Using In-Home Power Lines to Extend the Range of Low-Power Wireless Devices

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ABSTRACT

This work demonstrates the feasibility of using existing in-home electrical wiring to extend the operational range of certain wireless devices. Specifically, a wireless keyboard operating at 27 MHz, which has an operational range of 1.5 – 2 meters on its own, was extended to work throughout a 3-story 4,000 square foot / 371 square meter home by coupling the antenna port on its receiver to the power lines. Coupling between the keyboard and the power lines occurred over the air, and coupling at the receiver was accomplished capacitively by simply wrapping a wire connected to the receiver's antenna port several times around a standard electrical device cord plugged into a wall socket. This phenomenon of the power line as a communications infrastructure for inexpensive and low-power wireless devices has a variety of interesting potential avenues of research in the home.

INTRODUCTION

The power line has been shown to be a useful sensing infrastructure for the home. Previous work used the power line infrastructure to determine what electrical devices are activated [7], as a broadcast antenna to build a fingerprinting-based indoor localization system [6, 10], and as a passive RFID system, called PL-Tags [8]. Additionally, outside the home the power line has been used as a distribution mechanism for AM radiobroadcasts [13].

The PL-Tags system demonstrated the use of the power lines to couple the response of a passive RFID tag over very short distances (30 to 50 cm) to a nearby receiver. In this work, we wanted to test the capabilities of the power line as a receiver over greater distances, ultimately as a communications infrastructure to augment low-power wireless devices throughout the entire home. To examine this phenomenon, we performed several experiments with a software radio and a standard wireless keyboard operating at 27 MHz. We found that by coupling a receiver to the power line, the keyboard's range could be extended from 1.5–2 meters line-of-sight to non-line-of sight distances of up to approximately 30 m away. This encompassed most locations within a 3-story 4,000 square foot / 371 square meter home, all while maintaining the full functionality of the keyboard.

In the remainder of the paper, we discuss related work, the experimental procedure and simple hardware used to extend the keyboard's range, the theory and practice behind power lines as antennas, and the interesting implications of the power line as a wireless receiver.

RELATED WORK

The powerline as a radiofrequency (RF) antenna has been explored in various contexts as far back as the 1920's. Several patents describe various forms of a line cord antenna, whereby a receiver is coupled to the power line to receive high-powered broadcasts originating outside the home from TV and radio stations [2,9,11].

Power lines have also been examined as a transmitting antenna, whether intentionally or unintentionally. As an intentional radiator, they have been used to distribute AM radio broadcast signals over the main power distribution grid [13]. Within the home, they have been used to distribute RF signals of up to 20 MHz for an indoor localization system, for a cordless phone system transmitter, and for an in-home video distribution system transmitter [1, 4, 6, 10]. As unintentional radiators, power lines emit as RF energy the frequencies used by broadband over powerline (BPL) [3]. BPL signals are intended to be carried on the power lines, but nonetheless radiate as RF energy since the power lines were not designed as a transmission line for frequencies higher than the 50-60 Hz at which power is transmitted.

PL-Tags showed that the power line could be used as a receiver over very short distances for detecting low-frequency resonant RF energy from power line activated passive RFID tags [8].

Figure 1. USB receiver for a wireless keyboard with its antenna coupled to the power line by wrapping it around a standard line cord.

EXTENDING THE RANGE OF A WIRELESS KEYBOARD

We used a wireless keyboard to test the capabilities of the home power line as a receiving antenna since the keyboard in its standard configuration has a relatively short operational range of 1.5–2 meters. A Logitech wireless keyboard using a proprietary radio link operating at 27 MHz was used. Its receiver and antenna are illustrated in Figure 1. The keyboard's receiver connects to a computer via USB.

The first experiments were conducted using a Universal Software Radio Peripheral (USRP) [12] as the receiver. The USRP was capacitively coupled to the home power line at the basement electrical distribution panel by mounting an antenna inside of the panel door. It was thought that the distribution panel would be the optimal sensing location since all circuits in the house originate there. Thus, if the power line acts as a conduit for RF energy it picks up from the environment, it should channel those signals back to the distribution panel.

