Optical Collusion:

Bidirectional Free-Space Communication with LEDs

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2009-10-31

Abstract

Increasing diversity in technology markets has created the "last centimeter" problem: it is frequently the case that two devices are unable to communicate with each other even when placed side-by-side. Data cables for most devices are non-standardized or inconvenient to carry; as a result, many devices solve this problem with wireless communications protocols (IrDA and Bluetooth, for example). These protocols are themselves quite diverse, and require tranceiver circuits that may be too expensive or power-hungry to include in low-cost and/or low-power designs. One technology in particular, **LEDcomm**, offers a potential solution to both of these needs, by using a single light-emitting diode for both transmission and reception; however, it suffers from extremely strict range and data-rate limits. The current state of the literature suggests that this technology is underdeveloped and that these limits can be improved. One promising approach involves experimenting with the LEDcomm data transmission timings in order to capture an improvement in the data transfer rate. This document aims to summarize the relevant and related literature surrounding LEDcomm and to describe such an experiment.

1 Introduction

1.1 The "Last Centimeter" Problem

In the telecommunications industry, there has long been the concept of the "last mile" problem: the data link between the local branch office and the consumer (presumably one mile away) must be efficient, reliable, and most importantly, inexpensive. The huge fan-out of the telecom infrastructure (usually on the order of hundreds of consumers per local branch office) causes a prohibitive cost for even moderately expensive technologies. On the other hand, market pressures demand quality-of-service levels that the least expensive technologies cannot meet.

Similar influences in technology markets has given rise to the "last centimeter" problem: it is frequently the case that two devices are unable to exchange data even when placed side-by-side. This is not a new problem, merely a new name for an old problem, dating back to the era of the null-modem cable. Recently, however, the abundance and diversity of personal technology has given the problem new importance: interdevice communication must fit within the cost, power, and size constraints demanded by the modern personal technology market.

Many solutions to this problem exist, each with its own advantages and disadvantages in terms of cost, power consumption, and convenience. Until recently, data cables were the predominant solution; however, data cables are often non-standardized or inconvenient to carry. As a result, many devices use wireless communications protocols for data exchange.

1.2 Motivation

Wireless protocols are diverse, ranging from the IrDA protocol used by television remote controls to the recent explosion of WiFi and Bluetooth devices. However, all of these protocols require tranceiver circuits that may be too expensive or power-hungry to include in low-cost and/or low-power designs[1]. One technology, called *LEDcomm* by its developers, stands out as a low-cost, low-power solution. Consisting of a single light-emitting diode operating as both transmitter and receiver, its cost of implementation is negligible, and its power consumption is minimal [1]. Since the LED can continue to function as an indicator, this technology can be added to an existing design, using an already-present LED. In this situation the only additional cost is one input/output pin on the driving microcontroller; power consumption is actually *reduced* compared to an always-on LED.

There is, unfortunately, a catch: the LEDcomm protocol has extremely strict limits on range and data-rate; improvements to these limits are mentioned as examples of "future work" [1], and a lack of further mention in the current body of literature suggests that the technology remains underdeveloped.

2 Photodetection with Light-Emitting Diodes

2.1 Photodiodes

2.1.1 Ideal vs. Real Diodes

Ideal diodes act as one-way gates. Current in the "forward-bias" direction meets zero resistance; in the "reverse-bias" direction, resistance is infinite. Typical modern diodes are fabricated as a junction of positively and negatively doped semiconducting materials, and have somewhat messier electrical characteristics [4].

The diode forward voltage (v_d) and breakdown voltage (v_{br}) are the minimum voltages at which current will flow freely in the forward- and reverse-bias directions, repectively (Figure 1). Generally speaking, the breakdown voltage is relatively large, and the forward voltage is relatively small, so that a diode will have near-ideal behavior over a wide voltage range; however, exceeding the breakdown voltage will usually destroy the diode. Also, some “leakage” current will exist whenever a diode is reverse-biased [2].

