SNUPI: Sensor Nodes Utilizing Powerline Infrastructure

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ABSTRACT

A persistent concern of wireless sensors is the power consumption required for communication, which presents a significant adoption hurdle for practical ubiquitous computing applications. This work explores the use of the home powerline as a large distributed antenna capable of receiving signals from ultra-low-power wireless sensor nodes and thus allowing nodes to be detected at ranges that are otherwise impractical with traditional over-the-air reception. We present the design and implementation of small ultra-low-power 27 MHz sensor nodes that transmit their data by coupling over the powerline to a single receiver attached to the powerline in the home. We demonstrate the ability of our general purpose wireless sensor nodes to provide whole-home coverage while consuming less than 1 mW of power when transmitting (65 μW consumed in our custom CMOS transmitter). This is the lowest power transmitter to date compared to those found in traditional whole-home wireless systems.

Author Keywords

Wireless sensing, ultra-low-power radio, powerline

ACM Classification Keywords

C.2.1. Network Architecture and Design: Wireless Communication; B.0. Hardware: General

General Terms

Design, Experimentation, Measurement

INTRODUCTION AND MOTIVATION

The success of many domestic ubiquitous computing (ubicomp) applications, especially as we transition from instrumented living laboratories and into real homes, will be contingent on practical and long-lived sensing solutions. These solutions must be easy to deploy and maintain [3].

Figure 1. Both sides of operational SNUPI sensor nodes

While battery-powered wireless sensor nodes are typically easy to *deploy*, to date they have not been easy to *maintain* due to the need to frequently change the batteries. Traditionally, the dominant factor in determining battery life for these nodes has been the power cost of wireless communications, not the sensing or computation tasks. This paper presents a new technique for wireless communication from sensor nodes in the home that reduces communication costs so significantly that battery life is now dominated by the cost of the sensing and computation, a complete reversal of the status quo.

Although low-power radios are available [22], their range is so limited they are not viable for whole-home sensor networks with a single base station. To reduce power, a common approach is to implement a multi-hop mesh network where each node only needs to communicate with nearby nodes, rather than communicating the full distance to the base station. This approach reduces the power consumption of the transmitter but requires significant power to continuously run a receiver on every node.

We have developed an approach for wireless sensor nodes, which dramatically reduces the power consumption of each node while continuing to offer whole-home range. SNUPI (Sensor Nodes Utilizing Powerline Infrastructure) nodes contain an ultra-low-power transmitter that extends its range by coupling its wirelessly transmitted signal to the existing powerlines in order to obtain whole-home range. Several commercial networking and home convenience products currently use the home powerline infrastructure as a medium for communicating high frequency signals;

UbiComp '10, September 26–29, 2010, Copenhagen, Denmark.

however, in all of these systems both the sender and receiver are directly connected by wire to the powerline [13, 14, 29]. In the SNUPI system, only the base station receiver is wired directly to the powerline (*i.e*, plugged into an outlet). Each node in the sensor network transmits wireless signals that couple to nearby powerlines, creating signals that travel through the infrastructure to the base station receiver. In this way, the sensor nodes can transmit at much lower power because signals do not need to propagate over-the-air for the entire path to the receiver, they only need to propagate to the nearest powerline.

SNUPI is a fully-programmable wireless sensing platform that features an ultra-low-power 16-bit microcontroller, a 16-bit ADC, and a custom 27 MHz, 9.6 kbps frequency-shift-keying (FSK) wireless transmitter, which is capable of providing coverage within an entire home while consuming less than 1 mW. Our custom transmit-only radio accounts for just 65 µW of the 1 mW, rendering its power consumption as negligible when compared to the ultra-low-power microcontroller. Our initial prototype of the SNUPI sensor node measures 3.8 cm by 3.8 cm by 1.4 cm and weighs only 17 grams including the battery and antenna (see Figure 1). The battery life of a SNUPI node with a simple light sensor beaconing once per minute will dramatically outlive the 10 year shelf-life of its small 225 mAh coin-cell battery.

The use of the powerline as a receiving antenna offers a number of advantages because its length makes it an ideal receiving antenna at low frequencies (10–40 MHz). First, this allows us to greatly reduce the power output of the radio, while still achieving a practical communication range. Second, the efficiency of the powerline antenna, allows us to reduce the size of the antenna on the sensor node itself (see Figure 1), despite it having to operate at lower frequencies where ideal antennas are prohibitively large. Finally, only a single powerline-connected base station receiver is needed for whole-home coverage, thereby reducing the installation time by an end-user.

In this paper, we discuss the design and implementation of SNUPI, examine a series of experiments that characterize the performance of SNUPI as a viable ultra-low-power whole-home wireless sensing solution, and compare our approach to traditional sensor systems found commercially and in the research literature.

BACKGROUND AND RELATED WORK

Recent work in ubiquitous computing has examined repurposing the existing infrastructure of a home as a means for extracting relevant activity information, thus reducing the need for complex distributed sensing systems [6, 10, 11, 18, 19, 20, 21, 25]. Although this infrastructure-mediated sensing approach helps address many practical obstacles to deployment of home activity sensing, it is inherently limited by what information can be practically and reliably extracted from a home's infrastructure. Thus, a need still exists for distributing sensor nodes where obtaining certain data in the home is impossible using just the infrastructure. Our work attempts to strike a balance between minimizing the need for additional infrastructure requirements (*i.e.*, reducing the receiver down to a single base station), but still allowing the flexibility of deploying long-lived wireless sensors throughout the home.

