LightWave: Using Compact Fluorescent Lights as Sensors

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ABSTRACT
In this paper, we describe LightWave, a sensing approach that turns ordinary compact fluorescent light (CFL) bulbs into sensors of human proximity. Unmodified CFL bulbs are shown to be sensitive proximity transducers when they are illuminated. This approach utilizes predictable variations in electromagnetic noise resulting from the change in impedance due to the proximity of a human body to the bulb. The electromagnetic noise can be sensed from any point along a home's electrical wiring. This allows users to perform gestures near any CFL lighting fixture, even when multiple lamps are operational. Gestures can be sensed using a single interface device plugged into any electrical outlet. We experimentally show that we can reliably detect hover gestures (waving a hand close to a lamp), touches on lampshades, and touches on the glass part of the bulb itself. Additionally, we show that touches anywhere along the body of a metal lamp can be detected. These basic detectable signals can then be combined to form complex gesture sequences for a variety of applications. We also show that CFLs can function as more general-purpose sensors for distributed human motion detection and ambient temperature sensing.

Author Keywords
Capacitive sensing, EMI, CFLs, interaction, gesture, proximity sensing.

ACM Classification Keywords
H5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

General Terms
Algorithms, Experimentation, Measurement.

INTRODUCTION AND MOTIVATION

Developing easy-to-deploy sensing approaches has long been a focus of ubiquitous computing research. In particular, home environments are very challenging to instrument because they demand sensing solutions that are unobtrusive, low-cost and easy to maintain. The desire for new types of sensors in home environments also extends to a need for new interaction modalities that can be enabled by these easily deployed sensing infrastructures.

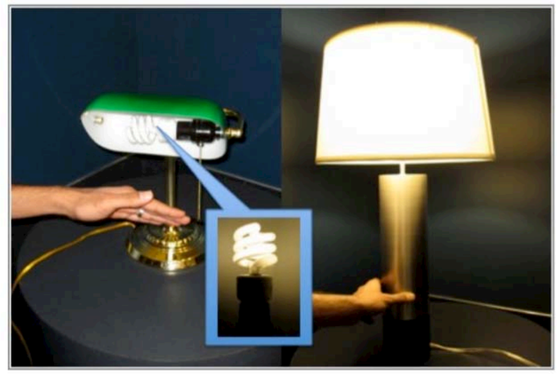

Figure 1: A user performing a hover gesture (left) near a compact fluorescent light (CFL) lamp, and a user touching the metallic base of a lamp (right). Both of these gestures can be detected using a single plug-in module.

In a typical sensing solution, one sensing system is required at each interaction point in the interaction space. For example, capacitive touch sensors can be used to turn any surface into an interaction point; however, an individual capacitive sensor is required on *each* interaction surface. Recently, video and depth cameras have been used to dramatically expand the interaction space; however, the user can only interact directly in front of the camera, and therefore many cameras are needed to allow interaction anywhere within a large space. Although many of these natural user interaction systems may be low-cost on a per sensor basis, the number of sensors required to instrument an entire interaction space make these systems potentially cost-prohibitive, as well as time-consuming to install and setup, and difficult to maintain, in the case of battery powered devices.

To alleviate some of these challenges, past solutions have looked at leveraging the existing infrastructure for sensing [3,14,7,8,10,13,14,15]. Some approaches have used the motion sensors found in alarm systems [1] and the changes in airflow through the HVAC system for detecting human motion [15]. Some have eliminated the need to instrument the environment by requiring the user to carry or wear a sensor-enabled device [9,11,12]. However, the need to wear sensing devices may make these approaches undesirable in the home setting. Another approach is to take advantage of the existing devices in the home and *repurpose* them as sensors. For example, researchers have shown how ordinary LEDs can be used as a both light emitters as well as light detectors [6].

In this work, we build on this general concept by introducing an approach that repurposes existing compact fluorescent lamps (CFL) as human proximity sensors. This approach requires *no modification to* the CFL bulbs, the lamp fixtures, or the human body, and many CFL fixtures can be used as sensors using only a *single* interface device plugged into any available electrical outlet. Our approach uses variations in the electromagnetic interference (EMI) generated by all CFL bulbs. We show that these "signals of opportunity" generated by the CFL's built-in power supply contains a characteristic pattern of fundamental and harmonic components that vary with the proximity of a human hand or body. These variations result from the change in CFL bulb-circuit impedance as a human body or another conductive object approaches the lamp. Thus, in essence, it can be thought of as an already-ubiquitous capacitive sensor (see Figure 1)

We demonstrate this phenomenon by evaluating it in the context of sensing and detecting a variety of basic gestures performed by a user, including: (1) *hover*: the passing of a hand near a CFL-equipped lamp, (2) lamp *shade touch*: touching the lamp shade with one or more fingers, and (3) *bulb touch*: touching the bulb with one or more fingers. Note that CFL bulbs operate at very low power compared to incandescent bulbs and as a result they do not get dangerously hot when installed in an open fixture (40 degrees Celsius for a 13W lamp). We mainly explored touching the glass on the bulbs to better understand the possible gamut of observed signals and their properties. Touching the bulb itself is one possible interaction technique, even though it may not be appropriate for all lamps. We anticipate that hovering or touching the lampshade or metallic base will prove to be more useful gestures in most cases.

Although our focus is initially the detection of simple gesture events, we use it to show the robustness and significance of using CFLs as a sensor. We have also observed other interesting properties of the CFL and its built-in power supply that could be used as a more general purpose distributed sensor, such as monitoring the changes in ambient temperature, detecting distance of user's hand from the lamp, or human motion detection.

