still surround the creation and deployment of the smart grid, the need for a reliable communications infrastructure is indisputable. Developers of the IEEE 1901.2 standard identified difficult channel conditions characteristic of low-frequency powerline communications and implemented an orthogonal frequency division multiplexing (OFDM) architecture using advanced modulation and channel-coding techniques. This strategy helped to ensure a robust communications network for the smart grid.

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In Fall 2009, the idea for a new smart grid communications standard, IEEE P1901.2, began taking shape. The concept for IEEE P1901.2 came as the result of collaborative efforts between numerous Tier 1 semiconductor manufacturers and global energy suppliers who sought to develop a standards-backed utility communication solution that was 100% reliable in all mediums, in all countries. A bold and complex undertaking, the effort to make IEEE P1901.2 a reality continues to require deft maneuvering by all involved.

The standard's developers faced a daunting task—address both existing and newly added current requirements, as well as forward-looking requirements in the 10- to 20-year horizon. Furthermore, the standard needed to compensate for critical challenges and obstacles such as the harsh low-voltage, medium-voltage, and transformer-channel conditions that have traditionally hampered high data rate, robust, through-transformer powerline communications (PLCs). Reliable, efficient communications solutions were essential to successfully realize the smart grid.

PLC Problems

The obstacles involved in updating utility grid communications have roots that stretch back many years. Well before "smart grid," "smart meter," "eMeter," "EV" (electric vehicle), and "PEV" (plug-in electric vehicle) became familiar terms, utility companies began investigating potential solutions to one of their most fundamental operating challenges: reliably maintaining efficient communications in rugged environments.

For low-frequency (LF) PLCs, negative signal-to-noise (SNR) conditions are a recognized and expected problem in addition to varying impedance on the line; for PLCs through transformers, signal attenuation of 50dB or more is also common. Generally for PLCs, channel characteristics and parameters vary with frequency, location, time, and the type of equipment connected to it. Furthermore, the power line is a very frequency-selective channel, with channel noise, background noise, and impulsive noise often occurring at 50Hz/60Hz and group delays lasting up to several hundred microseconds.

These conditions on which LF PLC must operate can be best understood from measurements taken on the line, starting with channel noise on the low-voltage line, as illustrated in **Figure 1**.