Powerline Communications

Although designed as a transmission line for low-frequency AC electrical power at 50–60 Hz, the in-wall residential powerline is capable of carrying higher frequency signals. This phenomenon has been successfully leveraged for a variety of in-home communications applications. X10 and Insteon are two well-established low-data-rate powerline communication technologies that enable home automation and control [14, 29]. The HomePlug Powerline Alliance maintains a standard for high-data-rate home networking over the powerline on which numerous commercial consumer devices are based [13]. These devices typically act as a bridge between wired Ethernet networks and the powerline network, and can currently provide data rates up to 200 Mbps. In all of these systems, both the transmitter and receiver are wired directly to the powerline.

Powerline for Sensing Applications

There are several systems that leverage the existing powerline infrastructure for sensing and location tracking [19, 20, 25]. The PowerLine Positioning (PLP) system [21, 25], which tracks the location of small active tags throughout a home, makes use of the home powerline as a transmitting antenna for signals between 447 kHz and 20 MHz. Other work has looked at passively listening to the powerline in order to infer electrical activity from the noise generated by the switching of electrical devices [11, 19]. Researchers of sensor networks have also exploited the 60 Hz AC line radiation for synchronizing distributed sensor nodes [23]. In contrast to this work, we attempt to use the powerline as a wireless *receiving* antenna for communication back to a base station receiver.

Powerline as a Receiving Antenna

The PowerLine Positioning (PLP) system [21, 25] demonstrated the power infrastructure could be used as a transmission antenna. The electromagnetic principle of reciprocity therefore dictates that the powerline should work equally well as a receiving antenna. The powerline's ability to receive wireless signals is a well-known phenomenon, but only recently has it been exploited for in-home communication. This was first shown with the PL-Tags system, in which tags were briefly excited to create a low frequency (few hundred kHz) burst, which was coupled to the powerline at very short range [20]. However, the ability for the powerlines to receive and propagate RF signals is strongly dependent on frequency, and therefore it is important to characterize the powerline over frequency.

Carrier Frequency Selection

Since wireless communication is subject to local and international regulations regarding the use of the radio spectrum, we only considered frequency bands which are designated by the International Telecommunications Union (ITU) as unlicensed for wireless communications: 6.78, 13.56, 27.12, 40.68, 433.92, 915.00 MHz, and 2.45 GHz [15]. These spectra are used by a variety of wireless devices including consumer electronic devices. Most countries adhere to this standard when allocating the unlicensed radio bands, although notably 433.92 and 915.00 MHz are not globally available, and are heavily used in regions where they are available. We therefore eliminated these two frequencies from consideration.

The HomePlug standard, mentioned earlier, uses three of the unlicensed bands: 6.78, 13.56, and 27.12 MHz. We tested for interference at these frequencies due to HomePlug by measuring the power level on the powerlines at several locations in a home using a spectrum analyzer. We found that HomePlug devices generate significant interference at 6.78 and 13.56 MHz, yet no interference is seen at 27.12 MHz. Due to the growing popularity of HomePlug [28], we eliminated 6.78 and 13.56 MHz as options for the SNUPI sensor nodes.

For the remaining frequency bands, we conducted experiments in which we injected signals into the powerline at 27.12, 40.68 MHz, and 2.45 GHz using a signal generator connected to a custom powerline interface, and measured the signal levels at various locations of a 3 floor, 371 square meter home using a spectrum analyzer. We concluded that 27.12 and 40.68 MHz signals travel through the powerline with little attenuation in comparison to 2.45 GHz signals. To further test both 27.12 and 40.68 MHz, a small 4 cm x 4 cm loop antenna was excited with a signal generator, and placed at every position in a 1 meter grid (250 locations) of a 2 floor 280 square meter home. A spectrum analyzer was used to monitor the received signal at a single wall outlet. The spectrum analyzer was connected to the ground and neutral lines of the powerline, and a simple high-pass filter was used to block the 60 Hz signal from the powerline. A similar experiment, using sparser grid, was also conducted on a 75 square meter apartment. From these experiments, we found that both 27.12 and 40.68 MHz perform very well; however, 27.12 MHz was chosen due to the availability of crystal resonators and power consumption can be reduced by operating at lower frequencies.

These whole-home experiments showed that we were able to couple a 27.12 MHz signal to the powerline from anywhere in the home, and detect the signal at a single central location on the powerline with a signal to noise ratio (SNR) of at least 3 dB, when using an antenna output power of only -45 dBm, assuming a 50 Ω load. This extremely low-power result motivated us to design a full sensor node that could operate while consuming less than 1 mW of total power while transmitting.

Low-Power Sensor Nodes

A number of wireless sensing platforms exist both in the research community and commercially. MITes is a low-power sensor kit that was designed for long-term deployments to sense human activity [27]. A number of other platforms have also been available to the ubicomp community, such as Smart-Its [16], uParts [4], Berkeley / Crossbow Mica-family motes [7], iMotes [17], and BTNodes [5]. Commercially available platforms include sensor nodes available through EnOcean [8], various ZigBee platforms [30], Crossbow Motes [7], and SunSPOTs [26], among others. As we discuss later, these solutions are often very power hungry when used for long-range in-home applications, even at low bitrates of 10 kbps.

Work in the wireless sensing community has led to a variety of ultra-low-power wireless solutions that typically are not as programmable and include only an ADC and a radio in a single chip. These solutions are limited in range to a few meters line-of-sight, but operate under 1 mW of power [22]. We show how our custom transmitter consumes even less power than these short range radios.