An important implication of our approach is that each CFL in a home can be thought of as a low-cost general-purpose sensor that is inherently networked since all bulbs are connected to the power line. Only a single power line interface is needed to observe all of these CFLs. Since CFLs are also becoming increasingly ubiquitous due to their much higher efficiency compared to incandescent lamps, longer lifespan, and potential cost savings from reduced electricity consumption, we can expect them to be installed in many locations in a home already. Modern commercial and residential buildings looking to comply with certain "green" certifications, such as the LEED building certification system, require that the lighting be Energy Star® compliant (in the US, and similar programs across the world). Additionally, many utilities and power companies have programs that subsidize the purchase of or give away CFL for residential customers[1].

The specific contributions of this paper are:

1) The novel use of CFLs as capacitive sensors that require no additional instrumentation of the bulb, light fixture, or human.
2) A set of experiments that show the reliability of detecting hand gestures across different people as well as different CFL bulb brands, shapes, styles, and lighting fixture types. Additionally, we show that multiple CFLs (even of similar brands) can be distinguished when operating simultaneously.
3) We also show how CFLs could be used for human proximity detection and general ambient temperature sensing.

RELATED WORK

Capacitive and Electric Field Sensing

The fundamental phenomenon that LightWave leverages is variations in the observed EMI generated by the built-in CFL power supply. This EMI varies in response to changes in the impedance of the CFL bulb circuit due to variations in the local electric fields surrounding the bulb. These electric field variations are caused by the movement of grounded conductive objects in the space near the bulb. When the bulb is illuminated, the ionized gases within the bulb are conductive and they form the sensing electrode of a capacitive sensor.

Capacitive sensing has a long history in sensing human proximity. The first popular use of electric field (EF) sensing for machine control, or 'performing gestures' was Leon Theremin's musical instrument. The Theremin instrument is played by moving the body with respect to two antennas, one to control the pitch of sound and other to control the amplitude. This allows the performer to play music without making physical contact with the device. The capacitance between the human body and the Theremin's antenna is small, on the order of hundreds of femtofarads to a few picofarads. This capacitance detunes an L-C oscillator inside the Theremin causing an easily detectable frequency shift. EF sensing based on a similar concept has

[1] EU mandate to adopt CFLs. http://europa.eu/rapid/pressReleasesAction.do?reference=IP/08/1909

since been applied to graphical and human computer user interfaces for sensing touch and 2-D motion gestures as well as for sensing the position of a person in a room. These systems can operate in shunt mode where the human shunts an electric field to ground, or transmit mode, where the human conducts the electric field to a receiving electrode [17,18].

The key requirement for EF sensing is the presence of an electric field created by a high frequency oscillator. In prior work, such a field is explicitly generated by dedicated circuitry, which is installed at each point where sensing is desired. Cooley et al. demonstrated a human proximity system that uses modified fluorescent lamps as capacitive sensors, by monitoring distortions in the lamp's EF over time depending upon how people move under it. Though electromagnetically similar to our work, Cooley et al.'s approach requires that the lamp be instrumented with additional circuitry to measure the EF [5]. LightWave on the other hand does not require any additional instrumentation, since it does not measure the change in EF directly, but instead its effect on the variations in existing conducted EMI, which can be measured from anywhere in the home. Other work in the defense community has exploited ionized gases in fluorescent tubes as plasma-based radio frequency communication antennas that "disappear" when the voltage that ionizes the gas is removed [2].

EMI Sensing in a Home

Researchers have considered using the EMI generated from switch mode power supplies (SMPS) to infer the use of electronic devices in the home, including CFLs [10]. Although our approach uses a similar method of monitoring the power line for this EMI noise signal, prior work has largely focused on the presence or absence of this noise over the power line. In addition, the signal characterization was focused on identifying stable, environment-invariant signal features such as center frequency, bandwidth, and variance whereas LightWave examines the EMI noise signal much more closely to detect small changes in the CFL's operating parameters. Gupta et al. also showed that it is possible to differentiate among similar devices in the home using a single monitoring point, which implies that one could use a collection of CFLs already installed in a home as distributed sensors.

Recent work has also examined the use of radiated electromagnetic noise for gestural interaction by looking at the amount of noise coupled onto the human body, by using the body itself as a receiving antenna. The amount of noise picked up by the body is then used to infer physical touch points in the home [4]. One drawback of this approach is that it requires the user to carry a custom device for detecting this EM noise being coupled to the human body. In a way, our approach is the reverse since the human body is changing the characteristic EMI of the CFLs attached to the power line, and does not require the instrumentation to be carried by the human.

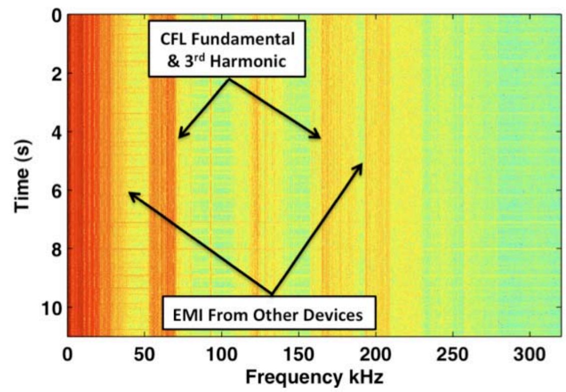

Figure 2: Spectrogram showing electromagnetic interference that various devices produce as observed on a power line. Only part of the full spectrum (500 kHz) is shown for clarity.

BACKGROUND AND THEORY OF OPERATION

Electromagnetic Interference On the Power line

Electrical noise present on a power line when a device is operational is called conducted electromagnetic interference, which can be classified into two types: transient and continuous. Transient noise is characterized by the short duration for which it can be observed, generally tens of nanoseconds to a few milliseconds. Transient noise is most often observed in conjunction with a switch open or close event. Continuous noise on the other hand can be observed for as long as the device is operational. A CFL bulb is an example of a device that generates continuous noise, which is then conducted onto the power line due to its physical connection with the power line. Since a home's electrical infrastructure is interconnected in parallel, conducted EMI coupled onto the power line at one location propagates throughout a home's electrical infrastructure. Figure 2 shows EMI observed on a typical power line infrastructure.