To sense the keyboard's signal, we tuned the USRP to 27 MHz and observed the FFT of the radio spectrum in that region. As keys were pressed, a spike at 27.146 MHz could be seen. The received signal strength of the keyboard using the power line as a receiving antenna was examined at 24 locations spread throughout all floors and rooms of the test home. Of these 24, the keyboard's signal was visible at 20 locations. Without coupling the USRP's antenna to the power line at the distribution box, the keyboard could not be sensed at any of these locations.

While this method provided proof that the keyboard's signal could be received almost anywhere within the home using the power line as a receiving antenna, the question remained as to whether the signal-to-noise ratio (SNR) was great enough to decode the keyboard's signal accurately. While demodulation could also be performed with the USRP and appropriate software, we were unsure of the keyboard's modulation scheme and also thought it an impractical result that the range of the keyboard could be extended using an expensive piece of sensitive radio equipment. We thus set out to test the functionality of the keyboard's own receiver when coupled to the power line.

To couple the keyboard's receiver to the power line, we soldered an approximately 50 cm wire to the antenna input location on its board. The other end of this wire was coiled around a standard electrical device cord plugged into a wall socket. This setup provides capacitive coupling to the power line similar to the distribution box method, while allowing the keyboard receiver to be located in a more realistic setting away from the main distribution box and near the computer it is intended to operate.

In this scenario, we define sensing the keyboard as the appropriate letters from the pressed keys appearing on screen. When testing the same 24 locations within the test home with this receiver, we found that while the keyboard could not be sensed at all the chosen locations, when moved in close proximity (within approximately 50 cm) to a power outlet, it could be successfully sensed at even the far end of the home. Thus, coupling of the keyboard's signal through the power lines extends the operational range of this keyboard from about 2 meters to anywhere with a power outlet in close proximity in the home. Tests with the USRP demonstrated that the keyboard's signal can in fact be sensed at those locations away from a power outlet where the keyboard's receiver failed to work. Therefore, a simple and inexpensive op-amp (approximately $5 USD) can be employed to boost the signal coupled from the power line sufficiently for the keyboard receiver to accurately demodulate it.

POWER LINES AS ANTENNAS

Having demonstrated the use of home power lines as a conduit for RF signals at 27 MHz, we now discuss some background on the use of power lines as both receiving and transmitting antennas.

Basic electromagnetic theory tells us that a time-varying voltage on a wire will produce an associated time-varying electromagnetic field around the wire, and that a time-varying electromagnetic field near a wire will produce an associated voltage on that wire. This is the basic premise of antennas. Since the power lines in a home are essentially a

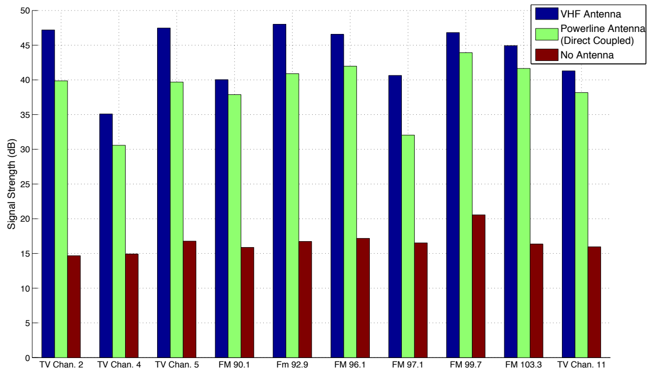

Figure 2. Received signal strength (RSS) for various over-the-air broadcast television and FM radio stations. RSS was measured with a standard VHF television antenna, no antenna, and the power line as antenna with the receiver directly coupled to the power line.

collection of wires, they are subject to this effect. Additionally, the antenna reciprocity theorem tells us that any antenna is an equally good transmitter or receiver. Thus, the power line, as a collection of wires, is capable of transmitting and receiving RF energy.

