Optical-based Analog Front End for Low-Speed Powerline Communications In The Home

White Paper

The use of high-voltage power lines to carry voice signals has a history dating back to the early 1920s, with low-frequency amplitude-modulation systems operating over lines with voltages as high as 220,000—providing reliable voice links between power generating stations and dispatchers' offices. Later, the power utilities' carrier-current communications systems were refined to use single-sideband (SSB) multiple-carrier technology, and gradually expanded to include telemetry. This provides continual monitoring of load, voltage, and other power-system characteristics, as well as remote control of switching stations in remote locations.

Carrier-current systems that operate over the 120/240-volt AC electrical wiring in homes and commercial buildings have also been around for many years. Some examples include intercoms and baby monitors; remote controls for lights, switched AC outlets and appliances; and carrier-current AM radio transmitters using power wiring to broadcast programming within limited areas, such as building and educational campuses. More recently low-speed digital communications systems for use over power wiring have been deployed. The common feature of all these systems is that they operate with low-tomedium frequency carriers and narrow transmitting bandwidths.

In Europe, the European Committee for Electrotechnical Standardization, CENELEC, produced EN50065, a standard covering the requirements for transmitting and receiving digital signals over 120/240-VAC wiring, using carrier frequencies in the 3 kHz to 148.5 kHz range. The U.S. Federal Communications Commission has regulations for similar applications within the 45 kHz to 450 kHz frequency range. In Japan, powerline communication is permitted in the 10 kHz to 450 kHz range.

Today, low-frequency powerline carrier modems can be used for many additional applications in homes and businesses, including:

- Home appliances
- Heating and ventilation control
- Lighting control
- Low-speed data communications networks
- Signs and information displays
- Fire and security alarm systems

These applications and frequencies are very different from the Broadband over Powerline (BPL) networking technologies, which are designed to provide networking and Internet access at DSL or cable modem speeds over electrical power wiring. "Home BPL" operates over the 120/240 VAC low-voltage distribution wires, while "Access BPL" operates over the medium-voltage (1 kV – 40 kV) power distribution network, to carry data over longer distances. BPL carrier frequencies are in the 1 to 80 MHz high frequency range.

Significance of the Analog Front End (AFE) to Powerline Modems

The use of digital signal processing techniques has significantly improved communication performance, but the troublesome problem of how to couple the analog-modulated signals from a powerline modem to and from electrical wiring has not been eliminated. The analog signal processing circuitry, together with other components required to couple the modulated signal on and off the powerline, are collectively named the analog front-end (AFE).

The AFE is called upon to provide voltage and current signal amplification, as well as provide galvanic isolation to protect the user and interfaced equipment from both the nominal 120/240 volts and the transient voltages, which are common to power wiring. It is traditionally a complex circuit combining many discrete components with bulky isolation transformers.

This article introduces a new approach to the AFE, using optical coupling technology to provide significant improvements in the areas of power efficiency, system robustness, and overall solution cost.

Figure 1 shows a block diagram of a typical powerline communication modem for use in home automation applications. The modulated signal is generated with a digital look-up table and a digital-to-analog converter (DAC). Demodulation is also carried out digitally, by first converting the received analog signal into the digital domain with an analog-to-digital converter (ADC), and then by applying subsequent digital processing. These two functions are typically integrated into a single modulator/demodulator (modem) IC, fabricated using a low-voltage CMOS process.

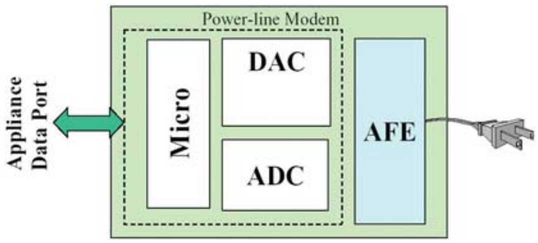

Figure 1. Typical frequency-shift keying (FSK) powerline communication modem (PLM) for use in home automation applications.

The use of CMOS IC processes allows the optimization of the die size, cost, and power dissipation. However, it makes the integration of analog circuitry problematic, meaning some, if not all, of the analog signal processing circuitry must be provided externally.

Although the modulator/demodulator topology used in the digital IC has a significant impact on overall communication performance, it is fair to say that, in many cases, the performance of the AFE has an equal, if not greater, influence on the overall performance of the powerline modem.