Continuous noise is usually intrinsic to the device's operation and internal electronics. A CFL lamp, for example, generates EMI at frequencies that are harmonically related to its power supply's internal high frequency oscillator.

Variations in CFL's Line-Conducted EMI

When a human is in proximity to a CFL, the conducted EMI changes in amplitude, fundamental frequency, and the distribution of harmonic energy among the harmonics. LightWave detects these changes in amplitude and shifts in frequency to infer when a human is in proximity to the lamp, and determine what kind of interaction took place. To better understand how the EMI changes as a result of human proximity, it is essential to understand the basic operation of a CFL. Figure 3 shows a highly simplified block diagram of a typical CFL.

A CFL has two main components: a gas filled tube (e.g., the bulb), and an electronic circuit called a ballast. In a CFL, the ballast is integrated with the bulb into a single unit; however, in other styles of fluorescent fixtures the ballast is

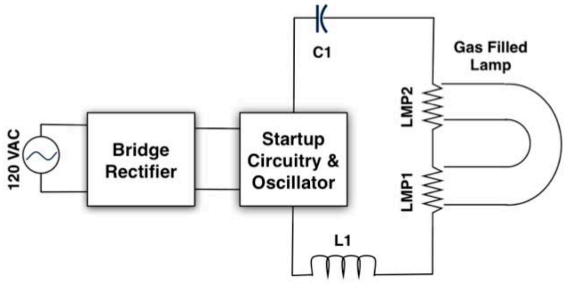

Figure 3: Simplified block diagram of a CFL. L1-Lamp-C1 forms a series resonant circuit. Human proximity causes the effective capacitance to change and detune the oscillator.

separate from the bulb. The ballast is connected to the line voltage (120V/ 60 Hz AC in the US), which is rectified and stepped up by a high frequency switching power converter to around 300 V AC, which drives the fluorescent tube. The reason for using high switching frequencies, typically around 40 kHz, is the increased efficiency of the power converter circuit as well as the smaller size of components, thus making the entire CFL unit both compact and more efficient. This high frequency can be achieved by a variety of methods – from simple L-C resonant oscillators in cheaper lamps to microcontroller-controlled oscillators in others. Irrespective of the mechanism to generate the high frequency, the purpose of the resonant circuit is to stabilize the current through the fluorescent tube as the bulb warms up, and then maintain equilibrium in lamp current and voltage. Thus during operation, the oscillator is at resonance with the L1-Lamp-C1 series network as shown in Figure 3.

This equilibrium can be disturbed in many ways, including changes in the supply voltage, current, or failure of a component. Additionally the bulb's equilibrium state is disturbed by capacitive and/or ambient temperature changes in and around the lamp. This state change can be detected in the bulb's EMI signature.

The bulb itself serves as a sensing electrode because the CFL's electronic ballast generates a strong electric field inside the bulb to ionize the internal gases and produce light. However, this process also produces a strong electric field around the periphery of the bulb, because the ionized gases act like a single equipotential electrode. The field that results is similar in essence to electric fields that are explicitly generated for capacitive proximity sensing [18], with the difference that, the former is a *by-product* of the way CFLs functions and latter is intentional.

By moving a hand in the vicinity of the CFL, the electric field surrounding the bulb is disrupted and there is an increase in the effective capacitance in the lamp circuit since the human body is essentially a capacitor to ground. In a traditional capacitive proximity sensor, this change in capacitance results in a change in displacement current, which is sensed directly. In contrast, the displacement current being coupled from a CFL results in a small

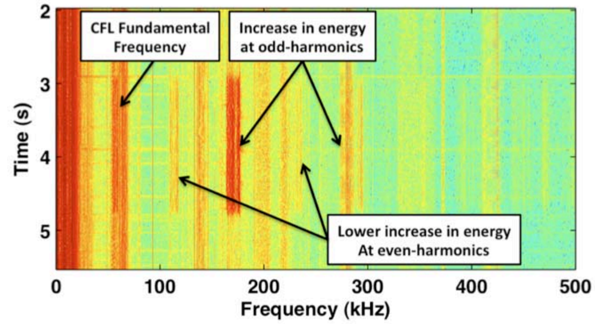

Figure 4: Spectrogram showing change in observed EMI as a result of touching the CFL bulb, which causes a large capacitive change resulting in increased energy.

imbalance in the oscillator and bulb equilibrium, resulting in a shift of the CFL's fundamental resonant frequency by 1–5%. A balanced oscillating circuit tends to suppress even-order harmonic products, while unbalancing it tends to enhance odd-order products. Figure 4 shows how the energy at odd-harmonics increases when a bulb is touched – creating an even more significant imbalance than that created by human proximity. It should be noted that multiple similar CFL bulbs could be operating simultaneously in an environment or on a common electrical circuit without effecting LightWave's ability to detect the change in energy. This is because, the harmonic energy only increases when the capacitance changes, thus two lamps could be on, but neither could be generating increased energy at the odd-harmonics.

When a user brings their hand close to the CFL lamp, it causes an increase in energy at the harmonics, but the change is much smaller and harder to visualize on a spectrogram. These changes are only reliably detectable after significant filtering and post processing as described in the following section.