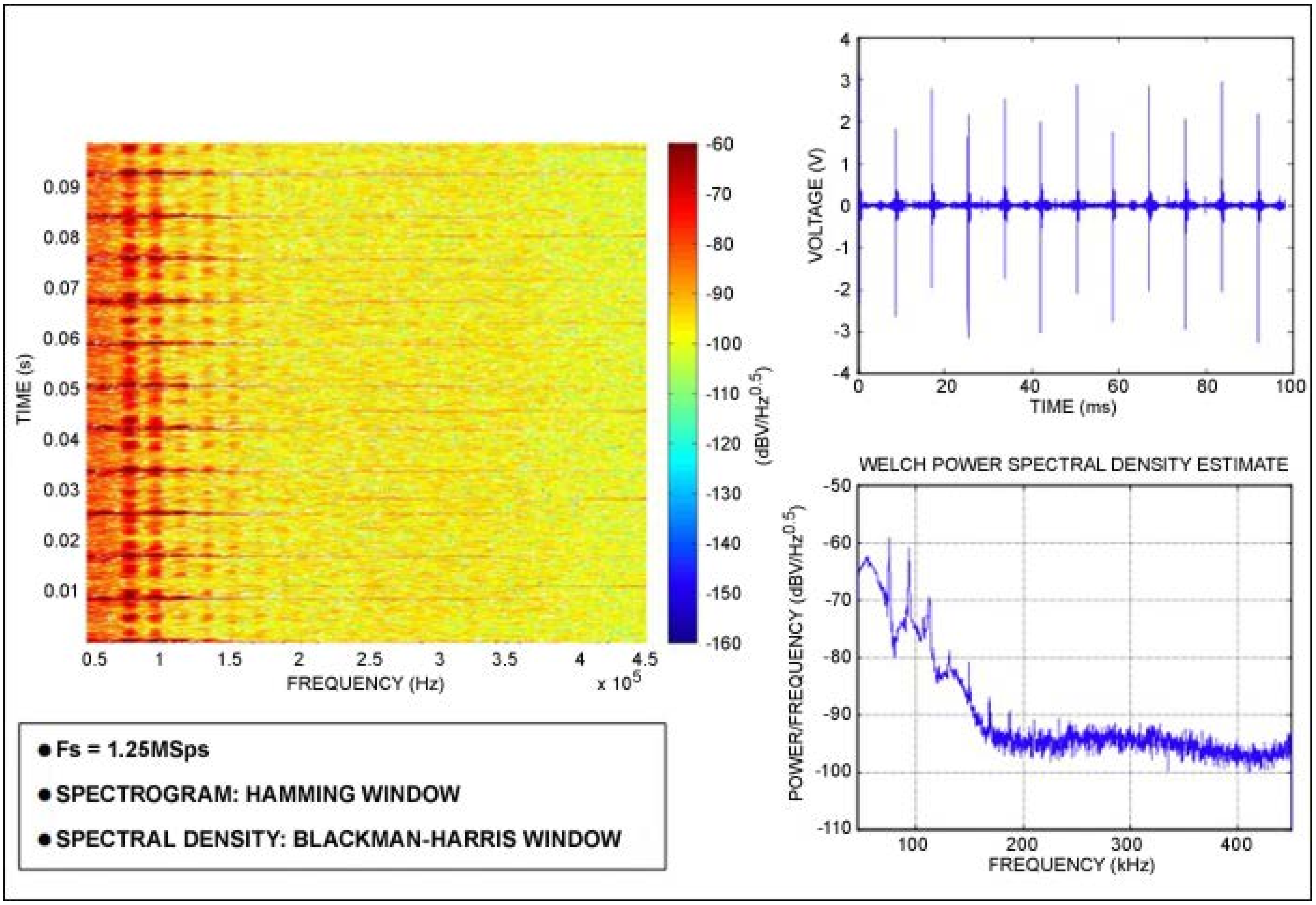

Figure 1. Channel noise on LV line. Image courtesy of Texas Instruments.

Added background noise:

$$\eta_C(f) = 10^{(K - 3.95 \times 10^{-5} f)} \qquad \text{(Eq. 1)}$$

Figure 2 shows where K has the normal distribution N(μ,σ) with μ = 5.64, σ = 0.5, and f is the frequency in Hz.

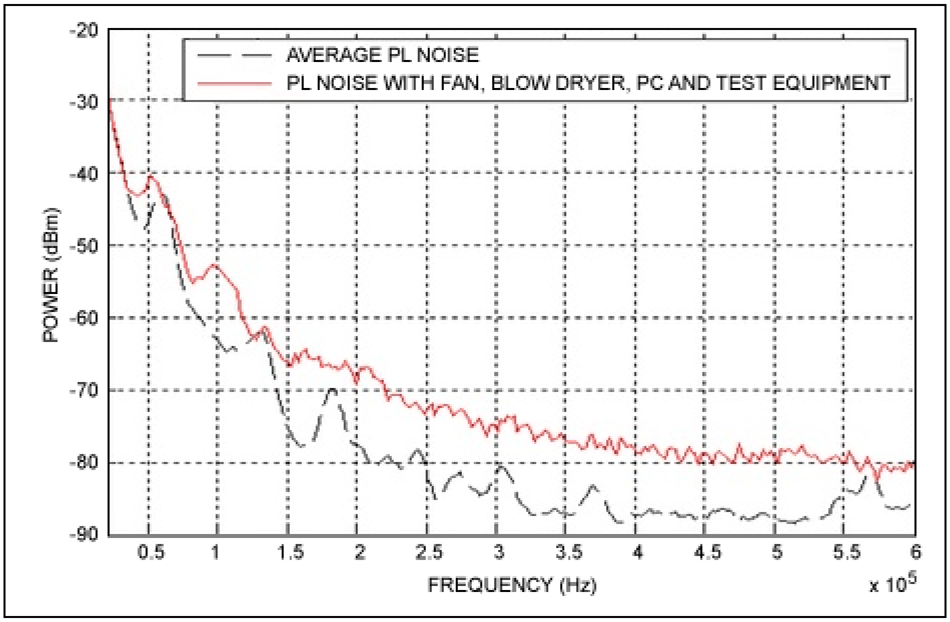

Figure 2. Background noise.