AFE Requirements

The power line communication medium is a difficult environment compared to dedicated STP (shielded twisted pair) or coaxial cables. It places additional constraints and requirements on the AFE, particularly in the areas of:

- Insulation for voltage safety
- Surge voltage immunity
- Line attenuation
- Electromagnetic interference (EMI)
- Electromagnetic compatibility (EMC)

The 120 or 240 volts on home power wiring are potentially dangerous to the user. International safety norms and equipment regulations require the use of appropriate insulation barriers to protect the end user from the risk of electric shock. The traditional method used in powerline modems to provide safe insulation is an appropriately constructed and certified isolation transformer for coupling the modulated signal to and from the power line.

High voltage transient surges are a frequent occurrence on the power line and are considered to be normal and inevitable. However, without sufficient protection, all electrical circuitry is at risk from surge voltage-related damage. In particular, semiconductor devices are vulnerable, since they can suffer either immediate catastrophic failure or accumulated damage, resulting in shortened lifetimes.

In most power line-operated electronic equipment, the only coupling mechanism between a power line voltage transient and the sensitive low-voltage circuitry is through the power supply. The low voltage circuits are normally very well protected from power line transients by the inherent low-pass filter characteristics of the power supply itself. Consequently, the risk to the low voltage circuits is normally considered insignificant. The powerline modem, however, necessitates a higher-frequency communication path between the power line and the low voltage circuitry. Unfortunately, this path not only enables data communications, but also opens up the possibility of the transfer of power line surges into the sensitive low voltage circuitry.

To minimize this risk, it is common practice to incorporate supplementary over-voltage protection in the form of clamp diodes, silicon avalanche diodes, and MOVs (metal oxide varistor). All of these protection devices have a significant amount of parasitic capacitance, which has the propensity of attenuating received signals. This means that the highest level of protection could also severely attenuate the desired communications.

Electromagnetic Compatibility

The operation of powerline modems can potentially create objectionable interference to radio-frequency appliances such as radios and televisions, either by interference conducted through the power wiring, or radiated over the air from the power wiring.

With respect to conducted interference, manufactures of powerline modems must ensure that the frequencies and amplitudes of the modulated signals meet applicable international conducted emission profiles, and guard against inadvertently transmitting out of band harmonics.

Electromagnetic emissions are similarly regulated. In the case of powerline modems, electromagnetic interference (EMI) is of particular concern, because most wiring is not shielded in any effective way. Unshielded communication cables subjected to common-mode currents have a very high propensity to propagate electromagnetic interference. Electromagnetic emissions can be minimized by either reducing the common-mode voltage, or by increasing the common-mode impedance by minimizing the parasitic capacitance of the coupling device.

Attenuation

Communication signals on the power line are subjected to various degrees of attenuation, which vary with time and frequency.

One of the worst culprits for attenuating PLM signals are the capacitors installed to filter out the switching harmonics of switched-mode power supplies and lamp ballasts. On the one hand, implementers of PLM are grateful that these filter capacitors are installed, because they attenuate conducted noise transients. The downside is that the same capacitors can result in a very low power line impedance at the carrier frequencies used by home PLMs. Consequently the first measure taken to minimize attenuation of the transmitted signal is the use of a low impedance coupling circuit and a transmitter output stage, with a high output current capability. This ensures minimum attenuation at the signal injection point. To counter inevitable attenuation of the transmitted signal, the AFE receiver circuit amplifies the received signal before demodulating.

Immunity to Electromagnetic Interference

Electromagnetic interference immunity is the ability of the receiver to reject the interference generated by conducted and electromagnetic radiation, whether intentional or unintentional. The EMI immunity performance of the PLM can be optimized in several ways. The first method is to maximize the signal-to-noise ratio (SNR) by minimizing the noise observed at the receiver. The second is to use noise-tolerant communication methods such as forward error correction (FEC) coding. The third method involves the use of multiple carrier frequencies. In practice, using a combination of these methods provides satisfactory EMI immunity. With respect to the AFE, reducing the amount of noise reaching the receiver enhances EMI immunity.

Noise propagates into the PLM receiver circuit in two ways, differential mode and common mode.

With differential noise, the noise is injected from the noise source as a voltage between the live and neutral wires of the power wiring. This differential noise signal is subject to the same attenuation effects as the transmitted modem signal. Consequently, the amount of differential noise at the receiver will be dependent on the position of the noise injection point relative to the location of the receiving point.

In the case of common-mode noise, unshielded cables act as good antennae for picking up electromagnetic signals from both intentional emitters, such as radio stations, and unintentional emitters, such as universal motors and lamp ballasts. The power line is no exception. Since the live and neutral conductors run in close proximity to each other, electromagnetic noise is equally coupled onto both.

The amplitude of the common-mode noise coupled onto the power line will depend on the length of the conductors, and their position relative to the devices radiating the electromagnetic noise. The power line impedance loads do not attenuate the common-mode noise voltage in the same way as they do to differential-mode noise. The consequence is that the common-mode noise becomes more significant in the case of heavily attenuated communications signals.