Other work has demonstrated wirelessly powering RFID-based sensors using long-range RFID readers. For example, the Wireless Identification and Sensing Platform (WISP) is a passive UHF RFID tag that uses an ultra-low-power microcontroller for sensing and communication [24]. Although promising, these solutions are limited in range, and require considerable RFID infrastructure, which may not be commonly found within the home environment.

HARDWARE AND SOFTWARE DESCRIPTION

The SNUPI sensor node is a generic fully-programmable platform for whole-home, low throughput, ubiquitous computing applications. In many of these low throughput applications, battery life is the most important design criteria. For this reason, SNUPI was designed specifically to maximize battery life by minimizing power consumption. The initial prototype of the SNUPI sensor node measures 3.8 cm by 3.8 cm by 1.4 cm, weighs only 17 grams including the battery, and has whole-home range while consuming less than 1 mW of power when transmitting (the radio itself only consumes 65 µW). In order to minimize power consumption over long periods of time, each part of the node is duty cycled to only consume power when needed. Between transmissions the node is in an ultra-low-power sleep state, and a timer on the microcontroller is used to periodically wake up the node in order to sample and transmit a packet of data. Figure 2 shows a high-level block diagram of the SNUPI node, and Figure 1 shows the completed node. The following sections describe the design of each sub-system of the SNUPI sensor node.

Custom CMOS Transmitter

Traditionally, the RF radio is the most power intensive component of any wireless sensor node. Therefore, our main focus was to dramatically reduce the power consumption of the radio. In typical transceivers, most power is consumed during receiving, a task that must always be active in order to prevent data loss. To reduce the power consumption of the SNUPI node, we removed the receiver. SNUPI therefore uses a unidirectional

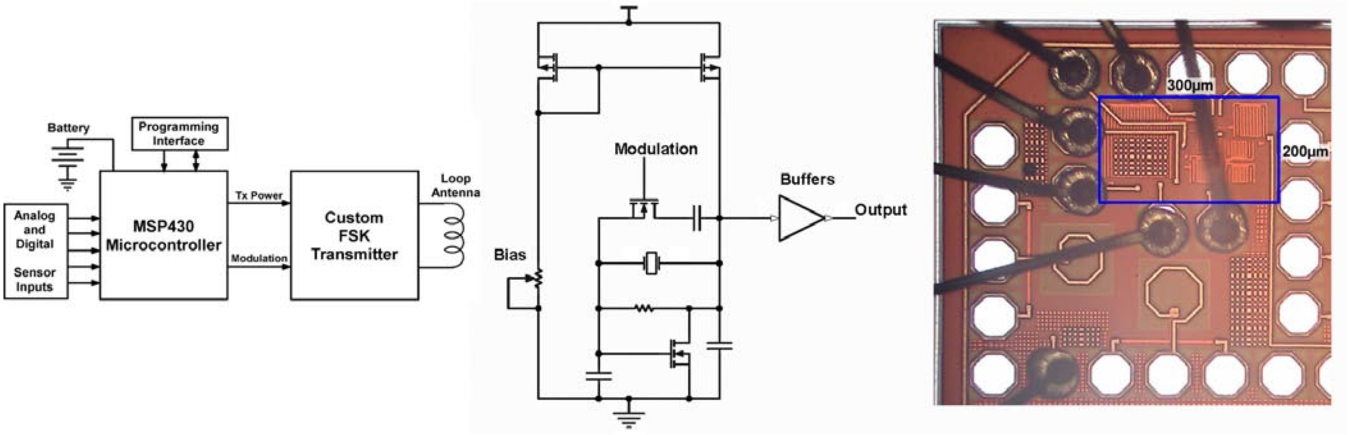

Figure 2. (left) High-level block diagram of SNUPI sensor node. (center) schematics of our custom FSK transmitter. (right) 20X microscope image of CMOS silicon die containing our custom transmitter. The transmitter circuitry is within the blue square

communications channel, meaning that each node can only send data. This significant reduction in power comes at the cost of communications reliability. Without two-way communication, there is no handshaking to ensure that data sent from the node is actually received by the base station. This limitation will be discussed later.

Although removing the node receiver reduces the overall power of the radio, there are many optimizations that can be made with the transmitter itself. Our goal was to design a 27 MHz transmitter using minimum power. The efficiency of the home powerlines as an antenna at 27 MHz and their proximity to the nodes allows for further power reduction. We implemented a binary frequency shift keying (2-FSK) transmitter using a Pierce oscillator with a 27.0 MHz crystal resonator (schematics shown in Figure 2). To modulate the transmitter, a small 4 pF on-chip load capacitance across the crystal resonator is switched to cause a 10 kHz frequency shift. The crystal oscillator has a relatively slow startup time, between 1 and 4 ms, which varies as a function of the oscillator bias current such that the startup time is longer when the oscillator consumes less power.

A digital buffer chain isolates the oscillator from the low impedance (~350 Ω) loop antenna. In order to save power, the buffers use a very low supply voltage. By adjusting this supply voltage, the output power of the antenna can be varied by 18 dB. At the minimum output power, the radio consumes only 35 µW (900 µW for the whole node), and at the maximum output power, the radio's power consumption is 190 µW (1.5 mW for the whole node). This power range is specified by the component values used in our prototype, and therefore the power range could be shifted or extended using different sized components.

This transmitter design can be made very low-power as long as the stray capacitance is not too large. Using a discrete transistor implementation on a prototyping board, we demonstrated that we could achieve whole-home range while keeping the power below several hundred µW. In order to further reduce the power, we implemented the oscillator on a single silicon die using a 0.13 µm CMOS process, which resulted in only 65 µW of power for whole-home range. Figure 2 shows a microscope image of the transmitter die, which was wire-bonded to the custom SNUPI printed circuit board (PCB).