Figure 3 shows impulsive noise, where the time between two bursts is a random variable with an exponential distribution, and the duration of each burst noise is another random variable with exponential distribution.

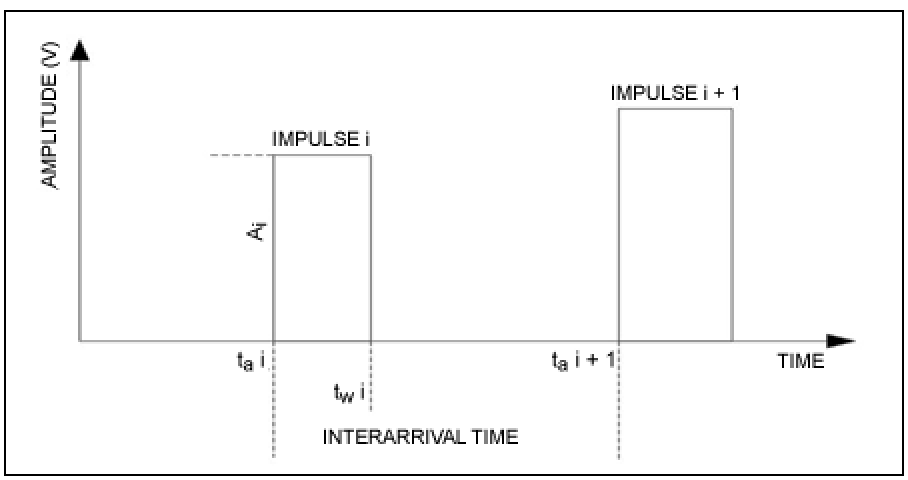

Figure 3. Impulsive noise distribution.

OFDM Offers Robust Communications

To overcome the difficult channel conditions often observed in LF power lines, IEEE 1901.2 LF PLC adopted an orthogonal frequency division multiplexing (OFDM) architecture using advanced modulation and channel-coding techniques to efficiently utilize the limited bandwidth of European Committee for Electrotechnical Standardization (CENELEC), Association of Radio Industries and Businesses (ARIB), and Federal Communications Commission (FCC) bands.

This OFDM architecture facilitates deeply robust communications over the power line channel. The allowed bandwidth is divided into a number of subchannels, which can be viewed as many independent phase-shift keying (PSK) modulated carriers with different noninterfering (orthogonal) carrier frequencies. Furthermore, convolutional and Reed-Solomon (RS) coding provide redundancy bits, allowing the receiver to recover lost bits caused by background and impulsive noise. A time-frequency interleaving scheme is then used to decrease the correlation of received noise at the input of the decoder, providing diversity.

The system performs an inverse Fast Fourier Transform (IFFT) on the complex-valued signal points that are produced by differentially encoded phase modulation, including differential binary (DBPSK), differential quadrature (DQPSK), and differential eight-ary (D8PSK), and are allocated to individual subcarriers generating the OFDM signal. An OFDM symbol is built by appending a cyclic prefix to the beginning of each block generated by IFFT. The length of cyclic prefix is chosen so that a channel group delay will not cause successive OFDM symbols or adjacent subcarriers to interfere, and a blind channel estimator technique is used for link adaptation. Based on the quality of the signal received, the receiver decides on which modulation scheme will be used. Moreover, the system differentiates the subcarriers with bad SNR and does not transmit data on them. A system block diagram is illustrated in **Figure 4**.