SYSTEM DESCRIPTION AND IMPLEMENTATION

Electromagnetic interference conducted onto the power line by various electrical devices can be measured by sampling the voltage on the power line at appropriate frequencies. Since the power line has a very strong 60 Hz signal (50 Hz in Europe and Asia) meant to power electrical appliances, it is necessary to reject this 60 Hz component using high dynamic range analog circuitry. Our prototype system makes use of an analog high-pass front end, similar to one described by Gupta et al. in [10], but modified for a wider frequency response (corner frequency of 5.3 kHz). The signals from the front end are then digitized using USRP-1 (Universal Software Radio Peripheral), a general purpose, software configurable FPGA-based digitizer equipped with a 12-bit dual-channel ADC. The digitizer is configured to sample the voltage at 1 MS/s and compute a 16,384-point Fast Fourier Transform (FFT), yielding 61.03 FFT vectors per second. The magnitude in dB of each FFT vector is then computed before it is fed into the signal processing chain (see Figure 5), for further processing and detection of events.

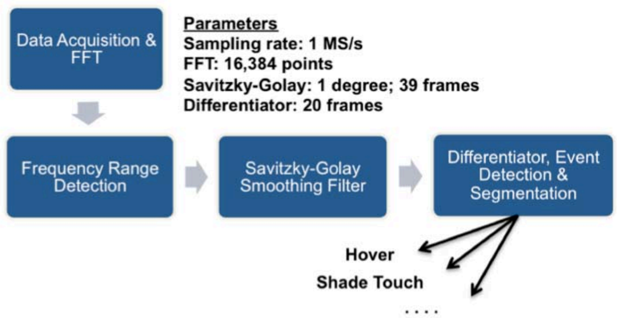

Figure 5: Stages of the signal processing chain that condition the input signal, apply differentiators, detects and segments events.

We define events as instants in time when a human is in proximity to a CFL and performing a gesture. Since our input signal is real valued and we are only interested in the magnitude, the magnitude FFT vectors are symmetric around baseband, and hence half of the bins are redundant. These are truncated, reducing the number of points in the FFT vectors to 8192 across a spectral width of 500 kHz.

Frequency Range Detection

As described earlier, human proximity to a CFL appears as increased energy in harmonics of the fundamental frequency at which the CFL produces EMI. Thus, the first step is to identify the fundamental and harmonic frequencies. Though most CFLs have a switching frequency between 40 kHz and 120 kHz, it can vary from one brand to another and thus setting a global range for all lamps is not practical. If the range to monitor is set too wide, the aggregate noise power from other sources reduces the overall signal to noise ratio. This makes the detection of changes in harmonic energy less reliable. Thus, a potential solution is to setup multiple narrow ranges specific to each CFL lamp and monitor each simultaneously.

Earlier prototypes of LightWave required that these frequency ranges be set manually for each lamp. This manual approach was later discarded in favor of a simple one-time calibration step, which involves switching each lamp on and off twice. By turning the lamp on and off, LightWave can detect the fundamental and its harmonic by looking for presence and absence of EMI on the power line. Actual measurement of the frequency of the fundamental is made only during the second on/off sequence, since during first interval the CFL bulb could be warming up, during which the frequency changes until the bulb reaches thermal equilibrium with its environment.

Once the frequency range for the desired bulb's 3rd harmonic is identified, a sum across this entire band is computed. For each FFT vector in time, a sum of energies in this range of frequencies is computed. Figure 6 (left), shows such a running sum plotted over time for a lamp. When the energy in this range increases as a result of a gesture or human proximity, the sum also increases. The reason a sum over a frequency band is computed instead of tracking individual frequency bins over time is because even when the CFL is in equilibrium, its fundamental frequency shifts a few kHz over time due to temperature changes. Tracking a range of frequencies (in tens of kHz) is immune to such small shifts.

Smoothing the Summed Energy

As evident from Figure 6 (left), the tracked sum over time is quite noisy and cannot be directly used for reliable event detection. In addition to EMI noise from other appliances, occasional broadband noise also plagues the signal. The source of such broadband noise could be from flicking mechanical switches [14], noise from dimmers, or other switch mode power supplies. Prior to taking the sum in a range of frequencies, we discard FFT vectors where the sum across the entire spectrum is more than 4 standard deviations greater than the running mean over 15 FFT vectors.

To smooth the summed energy time series data, we experimented with several filters, beginning with the standard averaging FIR filters and a moving window Gaussian smoothing filter, but found that not only did they not remove the high frequency noise, but also 'smoothened out' the peak from the gesture event itself, making it flatter and more difficult to detect. We found that the Savitzky-Golay smoothing filter with a degree of 1 and frame length of 39 to be most effective (see Figure 6 (center)). Not only does it remove the high frequency noise, but it also maintains the underlying shape of the peak. We apply two passes of the same filter on the summed data, which

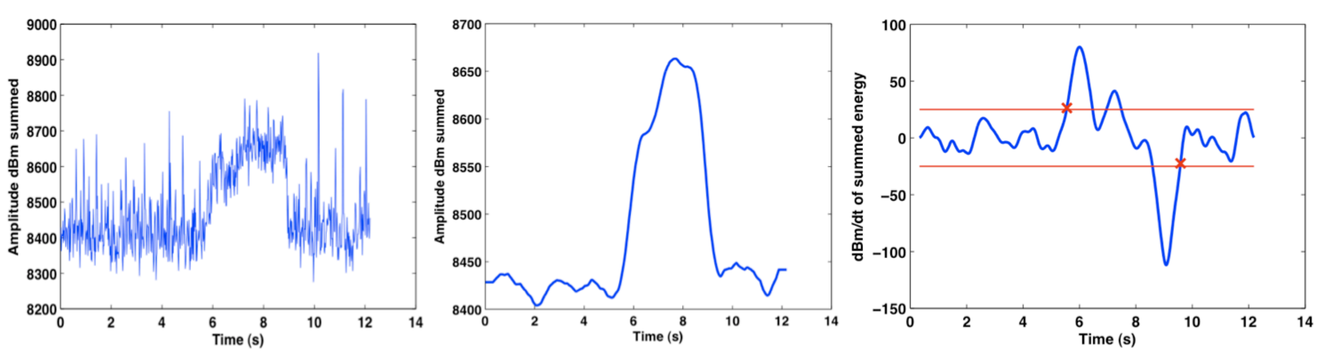

Figure 6: Summed energy in band over time shows increase in energy as a result of a hover (left), filtered summed energy (middle) and first derivative waveform along with start and stop of the hover event as detected (right).

minimizes noise and makes the event detection more reliable.