Microcontroller

A microcontroller is used to control the operation of the SNUPI sensor node. The Texas Instruments MSP430F2013 16-bit ultra-low-power flash microcontroller is used due to its ultra-low-power capabilities, including several clocking options, 2 KBytes of Flash ROM, 128 bytes of RAM, and a multi-channel 16-bit Sigma-Delta analog-to-digital converter (ADC). The microcontroller is used for timing control and computation. It controls powering the sensor, sampling data, and both powering and modulating the transmitter. The RF transmitter is powered directly from a digital output pin on the microcontroller so that the transmitter can be completely powered down during the sleep phase. In addition, the microcontroller can be used as a general computation platform since SNUPI exposes the MSP430 programming interface. A SNUPI node's firmware can be easily reprogrammed by connecting a programmer to the Spy-Bi-Wire (2-wire JTAG) interface. All ADC input pins are exposed on the SNUPI PCB so that a variety of different sensor connections can be used.

Antenna

The operating frequency of SNUPI is 27 MHz, which approximately corresponds to an 11 m wavelength. Since high efficiency antennas are typically on the order of one half wavelength in size, it is therefore not feasible to use a high efficiency antenna on a small wireless sensor node. In order to keep the senor node as small as possible, we constrained the size of the antenna to be the size of the node's printed circuit board (PCB), which is 3.8 cm x 3.8 cm. Although this yields a highly inefficient antenna, it is sufficient because the SNUPI node only needs to transmit far enough to couple to the nearest powerline, which in a home in rarely more than a few meters away. In addition, the size of the powerline infrastructure makes it a fairly efficient receiving antenna at 27 MHz.

Although the efficiency of the SNUPI antenna is very low, we optimized the performance as much as possible. After testing the impedance match and radiation efficiency of over 20 different antenna designs, we chose to use a 350 Ω loop antenna consisting of 6 turns of 22 AWG wire wound along the perimeter of the PCB. Multiple turns are used to increase the impedance and improve the radiation efficiency by increasing the radiation resistance. Heavier gauge wire is used to reduce the loss resistance of the antenna, which also improves the radiation efficiency [2].

Battery

The SNUPI node was designed for a 3.0 V battery, although it will continue to operate correctly down to 1.8 V, at which point the MSP430 microcontroller will cease to operate. Although high-capacity coin-cell lithium batteries can be purchased with capacities as large as 1000 mAh, they are often larger, heavier, and more costly than other coin-cells. For our prototype, we wanted to demonstrate that we could obtain very long battery life using a common, inexpensive battery. We therefore chose to use the CR2032, a very common 20 mm diameter, 3.0 V lithium coin-cell battery with a capacity of 225 mAh.

Communications Protocol

SNUPI is a fully-programmable sensing platform, and therefore many of the implementation details related to the communications protocol can be tailored to a specific application by changing and reprogramming the firmware on the microcontroller. This section will therefore describe the implementations used in our prototype; however, many of the details can be changed to suit different applications.

In order to reduce power consumption, we focused on implementing a very simple communications protocol. We use a star topology in which there is a single base station receiver and many transmitting nodes that communicate directly with the receiver. The powerline infrastructure serves as a very convenient channel for this type of network, because the powerlines are dispersed to almost every position in a home. Using this topology, our network uses a unidirectional version of the ALOHA protocol, in which many transmitters communicate in short bursts on the same channel [1]. Since each transmission is very short, the probability of a collision is low. The delay between each transmission is different among each transmitter to ensure that two transmitters do not become synchronized. Using this protocol we can implement a very simple unidirectional single-hop network and minimize the power spent in transmission. The limitations of this protocol will be discussed later.

Our prototype uses a 25-bit packet, which consists of a single start bit, a 7-bit node ID, a 16-bit payload, and a single parity bit. While the transmitter is starting up before the transmission and shutting down after sending the data, it transmits the “zero” value. The packet structure is entirely controlled by the firmware on microcontroller, and can therefore be changed for multiple applications, adjusting for the size of the node ID, payload, and error checking. The data is modulated using NRZ (non-return-to-zero) 2-FSK (binary frequency shift keying). The frequencies used to encode “one” and “zero” are 26.999 and 27.009 MHz, respectively. Because of the 10 kHz bandwidth, the current SNUPI prototype transmits at a bitrate of 9.6 kbps, which means that the entire 25-bit packet is transmitted in 2.6 ms. It takes less than 4 ms for the crystal oscillator and transmitter to power up, so the total on-time of each transmission is 6.6 ms. We later discuss how we would implement a version of the SNUPI node with a higher bitrate and a lower startup time.

PERFORMANCE ANALYSIS

To analyze the range and received signal of the SNUPI nodes, we have conducted an in-depth study in a 280 square meter, fully-furnished, single family home to determine the power requirements, range, and reliability of the SNUPI node, and to explore the preferred location of the base station receiver. The home used in the experiments was built with wooden walls and flooring and unshielded wiring in 1991, and was occupied by four residents during all testing. This section describes the methods, results, and discussion of these in-home experiments with fully operational SNUPI nodes.