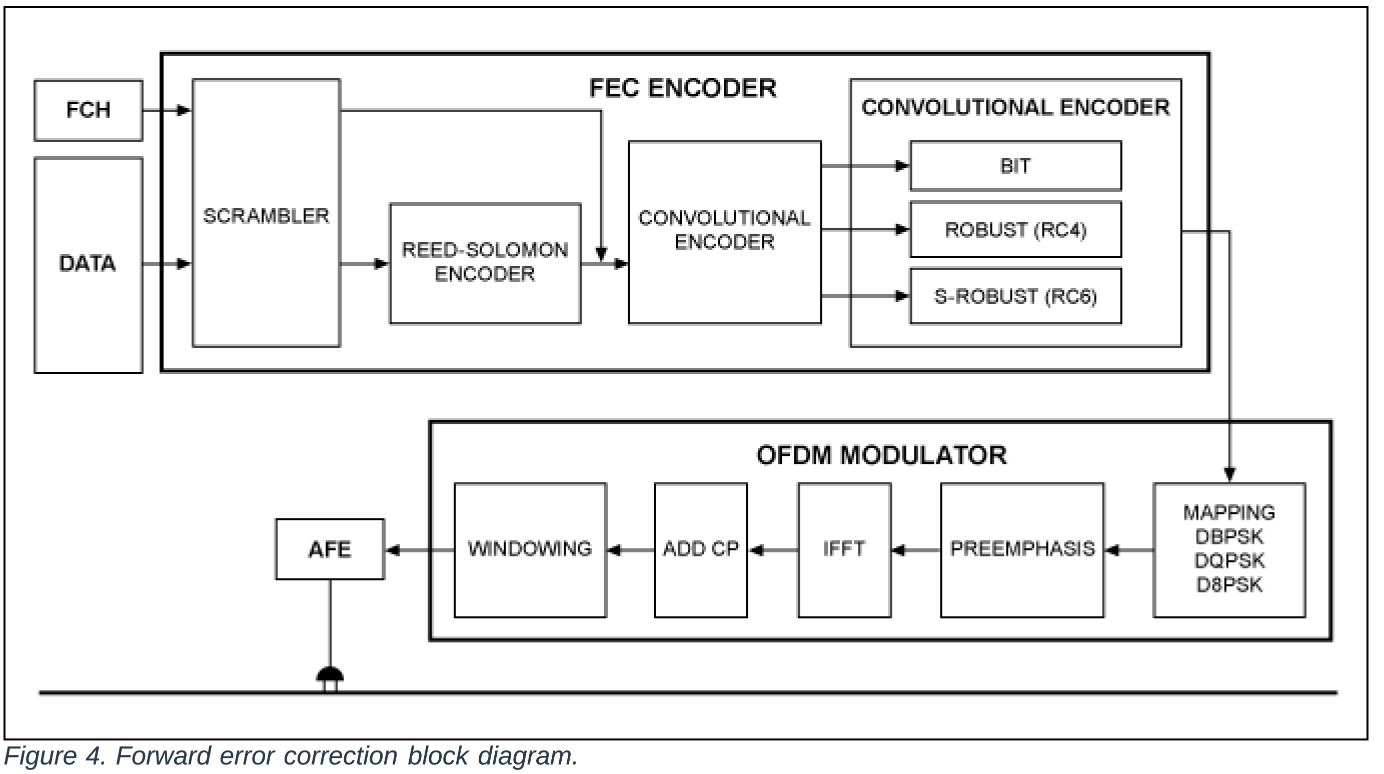

Figure 4. Forward error correction block diagram.

Each block plays an important role in combating noise in the channel. The forward error correction (FEC) encoder comprises a scramble followed by an RS encoder and a convolutional encoder. In Robust mode, an extra encoder, Repetition Code (RC), is used after the convolutional encoder to repeat the bits at the output of convolutional.

The scrambler block gives a random distribution to the data and the frame control header (FCH). The data and FCH stream is "XOR-ed" with a repeating pseudo-random noise sequence using the following generator polynomial:

$$S(x) = x^7 \quad x^4 \quad 1 \qquad \text{(Eq. 2)}$$

This is illustrated in **Figure 5**.