Event Detection and Segmentation

We make use of a moving window first order derivative filter with a frame size of 20 to obtain a signal that gives us an indication of any abrupt changes in the signal. Since small abrupt changes also cause the derivative filter's output to generate a peak, it is necessary to set a rejection threshold. That is, we only want to consider changes in summed energy that are abrupt as well as large in magnitude. We chose a threshold value of 25 dB/dt (dt = 20 frames, 0.327s), which has good sensitivity to detecting hovers and other gestures while still maintaining a low false positive rate. The ROC curve characterizing the tradeoff between true positive rate and false positive for different threshold values is described later in the paper. It should be noted that this single threshold works across all people and all lamps that we tested. Figure 6 (right), the red lines show the threshold.

When a hand approaches the lamp there is an increase in the summed energy signal producing a large positive spike from the derivative filter. As the hand moves away from the lamp, the summed energy signal decreases back to its baseline level, producing a comparable negative spike in the derivative filter. We leverage this phenomenon in finding the beginning and ending of an event.

We also leverage the expectation that a large positive derivative should be directly followed by a large negative derivative to prevent the algorithm from over-segmenting a single event. This is necessary because during the event the summed energy signal is larger than normal, resulting variations in the signal that are also more intense – for example, when a user's hand naturally moves closer or farther while performing a gesture. These subtle variations can also result in shifts in the derivative signal. An example is shown in Figure 6 (right). The signal rises above the positive threshold, falls below it and rises again (due to variation in signal *during* the event). We wish to ignore the second positive threshold crossing to avoid overly segmenting a single event. This is easily achieved by building hysteresis into our threshold values.

Events that surpass the derivative threshold must also meet a set of specific constraints. First, a positive derivative, which surpasses threshold, must be followed by a negative derivative value that surpasses threshold at least after 600 ms, but no more than 5 seconds. Second, the peak derivative value of a positive spike and magnitude of the negative spike must be within 30% of each other. This ensures that dissimilar spikes are not matched. Third, when two or more consecutive positive spikes are followed by a negative spike, the process is repeated for each spike, in chronological order. If a match is made, the remaining positive spikes are discarded and the algorithm moves on, begins searching for another positive spike after the matched negative spike. It should be noted that the

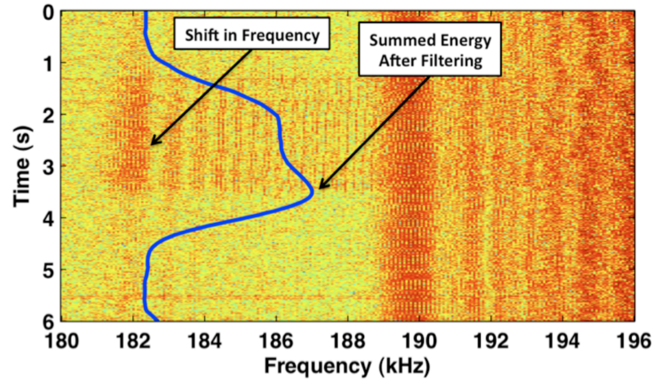

Figure 7: Summed energy in band (blue line) tracked over time overlaid with the spectrogram showing EMI from CFL. Notice the bump in blue line and increase in harmonic energy at 182 kHz in the spectrogram as a user hovers for 2.5 seconds.

maximum duration only limits the time for each gesture, not the time between them or the total duration of a complex gesture. For example, one can perform three hovers one after another forming a single complex gesture (at an application level) that lasts 6 seconds and each hover will be detected. Points marked with an 'x' in Figure 6 (right) show the start and end of a segment as found by this search algorithm. These segments are then outputted as events.

OBSERVABLE SIGNALS AND USING THE CFL AS A SENSOR

In this section, we detail the variations that LightWave can observe in the EMI signal from a CFL and the potential uses of it as a "sensor." Since not all of the minute changes in the EMI are visually apparent on a spectrum analyzer, our signal-processing pipeline was critical in identifying some of these signal variations.

Hover

As described previously, when a human is in proximity to a CFL lamp it can cause changes in capacitance of the resonating circuit resulting in variations in the observed EMI. This allows LightWave to sense hover gestures. Thus, when a person passes their hand close to a CFL lamp, it produces a detectable change in the energy levels of the EMI. This 1-bit binary information of whether a hand is near or not, coupled with timing information (time duration of the energy increase) can be used as a basis for complex gestures. Figure 7 shows how the EMI changes when a person hovers their hand close to a CFL. Observe how the energy in the 182–189 kHz band increases as a result. The small bumps are the slight movement of the person's hand under the bulb.

Touches on Lamp Shade, Bulb, and Base

Much like a hover, touching the lampshade or the bulb also causes an increase in the harmonics energy. Since CFL bulbs are not dangerously hot like incandescent bulb, especially when installed in an open fixture, we decided to experiment with touching the bulb as well. We measured the temperature of the bulb and found it to be around 40 °C

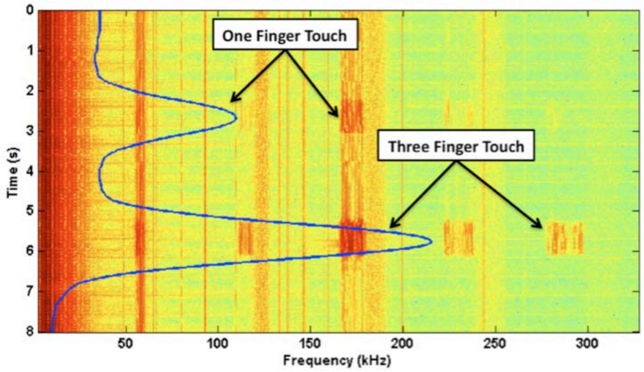

Figure 8: Notice the difference in amplitude of energy between a one finger touch on bulb and a three finger touch. Blue line is filtered sum of these energies over time.

for a 13W CFL. The key difference in a hover and touch is the amplitude of the energy increase.