Experimental Procedure

To explore the preferred location of the base station, we used a spectrum analyzer connected to our custom interface box, containing a high-pass filter to protect the equipment from the large low frequency signals on the powerline. The plug-in interface is attached to the powerline via the neutral and ground wires. Four different receiver locations were tested, marked with squares in Figure 3. For each receiver location, the signal to noise ratio (SNR) measured on the powerline was recorded while the SNUPI node was moved throughout the home. During these tests, the node was tested in the center of each room of the home (14 total positions tested for each receiver location). For all tests, the SNUPI node was set to a transmit power of 1 mW (65 µW for only the radio). This power setting was used to ensure that we could more accurately measure the SNR, even in locations with poor signal quality.

Once the best base station receiver location was found (shown as a triangle in Figure 3), a denser SNR mapping was performed in which measurements were taken with the SNUPI node in the four corners and the centers of every room (60 total locations). The node was typically 5 m or less from the nearest powelines. All nodes were placed at different heights, either on the ground or on top of furniture. The SNR results are shown in Figure 3.

This SNR mapping was conducted a second time using the same receiver location and the same node positions, but instead of connecting the spectrum analyzer to the powerline, an over-the-air dipole TV antenna (~1 m long) was used. This test was to confirm that the range of the SNUPI node is in-fact extended significantly by coupling over the powerline infrastructure rather than over-the-air.

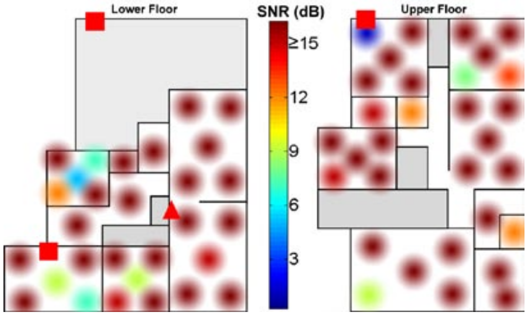

Figure 3. Whole-home mapping of SNR measured at the receiver location marked by the triangle for a SNUPI node transmitting at 1 mW (65 µW for the radio) at each of the mapped positions. In locations with more than 12 dB SNR, bit errors are insignificant, so the coloring does not reflect SNR values greater than 15 dB. The squares indicate the other receiver locations tested

Base Station Receiver Location

In order to locate the preferred location of the base station receiver, we measured the received SNR using four different receiver placements: physically centrally located, electrically centrally located (breaker panel), in an upper-corner of the home, and in a lower corner of the home, which was also very near the position with the worst SNR, due to limited electrical outlets and powerlines. From these tests, we found that the preferred receiver location is the one that is physically centrally located around the area in which the sensor nodes will be located. Signals that are coupled to the powerline farthest from the receiver are attenuated significantly over the powerline, and for this reason a centrally located receiver appears to be the best. The receiver can be placed inside rooms in which there is a very low SNR due to long distances from the node and the powerline (*i.e.*, placing the node at the center of a large open room) in order to improve the SNR from these locations. We also found that the receiver location on the upper floor was very ineffective, and covered less than 25% of the home, which tends to be at the periphery of the electrical wiring.

Range

Our tests showed that powerline coupling did in-fact significantly increase the range and signal quality. Using powerline coupling, 95% of the home was in range, while over-the-air communication gave only 77% coverage; however, it was determined that much of the success of the over-the-air communication was actually due to coupling between the TV antenna and the powerlines. This is based on the observation that signal strength improved as the distance to the powerline decreased, which is an expected result for powerline coupling, but not for over-the-air communications. Regardless, powerline coupling resulted in a higher SNR at every location tested, with an average improvement of 10 dB compared to over-the-air.

The SNR mapping in Figure 3 shows the relative signal strength throughout the home. The maximum SNR was 56 dB, and there was one position in which signal could not be detected; however, the average SNR was 22 dB. Figure 3 highlights the locations with SNR less than 15 dB, as these are the areas in which error rates may be significant. It can be seen that using a receiver capable of decoding a signal with at least 3 dB SNR, over 95% of the home is in range of a single base station receiver when the SNUPI transmit power is set to 1 mW (65 µW for the radio). By reducing the power consumption to 950 µW (50 µW for the radio), over 90% of the home is still covered. We later discuss how the range and power can be further improved.

From these experiments we gained insight regarding the optimal locations to place the SNUPI nodes. Since SNUPI couples to the powerline, as a general rule: the closer to the powerline, the better the SNR. Therefore, it is best to place the sensor along the wall of the room, where the wiring typically runs. The worst locations are typically the center of the room, or walls without any powerlines. However, for multi-story homes, the center of rooms on upper floors typically have electrical wiring in the floor, because of lighting fixtures from the lower story. One can imagine a consumer using the electrical outlets, light switches, and light fixtures as a way to help with sensor placement. It is also important to realize that SNUPI couples to anything connected to the powerlines, not just the wires in the wall. As an example, we found that the SNR can be increased dramatically by placing the SNUPI node near power cords, power strips, and transformers which are commonly used with consumer electronic devices.

SNUPI is not restricted to indoor use, as the exterior walls of the home are a good location due to the wiring in the walls. In addition, outdoor areas with wiring for lighting can cause the range of the network to be extended into the yard. Since copper plumbing is required by code to be grounded, this network also acts as an extension of the powerline antenna, therefore extending the range to bathrooms and other areas with few electrical wires. To test this, two of the node locations used in the aforementioned tests were placed inside bathtubs.