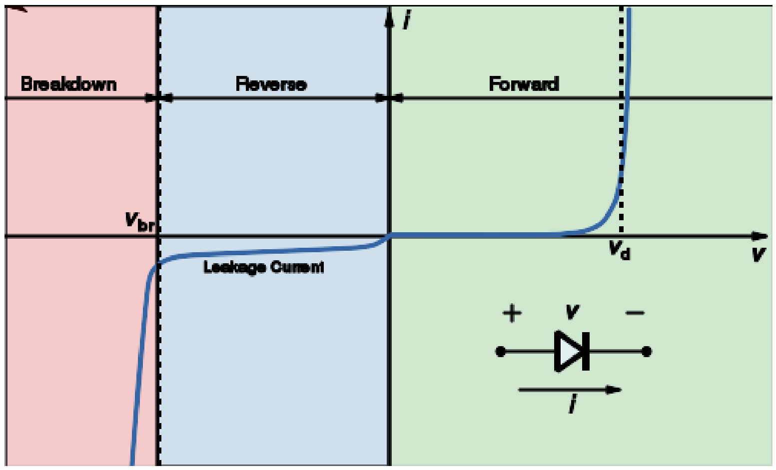

Figure 1: Current-Voltage curve for a typical diode (not to scale)

2.1.2 Photoemitters and Photodetectors

The semiconductor junction in a diode presents a potential energy barrier which electrons must satisfy all at once or not at all; electrons crossing the junction in the forward-bias direction release this energy as photons [2]. In the case of light emitting diodes, this effect can be observed directly: the emitted photons have energies corresponding to visible and near-visible wavelengths [4].

On the other hand, crossing the junction in the opposite direction requires the addition of energy; this energy is usually supplied by a reverse-bias voltage, and the result is leakage current. Impinging photons, however, can also supply this energy, allowing electrons on the low-energy side of the diode junction to cross over to the high-energy side. This will also generate a reverse-bias current across the diode. This effect is called “photocurrent”, and can be modelled as a DC reverse-bias voltage source in parallel with the diode [5].

All diodes are susceptible to photocurrent, and could theoretically be used as photodetectors. Since this is typically an undesired effect, most diodes are conveniently packaged in opaque materials. The notable exceptions are photodiodes and LEDs, which both require transparent or translucent materials. Although LEDs are not designed to be photodetectors, their ability to detect light has been known since their invention [4], and mass-production has made them inexpensive enough to be preferable to “proper” photodiodes in many applications (see Section 2.2.3 on the following page). As a rule of thumb, LEDs are sensitive to a moderate range of wavelengths, with peak response to light of slightly shorter wavelength than they emit [5].

2.1.3 Junction Capacitance

Junction capacitance is another deviation from ideal diode behavior, which has particular importance to photodetection [5, 1, 6, 4]. Semiconductor junctions require an abundance of charge carriers to operate as a diode. This accumulation of charge creates an effective capacitance which can be roughly modelled as a capacitor in parallel with the diode. When an applied voltage is removed from the diode, current briefly flows in the opposing direction until this buildup of charge in the diode junction is depleted.

The junction will discharge at a rate dependent on the presence of photocurrent: a forward-biased diode will discharge more slowly, and a reverse-biased diode will discharge more rapidly. This effect can be used to measure the presence of photocurrent.

2.2 Photodetection Methods

2.2.1 Measuring Photocurrent

To measure photocurrent directly, as is done in devices such as opto-reflective sensors and opto-isolators, the diode is connected directly to an analog to digital converter. This method is more suited to traditional photodiodes, since their greater efficiency leads to greater precision. The precision of the result is also directly dependent on the precision, and therefore the cost, of the analog-to-digital converter.

2.2.2 Measuring Junction Discharge

Measuring light using junction capacitance consists of two steps. First, a reverse-bias voltage is applied and the junction capacitance of the LED is charged. Then the microcontroller pin, connected to the LED cathode, is then placed in "input" mode. The illumination-dependent discharge rate of the junction capacitance is measured by determining the length of time before the input pin returns to a logic-low state. Alternatively, if boolean input is sufficient, a fixed threshold time is used. If the pin is logic-low at this time, light has been detected.