A hover event produces the smallest capacitive coupling, followed closely by touching the lampshade and bulb touch produces the most coupling. An interesting signal observed with touch gestures is that the amplitude of the signal is proportional to the surface area of the contact. That is, the energy amplitude of the signal observed is much higher when the bulb is touched with three fingers than when touched with one. Figure 8 shows an overlay of energy tracked over time for one-finger and three-finger touch on top of the spectrogram. Notice the amplitude difference between the first touch and the second. Also, for metallic lamp fixtures, it is even possible to detect touches on the base of the lamp (see Figure 1), which produce a similar response to the lampshade being touched.

Changes in Proximity

The change in proximity of a user's hand to the CFL, that is, whether the hand is moving away from the lamp or towards the lamp can be detecting by observing the slope of the signal. When the hand is moving towards the lamp, instead of seeing an abrupt increase in energy, a gradual increase is seen since the amplitude depends on how far the user's hand from the lamp is. Figure 9 shows an instance where the hand is moved towards the lamp and then abruptly removed. From our experience, the hand can be as far as 30 cm from the CFL bulb and be detected.

Detecting Ambient Temperature Change

In addition to variations in EMI as a result of capacitive changes from touches and human proximity, we also observe changes in EMI when the temperature of the CFL bulb or the ambient temperature around it changes. Instead of an increase in harmonic energy, changes in temperature cause the frequency to shift up to tens of kHz. Tracking the fundamental frequency over time can give an indication of changes in ambient temperature around the lamp. If calibrated, we can measure the true ambient temperature.

We observed that when the ambient temperature around the lamp is increased, it causes the frequency at which the CFL's EMI is observed to shift to a lower frequency. To

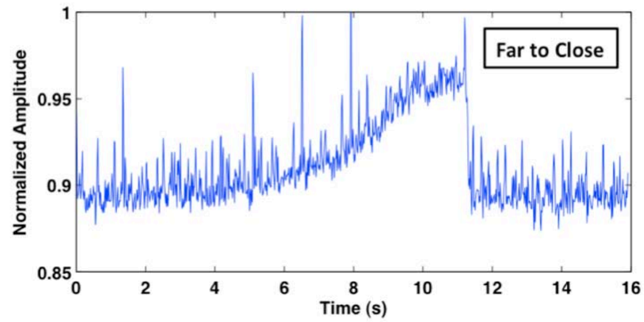

Figure 9: Amplitude of the observed energy depends on the proximity to the lamp. Amplitude gradually rises when a hand is brought closer over time.

verify this phenomenon, we performed two experiments. In both experiments, we put a CFL bulb on a tray along with a thermocouple based digital temperature sensor. We let the bulb stay on for 10 minutes to reach room temperature (temperature of environment at time was 27 °C). In the first experiment, we used a heated chamber whose inside temperature was around 65 °C. We then introduced the tray with the bulb and the temperature sensor into the chamber. The second experiment was similar, but instead of a heated chamber, we used a small refrigerator, with an internal temperature of 18 °C. Figure 10 shows the change in frequency as a result of the heated chamber experiment. The change in the CFL's fundamental frequency tracks closely with the change in ambient temperature.

With these preliminary experiments we wanted to confirm that EMI changes as the ambient temperature around the lamp changes. This change in frequency with temperature opens up the possibility of using CFLs in a home as distributed temperature sensors. This technique could also be used to monitor large or abnormal increases in lighting temperature to detect potential safety hazards. We also observed that the CFL as a temperature sensor has an incredibly fast response time, which can be used as an air movement or air convection sensor. For instance, this can

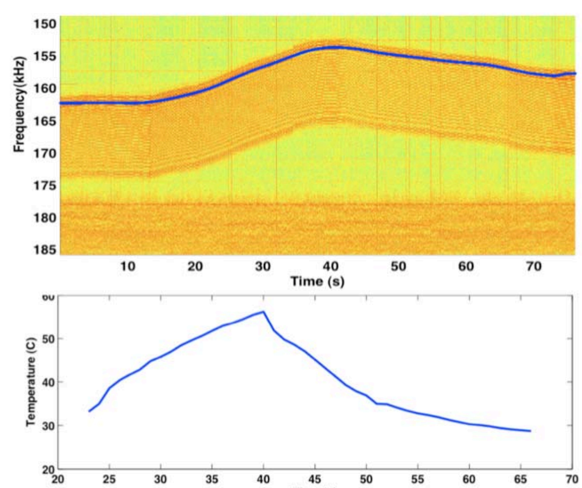

Figure 10: Shift in frequency (top) follows similar trend as ambient temperature (bottom).

be used for detecting air drafts, opening windows or doors, or potentially air movement created by people passing by.

CORE EXPERIMENTS

For our core experiments, we decided to evaluate the ability to build simple gesture event detectors using CFLs as proximity sensors. To validate our approach, and confirm its applicability across various people, different brands of CFLs and lamp fixture styles, we conducted experiments with 10 participants (7 males, 3 females). This was conducted in a simulated home environment in our lab with 6 lamps. We also conducted feasibility experiments with a subset of those participants and lamps in 2 actual homes.

Figure 11: Lamps that we used for our experiments. Two lamps (top left, top middle) were chosen to be similar for comparison. All lamps were on during the experiment.