Reliability

The SNR data presented in Figure 3 can be used to estimate the theoretical bit-error-rate (BER) for each sensor node location. The signal strength can be expressed in terms of the bit energy-to-noise density ratio (E_b/N_0), which is a function of the SNR, bandwidth (BW), and bitrate (r_b). Using E_b/N_0 defined below, the bit-error-rate can be calculated for 2-FSK using the following equation [12]:

$$\mathrm{BER} = \frac{1}{2}\,\mathrm{erfc}\left(\sqrt{\frac{E_b}{2N_0}}\right), \text{ where } \frac{E_b}{N_0} = \mathrm{SNR}\cdot\left(\frac{\mathrm{BW}}{r_b}\right)$$

For our prototype node, the bandwidth is 10 kHz, and the bitrate is 9.6 kbps. Using these values, Figure 4 plots the mapping from SNR to the theoretical bit-error-rate. For many users of a sensor node, it is more useful to know the rate of packet loss rather than the bit-error-rate. Assuming that the bit-errors are evenly distributed, we can estimate the packet loss using the fact that our prototype

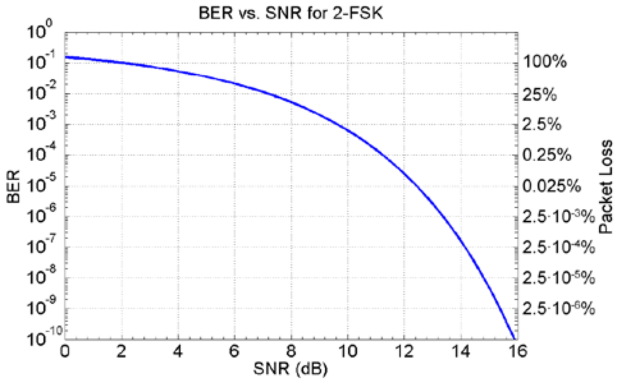

Figure 4.Thoeretical bit-error-rate and packet loss as a function of SNR for the SNUPI nodes

implementation uses 25-bit packets. Figure 4 also shows the expected packet loss.

The simplicity of our communications protocol comes at the expense of reduced reliability. For many wireless systems, data loss is intolerable, and as a result, complicated protocols are used to minimize the amount of data loss. However, in the case of low throughput in-home sensing, it is often the case that data loss is tolerable. For example, in environmental monitoring situations in which a data packet is beaconed once per minute, the loss of a packet every once in a while does not cause a problem. Since SNUPI was designed specifically for these applications, the reduced reliability is justified.

In applications in which a higher degree of reliability is required, the protocol can be changed to accommodate the reliability requirements. For example, longer error checking sequences such as cyclic redundancy checks (CRC), or error correcting codes (ECC) can be used. In addition, multiple retransmission schemes can be implemented to dramatically reduce the probably of data loss due to collisions, which pose a significant problem for large networks of unsynchronized transmit-only nodes [27].

IN-HOME SENSOR NODE TESTING

To demonstrate the successful transmission and demodulation of data sent from the SNUPI nodes to a plug-in powerline receiver, a simple experiment was setup to measure the light intensity in a home over a 3 hour period.

Base Station Receiver

We implemented a prototype base station receiver using a software defined radio. The Ettus USRP (Universal Software Radio Peripheral) was connected to the powerline through our powerline interface box, and the GNU Radio software platform was used to demodulate the signal. In order to demodulate the signal, we shift the incoming signal to baseband using a mixer and a low-pass filter, then use quadrature demodulation followed by another low-pass filter to generate the demodulated signal. The demodulated signal is then parsed to find each packet, which is checked for validity based on the ID bits and the parity bit. All packets with valid ID bits (*i.e.,* corresponding to ID values known to be presently in the system), and without parity errors are considered to be valid data.

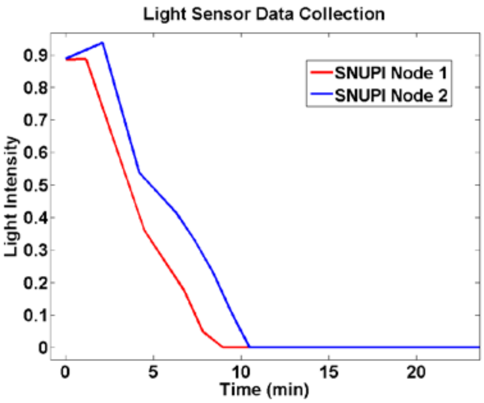

Figure 5. Light intensity data recorded simultaneously from two SNUPI nodes during 10 minutes of sunset, after which it became completely dark

Experimental Setup

Two SNUPI nodes were used simultaneously with the same base station receiver to demonstrate the ability for multiple nodes to share the same channel. Both nodes use an attached photo-resistor to measure light intensity which is sampled periodically once per minute, and then the data is wirelessly transmitted using the powerlines to the base station receiver. The nodes recorded the changes in ambient light due to the sun setting.

Results

Figure 5 shows a 25 min. segment of the 3 hour data collection in which there is a very noticeable decrease in the light intensity as the sun sets. After sunset, the room was completely dark, as indicated by the data. This experiment clearly demonstrates that SNUPI nodes can be used in a sensor network in which multiple nodes transmit data to be received by a powerline coupled base station receiver. Although no packet collisions were experienced in this short-term two node system, a longer deployment with more nodes is sure to produce collisions. The current protocol does not handle packet collisions, and the data is simply lost; however, as discussed earlier a more complicated protocol can be used to recover such data when robust data transfer is required.

COMPARISON TO EXISTING SENSOR NODES

To evaluate the novelty of SNUPI, it is essential to compare its power consumption to that of other similar sensor nodes. Since the application of the sensor node determines the required throughput of the data channel, we compare the *average power consumption* of each sensor node as a function of the *data throughput*. Our intended application area is whole-home sensing, and therefore we only evaluate nodes that work in this environment. In addition, this comparison is done independently of the sensor and the power supply (only the power consumption of the microcontroller, ADC, and transmitter are considered), and all nodes are configured to run in transmit-only mode.