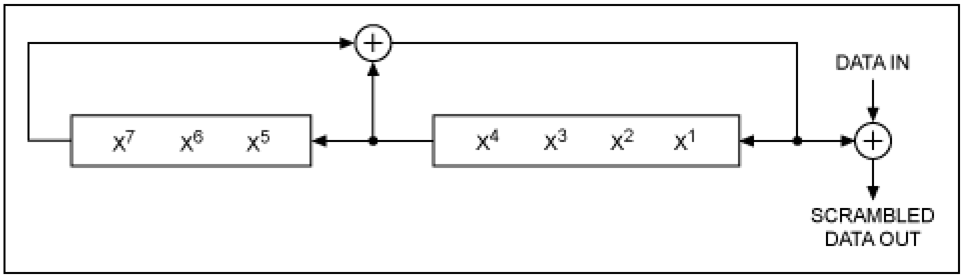

Figure 5. Data scrambler.

The bits in the scrambler are initialized to all others at the start of processing each physical frame, and the scrambler is reinitialized for FCH and data. The scrambler is not a critical part of the FEC; however, it is important to be a proven solution capable of generating a very random sequence with good autocorrelation.

Data from the scrambler is encoded by shortened systematic RS codes:

RS (N = 255, K = 239, T = 8) or RS (N = 255, K = 247, T = 4); in Robust mode, T = 4 is used

Code generator polynomial:

$$g(x) = \prod_{i=1}^{2T} (x - \alpha^i) \tag{Eq. 3}$$

Field generator polynomial: p(x) = x8 + x4 + x3 + x2 + 1

For the convolutional encoding, a rate of one-half is used with the restraint of K = 7, and with six tail bits inserted at the end of the frame to return the encoder to the state zero, as depicted in **Figure 6**.

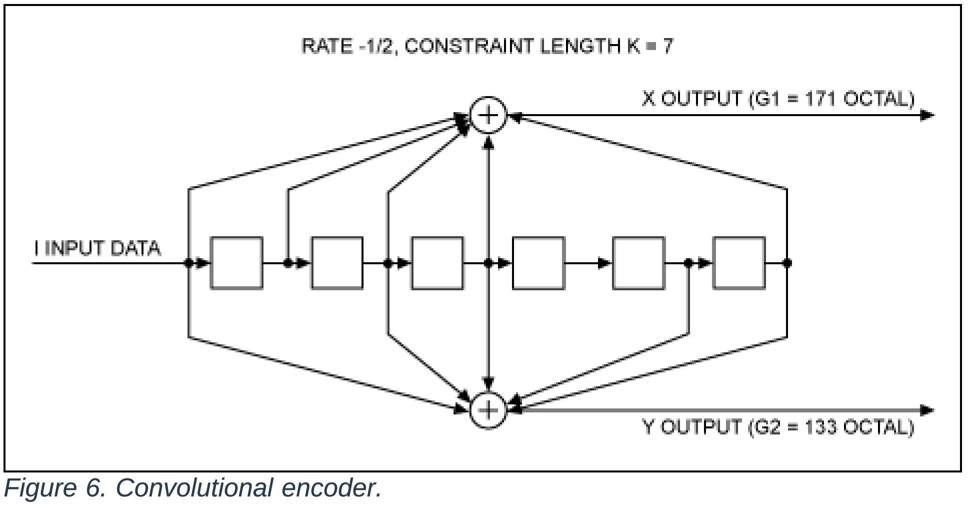

Figure 6. Convolutional encoder.

For the resulting performance graph in **Figure 7**, the decision of which solution to use was based on careful simulation and study comparing other approaches such as low-density parity-check code.