The amount of common-mode noise reaching the receiver is dependent on the leakage capacitance of the signal coupling transformer and the noise frequency. Ultimately, the receiver circuit is not directly affected by common-mode noise, but is affected by common-mode noise converted to differential-mode noise by unavoidable asymmetry in the cable, transformer, and receiver circuitry itself.

To reduce the influence of both differential and common-mode noise, a passive or active filter is used at the front end of the receiver. In this manner, noise frequencies outside the communication band can be very effectively removed.

More difficult to filter out are noise sources close to the transmitted carrier frequencies. It is these noise sources and the in band noise frequencies which ultimately cause the residual EMI immunity limitations for PLMs.

Optically Coupled AFEs

A transformer can inherently propagate signals in either direction, while optical coupling methods use a unidirectional combination of optical emitter and detector and can only propagate signals in one direction. To achieve bi-directional communication in an optical AFE, one transformer has to be replaced with two optical channels. Fortunately, optical packaging platforms allow multiple optical channels to be integrated into standard surface mount type (SMD) packages.

Figure 2 illustrates the construction of an integrated optical PLM AFE. Packaged inside the optical AFE are four discrete semiconductor elements: two LEDs (LED1 and LED2) and two BICMOS integrated circuits (IC1 and IC2). IC1 is ground referenced to the low voltage circuitry and IC2 is ground referenced to the power line.

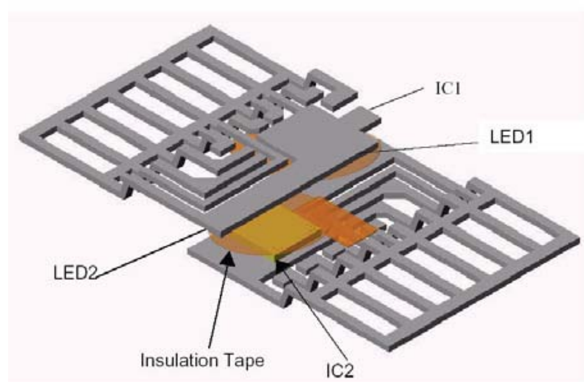

Figure 2. The leadframe used for the Avago Technologies' HCPL-800J, a bi-directional optical analog front end (AFE) packaged in a 16-pin SOIC (Small Outline IC) package.

Figure 3 is the block diagram of the AFE. With respect to the transmit optical path, IC1 includes a transconductance amplifier, which drives LED1 with a forward current equal to the sum of a DC biasing current and a current which is directly proportional to the analog input signal. The type of LED used has a very linear current-to-light transfer characteristic to minimize harmonic distortion resulting from the electrical-to-optical conversion.

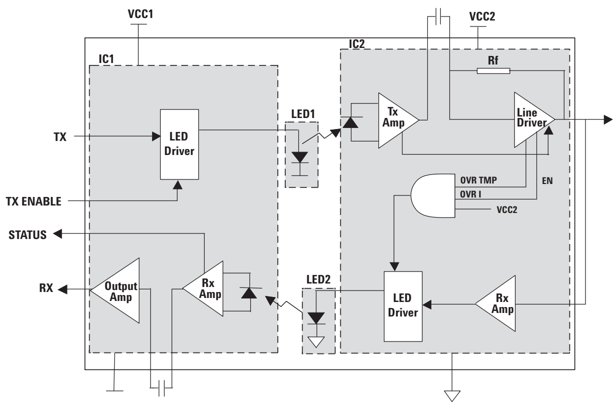

Figure 3. Block diagram showing the two CMOS ICs and the LED emitters used in the optical AFE.

On the power line side of the isolation boundary, a photodiode and photodetector amplifier are integrated into IC2, with the circuit converting captured photons to an output voltage which is linearly related to the light emission of LED1.

The output of the photodetector amplifier is coupled to the output stage via an external AC coupling circuit. The primary function of the coupling circuit is to remove residual DC offset voltage from the output of the photodetector amplifier. This coupling circuit may also include filtering or frequency shaping to remove out-of-band harmonics generated in the modulator or optical channel.

The operation of the receiver optical path is very similar to that of the transmitter path with the optical emitter and detector functions integrated in IC2 and IC1, respectively.

In addition to the basic function of coupling transmitted and received signals, other important features are integrated into the optical AFE. The first is the implementation of a highly linear line driver circuit, which is capable of delivering up to 1.0 A peak-to-peak. This high current capability ensures that an adequate transmit signal level is coupled onto the power line even in the case of very low power line impedance. The low distortion specification ensures that the generation of out-of-band harmonics is minimized.