Sensor Node (Frequency)	P_{on} (mW)	P_{sleep} (μW)	t_{on} (ms)	n_{tx} (bits)
SNUPI (27 MHz)	1.00	1.5	6.6	16
SunSPOT (2.4 GHz)	153	108.9	36	816
Crossbow Mica1 (916 MHz)	58.8	18900	16	232
Crossbow Mica2 (433 MHz)	36.3	42	10.6	232
Crossbow MicaZ (2.4 GHz)	65.1	7.2	41	928

Table 1. Measured power consumption parameters for each sensor node under comparison

Comparing sensor nodes based on their published data is difficult and certainly not unbiased, and therefore we directly measure the parameters of interest in a lab environment from each of the sensor nodes. The parameters of interest include the power consumption and time period of each of the two phases of operation, the on-phase (P_{on}, t_{on}), and the sleep phase (P_{sleep}). During the on-phase, a single packet of data is transmitted, and contains n_{tx} bits of data, excluding the packet header and footer. Using these measured parameters, we calculate the average power consumption of each sensor node as a function of the data throughput (R), expressed in bits per unit time:

$$P_{avg} = \frac{R\, t_{on}}{n_{tx}} P_{on} + \left(1 - \frac{R\, t_{on}}{n_{tx}}\right) P_{sleep} \text{ for } \frac{R\, t_{on}}{n_{tx}} \leq 1$$

When comparing the power consumption of several sensor nodes, it is important to attempt to normalize the performance of each node. For example, one node may consume significantly more power, yet it achieves a much greater range, and has a more reliable communications protocol. In this comparison we attempt to equalize the transmission range and the reliability of the nodes under consideration. We compare the average power consumption of SNUPI to several popular commercial wireless sensor nodes for whole-home sensing, the ZigBee-based SunSPOT [26] and the Crossbow Motes [7]. All nodes were configured to run in *transmit-only* mode in order to make a fair comparison to SNUPI, which does not have a receiver.

Table 1 shows the parameters measured from each of the sensor nodes, and Figure 6 plots the average power consumption of each sensor node as a function of the throughput using the equation above. In order to express these results in a more tangible way, we assume that all of the sensor nodes are powered from a 3 V, 225 mAh battery, and then we calculate the battery life of each node (see Figure 6) using a simplified model of battery life, where Q is the battery capacity and V is the battery voltage:

$$t_{life} = \frac{QV}{P_{avg}}$$

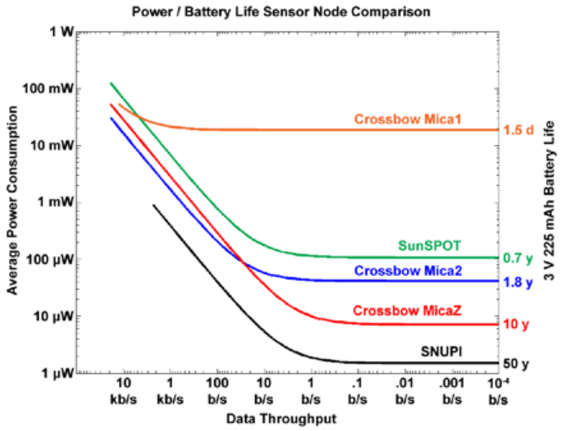

Figure 6. Average power consumption and battery life over throughput for five sensor nodes

Results and Analysis

It can be seen from the sensor node comparison shown in Figure 6 that at high throughput rates, the transmit power dominates, but for low throughput applications, it is the sleep power that determines the battery life of the node. From Figure 6, it is clear that the commercial nodes can operate at higher throughput rates than SNUPI, but for the entire range of throughput for which SNUPI operates, it consumes significantly less power. We discuss later how SNUPI's bitrate can be increased to accommodate high throughput applications. The sleep power of SNUPI is so low that without a sensor attached, the calculated battery life of the node is 50 years, which is far longer than the shelf life of the battery. Of course, a sensor can dramatically reduce the battery life of the node, but the SNUPI node still has a battery life five times longer than the next best sensor node.

In addition, we compare SNUPI to Bumblebee, a state-of-the-art 433 MHz wireless sensor node in the research community, which to our knowledge is the lowest power wireless sensor node in existence [22]. Bumblebee was designed for a very short range (<15 m) neural tag, and is therefore not suitable for whole-home applications. In addition, Bumblebee does not incorporate a general purpose microcontroller, but rather has a fixed ADC integrated onto the radio chip. Bumblebee has a startup time very comparable to SNUPI, but since it does not have a full microcontroller, the total node transmission power is significantly lower: 500 μW, compared to 1000 μW for SNUPI. Since these nodes are very different, it makes more sense to compare only the transmitter of each device. Bumblebee has 433 MHz radio that can transmit 15 m and consumes 400 μW, while SNUPI has a 27 MHz radio that can transmit data to anywhere within a 280 square meter home using only 65 μW of power.

DISCUSSION

Our initial results show that the SNUPI node has taken a significant step in overcoming the power consumption and battery life barrier that restricts the use of wireless sensor networks for long-term deployments in ubicomp applications. Here we discuss optimizations that could be applied to SNUPI to further increase performance, future work in designing the receiver, and a new class of ubicomp applications that can be enabled using SNUPI.