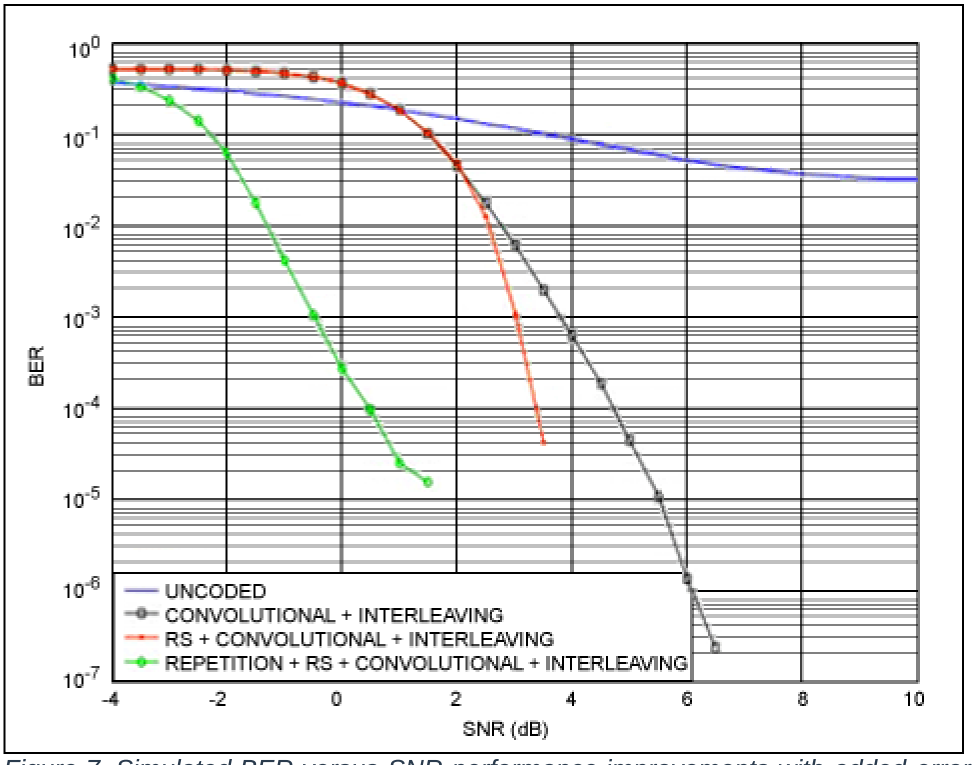

Figure 7. Simulated BER versus SNR performance improvements with added error correction.

The following parameters were used, with all results showing an advantage of concatenated code for the low block size typical in LF PLC systems:

- Block size (header and date)
- FEC encoder—concatenated (specifying coding rates of one-half, one-third, and so forth)
- Repetition rate (for example, 1, 2, 4, 8)
- Channel response (such as variable or flat)
- Target error rate (erasures, 0%, 5%, 10%, and so on)

The resulting IEEE 1901.2 solution combines multiple error-correction mechanisms to ensure reliable communication using RS decoding (which corrects errors due to impulsive noise) with Viterbi decoding (which corrects errors due to white noise), and a combination of repetition encoding and time/frequency interleaving for additional robustness to combat impulsive noise, jamming tones, and frequency fading.

IEEE 1901.2 and the Smart Grid

The world is continuing to move toward the practical implementation of a more intelligent, reliable, self-healing grid, and its benefits for industry and consumers alike are both understood and well-documented. With applications ranging from transmission and distribution to in-home automation, it holds the promise of a cleaner, safer, and more dependable energy future. However, widespread deployment has yet to become a reality, and the question of how we will finally realize the smart grid is one that is still being answered.

What is clear is that the nascent smart grid will require a robust technology framework capable of managing the diverse complexities associated with its deployment and operation. One of the most essential, mission-critical enablers of the smart grid is a reliable communications infrastructure; without this fundamental underpinning, ubiquitous implementation will remain impeded.

With power lines as one of the most pervasive elements in the legacy power grid, PLCs are an ideal, cost-effective solution for achieving the vast communications network needed to support the smart grid. In fact, PLCs already represent the most widely adopted communications medium for smart metering. However, for their continued advancement—and by association, that of the smart grid—broad adoption of flexible, forward-looking, and globally accepted communications standards such as IEEE 1902.1 is needed.

With the availability and adoption of such standards, the complex challenges facing the smart grid can be overcome. And as they are, the promise, potential, and opportunity heralded by the smart grid will well and truly be within reach.

For additional in-depth technical perspectives on the error correction mechanisms adopted in IEEE 1901.2, see: http://ieeexplore.ieee.org/xpl/freeabs_all.jsp?arnumber=5479944.

Related Parts		
MAX2990	10kHz to 490kHz OFDM-Based Power Line Communications Modem	Free Samples
MAX2991	Power-Line Communications (PLC) Integrated Analog Front-End Transceiver	Free Samples
MAX2992	G3-PLC MAC/PHY Powerline Transceiver	Free Samples
MAX2992EVKIT	Evaluation Kit for the MAX2992	

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