The optical AFE also includes an additional gain stage in the receive function, which may be used to amplify attenuated signals, ensuring optimal link integrity even in worst-case signaling environments.

The optical AFE incorporates integrated control functions. To ensure that the line driver does not unnecessarily attenuate received signals, it is important that the line driver be switched to a high impedance state while the PLM is receiving signals. Normally, this would require the use of an additional isolated communication channel to couple the transmit-enable signal from the modulator control circuit to the line driver. To minimize packaging complexities, the optical AFE allows digital control signals to be simultaneously multiplexed with the analog signals, allowing a single optical channel to simultaneously transmit analog and digital control signals. One of these digital signals is the transmit-enable signal.

Since the output stage of the PLM is totally isolated from the appliance, in some cases, the control circuitry of the appliance would have no way of determining whether the V_{cc2} power supply voltage is present and correct. To prevent such a scenario, an under-voltage detection circuit is included on IC2, which monitors V_{cc2} and transmits an indicator signal across the isolation boundary manner, similar to that used for the transmit-enable signal.

Protection Features

To ensure maximum robustness of the modem, the line driver circuit includes over-temperature and over-current protection. The over-current signal works in two ways. First, it clamps the peak output current to a safe sustainable level. Second, it transmits an over-current signal back across the isolation boundary. Normally, the peak output current is limited by the combined influence of the coupling impedance and the power line load.

Since the worst-case power line load can be very small, in some cases as low as 1Ω, the resulting peak current levels can potentially reach very high levels. To meet a realistic peak current limit, the coupling impedance has to be sufficiently large. Such high coupling impedance unfortunately will result in some attenuation of the transmit signal at nominal load conditions.

The provision of the isolated overcurrent signal facilitates an alternate peak current limiting strategy. That is to use the over-current signal to signal the microcontroller to progressively reduce the transmit signal amplitude until the over-current flag is disabled. Such a control strategy allows the use of a very small coupling impedance, maximizing coupling efficiency under all load conditions.

Conclusion

One of the first and most obvious advantages of an optical solution is the ability to construct a low profile SMD component that contains not only the isolated coupling mechanism, but also much of the analog signal processing components. This results in a large reduction in the number of components required, which in turn reduces the complexity and cost of a PLM. Figure 4 shows a complete powerline modem using an optical AFE.

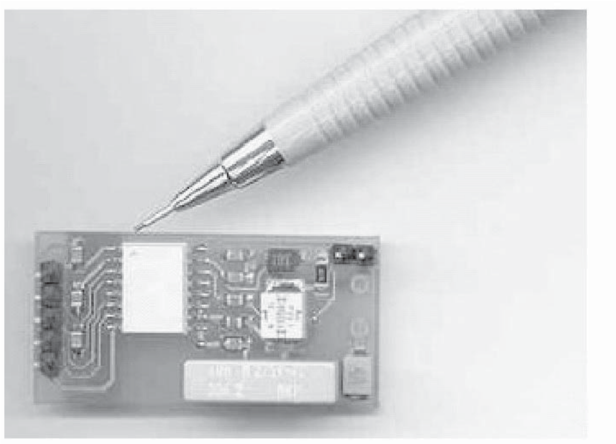

Figure 4. A complete powerline modem using the optical analog front-end.

In addition to these benefits, an optical solution offers performance advantages, particularly in the areas of EMC, EMI, and surge immunity. With respect to EMC and EMI optimization, reducing the parasitic capacitance of the isolation component increases the common mode impedance, which in turn reduces electromagnetic emissions and sensitivity to common mode noise transients.

The leakage capacitance of an optical signal-coupling device is directly related to the separation distance and coupling area between the optical emitter and detector. Unlike magnetic transformers, the optical signal coupling devices do not require close physical coupling to achieve satisfactory performance. Theoretically, optically coupled signal paths can operate through an optical fiber at distances of hundreds of kilometers, making the common-mode impedance infinitely high. In practical terms, optically integrated devices in standard SMD packages typically exhibit coupling capacitance on the order of 1.3 pF. This is a very significant improvement over magnetic transformers, which typically exhibit parasitic capacitances in the range of 30 to 100 pF.

Magnetic signal transformers are capable of not just transmitting and receiving communication signals; they are also capable of coupling high voltage surge transients. Conversely, optical coupling devices are only inherently capable of coupling low-power optical signals. Transient voltage surges are very effectively blocked from reaching the low voltage appliance circuitry. From a practical point of view this means that the overall robustness of an electrical appliance need not be degraded by the inclusion of a PLM.

References

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