We collected data for a variety of different lamp fixtures (see Figure 11) that included lamps with metal shade (3), glass shade (1), plastic shade (1) and no shade (1). The CFL bulbs used also varied in brand: GE (1), Energy Star certified GreenLite/Sylvania (1), Commercial Electric (1), ProLume (1) and a generic brand (2) from a local home improvement store. This collection of bulbs we used also varied in wattages from 12W to 26W (mean 16W).

Data Collection Procedure

Our simulated home setup included 6 lamps placed randomly throughout the lab space. The lamps were powered through separate residential style power source (a 60 Hz split single phase transformer). It should be noted that despite this isolating transformer, EMI from a large number of devices running in the building were observed, which made this have at least comparable EMI levels that would typically be found in a home environment. Our own data collection and monitoring equipment produced EMI, as well as the many computers and measurement equipment that operated in the lab space. Figure 2 is a spectrogram generated from EMI observed on our setup. Notice the large number of EMI from other devices.

Each participant in our experiment performed 5 different gestures, with each gesture repeated 4 times. The gestures included: a hover, touching the lampshade with two fingers, touching the lampshade with hand, touching the glass part of the bulb with one and three fingers. These 20 gestures were performed on each lamp one after another. To ensure consistency in where participants touched the lamp, we marked a spot on each lampshade. For one lamp that did not have any lampshade, instead of the two gestures involving touching the lampshade, we instead had the participants perform a hover to the left of the lamp and to the right of the lamp.

We built a data collection tool that allowed us to label the gestures as the users performed them. For each lamp, the software randomly ordered the sequence in which the gestures were required to be performed, in addition to randomizing the order in which each lamp was tested. This was done to minimize any temporal biases. Additionally, to minimize any effects from when the CFL lamps were turned on relative to start of the experiment, we turned the lamps off and only turned them on 5 minutes prior to each experiment. The entire experiment with each participant was repeated twice, on separate days to validate the stability over time. Each experiment took 45-50 minutes. The entire experiment ran for a period of two weeks during which we collected a total of 2400 events (120 per person, per session).

Feasibility in Homes

We randomly chose two lamps, and performed the same set of experiments in two different homes to confirm that the approach extends to an actual home. The homeowners were asked to continue their daily routine, thus lights and devices were being turned on and off as we collected the data.

RESULTS

Analysis of Hit Rate Accuracy

We chose a threshold of 25 dBm/dt (dt = 0.3277s) after plotting a ROC curve that characterizes the tradeoff between true positive rate and the false positive rate over the entire dataset (see Figure 12). The choice of 25 dBm/dt was based on maintaining good sensitivity (91.2%) towards detecting events while having a low (6%) false positives rate. All the results presented here on use this threshold.

Table 1 summarizes the hit rate for event detection and segmentation that we obtained for each lamp. Since hover events have the lowest energy change relative to other touch-based gestures and are more challenging to detect and segment, we show the hit rate for hover events from the first session across lamps for each user. Means for each session for all gestures are also shown. Overall, hovers had

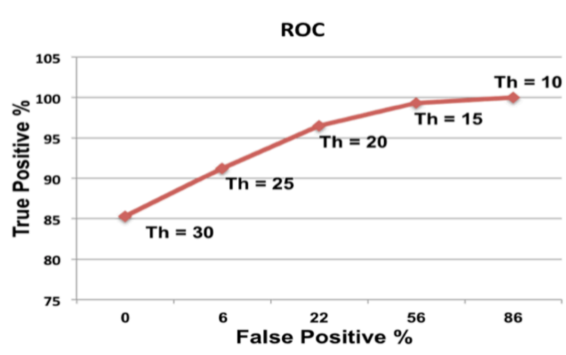

Figure 12: ROC showing tradeoff between the true positives rate and false positives rate for different threshold values.

Lamp	Hover												Bulb Touch One Finger		Bulb Touch Three Fingers		Shade Touch One Finger		Shade Touch with Hand	
	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	Mean 1st run	Mean 2nd run	Mean 1st run	Mean 2nd run	Mean 1st run	Mean 2nd run	Mean 1st run	Mean 2nd run	Mean 1st run	Mean 2nd run
L1	1	0.75	0.75	1	1	1	1	1	1	1	0.95	0.9	1	1	1	1	0.65	0.75	0.75	0.85
L2	1	1	1	1	1	1	1	1	1	1	1	0.95	1	1	1	1	0.725	0.775	0.8	0.85
L3	1	1	1	1	0.75	1	1	1	1	1	0.975	0.9	1	1	1	1	0.825	0.875	0.975	0.9
L4	1	0.75	1	1	0.75	0.25	1	0.75	0.75	1	0.825	1	1	1	1	1	*	*	*	*
L5	1	0.25	1	1	1	0	1	0.5	0.25	1	0.7	0.85	1	1	0.975	1	1	1	1	1
L6	1	1	1	1	1	1	1	1	1	1	1	0.9	1	0.975	1	1	1	0.975	1	1
Avg.											**0.908**	**0.917**	**1**	**0.996**	**0.996**	**1**	**0.84**	**0.875**	**0.905**	**0.92**

Table 1: Hit rate for each gesture. For hover events, per user (P1-P10) hit rate for 1st run and means are shown, while for others only means are presented across different participants.

an average hit rate of 90.8% for the first session and 91.7% for second. A key observation is that the mean hit rates we calculated are across all lamps and all users, suggesting the robustness of using a CFL as a "capacitive sensor." This hit rate suggests that is possible to build complex gesture from sequence of these basic gesture events. If a particular application can tolerate a higher false positive rate, then a lower threshold could be used to increase the overall accuracy.

Touches on bulb itself were easily detectable (100% and 99.6% between the two sessions), which can be attributed to the large energy change that passes the various event detection and segmentation checks. The average energy for bulb touch with three fingers events were 82.7 dB/dt (44.3 for one finger touches), roughly three times our set rejection threshold.