Antennas are carefully designed for use at a specific frequency or range of frequencies. The dipole is a common type of antenna that is usually designed to be one half or one quarter the size of the wavelength of the frequency it will be used at. The power line was never intended to be used as an antenna, however, and so its radiation pattern at various frequencies will differ greatly from standard antennas. Some of the RF devices and services that have been successfully received using the power line as an antenna are shown, along with their associated frequencies and wavelengths, in Table 1. Note that half the wavelength of the wireless keyboard's signal is approximately 5 meters. There are likely many straight stretches of power wiring in the walls of a home that extend distances on the order of 5 meters. This may account for our success at using the power line to sense this low-power device.

In addition to the experiments already described, we also performed a validation of previous work on line cord antennas to aid in the reception of high-powered TV and radio broadcasts from outside the home. To do this, we measured the signal strength of ten different TV and FM radio stations by coupling the USRP to the power line. We then compared the power line measurements to measurements taken with a standard TV VHF antenna (which also covers the FM radio band) and measurements taken without an antenna as a reference. Although the VHF antenna produces a higher signal strength at all ten stations tested, the power line antenna performs reasonably well by comparison.

Device / Service	Frequency	Wavelength
AM Radio	520 kHz – 1610 kHz	932m – 288m
Wireless keyboard	27 MHz	11.11m
FM Radio	88 MHz – 108 MHz	2.78m - 3.41m
NTSC Analog Television	54 MHz – 806 MHz	5.56m – 0.372m

Table 1. Various RF devices and services and their associated frequencies and wavelengths.

POTENTIAL USES

One application we envision for the in-home power line as a receiving antenna is for home wireless sensor networks. Current wireless sensor networks often use mesh networking as a means of extending the communication range of individual nodes. In a mesh network, wireless sensor nodes route packets for other nodes back to a central sink where all data from the sensor network is received and processed. In a mesh network configuration, sensor nodes are forced to constantly listen for and receive packets from neighboring nodes to forward them along.

The MicaZ is a popular wireless sensor network platform sold by Crossbow Technologies that operates at 2.4 GHz. The data sheet for the MicaZ reports that its RF transceiver draws between 11 and 17.4 mA when transmitting [5]. Interestingly, the data sheet also reports that the RF transceiver draws more power when receiving – 19.7 mA. Higher current draw for receiving is an important consideration when placing sensor nodes in a mesh configuration, as a mesh requires nodes to be in the high-power receiving state often, as packets to be forwarded along arrive from neighboring nodes.

In contrast to the MicaZ, a current draw of 5 mA was measured when transmitting for the wireless keyboard utilized in our experiments. The keyboard operates on 3 V, and was designed to use two AA batteries. A typical alkaline AA battery has a capacity of 3,000 mAh, meaning that the keyboard could transmit continuously for 25 days. Wireless sensors typically only transmit periodically, however, so its life would in practice be significantly longer. In contrast, the MicaZ, even if only transmitting, and not receiving as required for a mesh network configuration, has a lifespan of 7 to 11 days when continuously transmitting.

We thus see the power line as a potential conduit for RF signals from wireless sensor nodes within the home. Rather than placing sensor nodes in a wireless mesh configuration, each node can simply transmit its own packets without need to forward along packets from neighboring nodes. The RF signal from each node will couple to the power line through nearby in-wall wiring and outlets. The signal can then be received at the sensor network sink, whose receiver is coupled to the power line via a line cord as illustrated in Fig. 1. This method eliminates the power expenditures necessary to receive and forward along packets from other nodes. Additionally, given that the transmitter of the tested wireless keyboard has a lower power draw than the MicaZ transceiver yet could still be detected throughout the home, there is potential to use lower power transmitters than would otherwise have been possible with traditional antennas and over-the-air reception.

CONCLUSION

We have shown a simple low-cost technique for extending the range of mid-frequency consumer electronic devices by leveraging the power line as a reception antenna. This demonstration provides us with some new avenues of research for ubicomp, where we can start to imagine practical deployments of low-power distributed sensor nodes in the home.

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