Node Design Optimizations

Using the existing SNUPI prototype, several strategies can be used to increase the SNR and therefore improve the range and reliability. Since the SNUPI nodes have an adjustable power output, the easiest way to improve the signal quality is to simply increase the power output of the nodes in locations with poor SNR. This solution of course requires more power and therefore reduced battery life. The same change can be made in the opposite direction to increase the battery life of a node in a location with a higher SNR than needed. There are also ways of increasing the range without increasing the power. Since SNUPI couples its signals to the powerline, the distance between the node and the powerline is often the most significant parameter affecting signal strength. The powerline can also effectively be moved closer to a node, by running an extension cord plugged into the wall at one end near a SNUPI node placed in a location with poor SNR. From our testing, the presence of the extension cord (without a load attached) 1 m away from the node increased the SNR by 3 dB, and bringing the extension cord 0.5 m away increased the SNR by 11 dB.

There are several ways to improve the design of the SNUPI node itself. Increasing the bandwidth and bitrate would allow many more applications to take advantage of the ultra-low-power capabilities of SNUPI. Currently, the bandwidth is limited by the capacitance that can be switched in and out of the oscillator while allowing it to continue to oscillate. A different oscillator design or multiple oscillators can increase the bandwidth, because the radio now consumes negligible power compared to the rest of the node. The addition of an ultra-low-power receiver on the node would result in more reliable communications, and enable many additional applications. We plan to design an ultra-low-power 27 MHz receiver and explore bidirectional communications over the powerline.

Other design optimizations can further reduce the power consumption. The startup time is a source of wasted power, because both the microcontroller and the radio are on and consuming power during this time. The current prototype could benefit from a substantial decrease in startup time by changing some of the component values; however, this requires a complicated optimization of several circuit parameters. To design a robust prototype quickly, which could be duplicated many times, we chose a conservative design approach in terms of startup time. As discussed earlier, increased current will allow the transmitter to startup faster, and thus we could use a more complicated scheme to drive large currents initially to get the transmitter started, and then turn the current down to save power.

Because the power consumption of the node is dominated by the microcontroller rather than the radio, the most obvious next step would be to reduce the microcontroller's power consumption. Although the MSP430 is highly optimized for general purpose ultra-low-power applications, a custom circuit for only the control and computation required on the SNUPI node could result in significant power savings. In addition, this digital controller could be implemented on the same CMOS silicon die as the radio, and therefore reduce the size of the node.

There are several additional optimizations that can reduce the size of the node, which would enable several new applications. Currently, the size of the node is dictated by the antenna size. In this work, we show that the transmitting antenna on the node can be highly inefficient because the receiving antenna (*i.e.*, the powerline infrastructure) is very efficient at 27 MHz. It may be possible to further reduce the size of the antenna without a serious performance penalty. We envision integrating the antenna into the PCB by using a single copper trace, which could allow the remainder of the PCB to shrink down to the size of the battery.

Base Station Receiver Design

This work focuses on the design and implementation of the sensor node, but the base station receiver is an equally important element in a SNUPI-based sensor network. We will design and implement a base station receiver optimized for powerline coupling. This includes determining a method for choosing the optimal receiver location, finding a way to reduce losses by impedance matching the receiver to the dynamically changing powerline network, and designing a receiver to work well for signals with very low SNR.

Applications of SNUPI

Having truly long-lived (~10 years) and small wireless sensor nodes enables a breadth of ubiquitous computing applications in the home and other environments. These wireless sensors can be sealed and embedded in rigid devices with no requirement for wired connections to the outside environment, installed behind walls or hard-to-reach areas, such as crawl spaces and attics, or even inside the wall cavities of piping and ductwork. Using 27 MHz also addresses many challenges with signal absorption and attenuation caused by people and other objects, thus enabling a new class of long-lived wearable applications.

SNUPI is the lowest power radio to date that offers a practical communication range in the home with a single base station receiver. Despite this, it is not intended to replace existing wireless sensor network technologies for all applications. SNUPI has two limitations that preclude certain applications. First, SNUPI nodes obviously require a powerline infrastructure in close proximity. Second, nodes currently can only transmit, and are not capable of receiving data from the base station. We envision a wide array of applications for which these are not problems. One example is environmental sensing within a home, such as temperature, light, air quality, and humidity. The vision of a "smart" home typically includes at least some of these sensors for adapting a home's lighting and climate control. Yet, up until now, post-deployment maintenance of the power source has been a significant barrier to sensor deployment and the realization of this vision. Other smart home applications include easily deployable security systems via SNUPI-based motion sensors, glass-break detectors, or automatic leak detection via moisture sensors.

On-body sensors are also possible, opening up the health application space. Health-related sensors such as pulse oximetry, blood pressure sensing, stress detection via galvanic skin response, or glucose monitoring could be either worn on-body or even implanted in-body. Through our experimentation, we have seen that the proximity of a human body to the SNUPI node significantly increases the received SNR. We plan to explore this further, as such a property would make SNUPI an ideal node for any kind of wearable or in-body sensing system.

CONCLUSION

We presented SNUPI, a new platform for in-home wireless communication and sensing that extends both the range and battery life of wireless sensor nodes in a home. The novelty of the SNUPI node is both in the way it sends its data and in the ultra-low-power design of its components, where the radio transmitter is no longer the dominant power consumer. SNUPI is unique in that it uses the existing powerline infrastructure as its wireless communications channel, thus enabling whole-home range with a single base station receiver. In addition, it employs a custom designed ultra-low-power CMOS transmitter which allows it to operate for several years without replacing the battery.

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