We expected lampshade touches to perform well, but relative to both hover and bulb touches some of the lamps exhibited a lower hit rate. In particular, we found that L1 performed poorly (see Table 1). This lamp has a plastic lampshade (black frame with white shade in Figure 11). Lamp L3, which has a metal frame and a glass shade performed better than L1. The best performers were lamps L5 and L6, both of which have a metal body and metal shade. Clearly, the metal and glass shades are far more conductive, and hence easier to detect (see Table 2). In the case of L4, which did not have a lamp shade around the bulb and we found that there were no noticeable differences if the hand gestures or hovers occurring on the top, right or left of the illuminated bulb.

Interestingly, metal fixtures actually made the entire metal surface conductive and thus a touch gesture could occur anywhere on the stem or base. For example, the lamp on the right in Figure 1 with a stainless steel frame can be touched anywhere along the body, thus expanding the interactive area on the lamp. If a metal lamp was placed on another metallic surface, then that surface would also become a potential touch surface to some extent. Other metallic lamps exhibit this same behavior, where the entire lamp surface can act as a capacitive touch sensor. This was particularly evident in L2, which is the same style lamp as L6, but it performed worse because it was placed on a metallic table and appeared always grounded. The metal surface produces a grounding effect on the signal, thus touches to lamp had noticeably small increase in energy. When we placed L2 on a non-conductive surface, we found that the effect went away and the increase in energy was comparable to L6.

Overall, we found that we could reliably detect both touch and proximity gestures with a CFL. Much of the variations in performance were not due to the person or differences in CFL, but the style of the lamp itself (metal, plastic, glass, etc). This implies that even though the CFL bulbs act consistently, the various lamp styles can add some variation to what gesture can be reliably sensed.

	Hover	Bulb Touch One Finger	Bulb Touch 3 Fingers	Shade Touch One Finger	Shade Touch with Hand
L1	6.671	25.937	62.828	4.86	5.038
L2	6.155	43.521	77.853	8	8.837
L3	5.343	43.036	83.028	4.6	6.428
L4	6.23	40.114	69.43	*	*
L5	9.402	55.577	104.51	14.9	16.776
L6	6.594	45.201	85.4486	9.12	10.353
Avg.	**6.53**	**44.35**	**82.78**	**9.12**	**10.353**

Table 2: Average energy change (dB/dt) for each lamp and gesture. Notice the difference between the energy values for a hover vs. bulb touches vs. shade touches. Shade touch energy for L2 is low due to the grounding effect of the metal surface.

In-home Experiments

Table 3 summarizes the results of the in-home experiments. We found that our initial evaluation shows promising results for our approach extending to a home environment. The results are actually similar to those found in the lab. Given the lab scenario was likely noisier in terms of additional EMI noise on the powerline, these results seem plausible.

DISCUSSION AND FUTURE WORK

The use of CFL as a capacitive proximity detector by monitoring the variations in its conducted EMI appears to be a promising sensing approach. Our core experiments reveal that EMI signal is temporally stable across people. A single segmentation algorithm was developed to isolate and

	Hover	Bulb Touch One Finger	Bulb Touch Three Fingers	Shade Touch One Finger	Shade Touch with Hand
Home1	0.875	1	1	1	1
Home2	0.875	0.875	0.75	0.875	0.875
Avg.	**0.875**	**0.9375**	**0.875**	**0.9375**	**0.9375**

Table 3. Hit rate from the two in-home experiments.

detect the various gesture events across all of the different participants and various brands of CFLs. We also found that multiple CFLs (even those of similar brands) operating simultaneously can still be distinguished using our approach. There is enough of a difference in the operating frequency between two similar bulbs, that the odd harmonics are also distinguishable. If two CFLs do happen to have the exact same operating frequency and are operating simultaneously, as long as only one is interacted with at a time, LightWave will be able to detect events but may confuse the source lamp from which the events are being generated.

Although our methods primarily consider the 3rd harmonic, we found that there is an increase in energy not only at the 3rd but also the 5th and 7th harmonics. Our algorithm can potentially be improved by tracking energy in multiple higher order harmonics. This could also alleviate a key limitation of LightWave, which is the potential for a strong interfering device to mask the smaller energy changes from the CFL. Because the fundamental frequency of the CFL changes based on the ambient temperature (the temperature sensor effect), the location of the odd harmonics also changes. Thus, to use the CFL as both a temperature sensor and a capacitive proximity sensor, both the fundamental and its odd harmonics need to be tracked while it is operating. In any case, this would be good practice in general because of the slight fluctuations in ambient temperature could cause some sort of frequency shift.

To confirm that this phenomenon is exhibited by as many CFLs, we acquired 6 additional (different) bulbs of various wattages and found that all exhibited similar responses as the ones used in the core experiment.

Of course, LightWave's methods require that the CFL bulb be illuminated (and thus generating EFs and EMI) for it to be used as a sensor. This limitation could be in some cases seen as a feature, because the sensing system can be turned off on demand.

CONCLUSION

We present a new sensing approach that turns ordinary compact fluorescent light (CFL) bulbs into human proximity sensors. In addition, we present evidence that CFLs can also be used for more general purpose sensing applications, such as monitoring the changes in ambient temperature, human motion detection (if a person is in range of a CFL), or as a sensor for incipient failure of CFL failure. All of these new uses are enabled by monitoring the EMI over the power line from a single point. By using the CFL as a proximity sensor, we showed that simple gestures (waving the hand near the bulb, touching the bulb, touching the lamp shade, and touching the base of a metal lamp) performed near a CFL lamp can be robustly detected and segmented in the presence of other CFLs and electrical noise sources on the power line. This was confirmed both in the lab in and in actual homes. The growing popularity of CFLs and the increasing mandates on the use of CFLs for lighting may provide an opportunity to potentially scale some of these simple sensing approaches throughout the home with little installation effort.

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