Direct measurement of photocurrent and its resultant reverse-bias voltage requires less measurement time, but also requires more sensitive detection circuits.

2.2.3 Applications of Photodetecting LEDs

When first invented, light emitting diodes did not have the low cost that comes from mass production. As a result, traditional photodiodes were used in the majority of photodetecting applications. In the last two decades, however, mass production has led to a sharp drop in LED manufactuing costs, and they are being explored for use in applications that don't require the capabilities of more expensive photodiodes. In particular, applications using the capacitive light-sensing method described above have received more attention in recent years[3, 6].

The application of most interest to this research, however, are LED transceivers. The concept of using light emitting diodes for data transmission and reception has been around since the 1970s [4]. Similar technologies that use photodiodes for reception are currently in widespread use (IrDA, optical networking, etc.), but implementations using a single LED as transceiver have no mention in the literature except one: the LEDcomm specification developed by Dietz, Yerazunis, and Leigh[1].

3 LEDcomm

3.1 System Overview

A LEDcomm implementation consists of a microcontroller, a resistor, and a single light-emitting diode. The microcontroller alternates the LED between three states: a transmitting state, where the diode is forward-biased and light is being emitted; a charging state, where the diode is reverse-biased; and a sensing state, where the discharge rate of the diode's junction capacitance is measured to determine the presence and value of any incoming signal [1].

3.2 Tranceiver Design

The LEDcomm physical interface circuit is inexpensive and simple: the LED and its current-limiting resistor are connected to to one output pin and one input/output pin of the microcontroller. This is in contrast to the typical circuit for driving a light emitting diode, in which the anode of the diode/resistor pair is connected to voltage, and the cathode voltage is controlled by a microcontroller input/output pin. Commonly, an LED is already present in any product design, driven in this fashion. Therefore, as long there are any remaining available input/output pins on the microcontroller, *there is no material cost* to add a LEDcomm transceiver to an existing design [1].

Selection of the diode and resistor are not mentioned in [1], but several sources ([4, 5]) agree that the LEDs in both units should be identical, or as close as is practical. Choosing a resistor of lower value will increase the signal strength of transmitted data [5], up to the current sourcing capability of the microcontroller, and will also decrease the junction discharge times, leading to faster signalling limits. However, these benefits come hand in hand with larger currents and power consumption.

3.3 Line Signalling

Signalling in LEDcomm consists of four phases: an idle state, synchronization, and a transmission/reception loop. The system starts in an idle loop, waiting for an incoming signal. This loop consists of flashing the LED for 1ms, and then executing 40 light detection cycles (see Section 2.2.2) at 100μs each. When two detection cycles in a row report that light was detected, an incoming signal is assumed, and the synchronization loop becomes active.

The synchronization loop is similar, but is designed to bring the dvices into a synchronized receive/transmit loop. Instead of 4ms between flashes, the detection cycles terminate when a "trailing edge" is detected in the incoming signal, defined as two cycles with light detected, followed by ten cycles without. The detection phase then ends immediately (instead of continuing for 40 cycles) and the LED is flashed again. Once both devices have detected a trailing edge from each other, the synchronization loop consists of each device alternately flashing its LED for 1ms. The logic which terminates the synchronization loop and begins transmission, as well as the logic which detects a loss of synchronization, is not specified.

Data transmission is by pulse-width modulation, with a "1" bit consisting of a 1ms pulse, and a "0" consisting of 0.5ms. The receiving device uses the same logic as in the synchronize loop, keeping track of the number of cycles that detected light. If this number is seven or greater, the incoming data is interpreted as a "1"; otherwise, it is assumed to be a "0". Data reception alternates with data transmission; each device sends while the other receives.

4 Experimental Design

4.1 LEDcomm Signalling Limits

The signalling frequency limit of light-emitting diodes is quite high[5]; the signalling frequencies of LEDcomm are several orders of magnitude slower than the physical diode limits, presumably to compensate for the relatively low signal-to-noise ratios LEDcomm must tolerate. However, the authors of the LEDcomm specification speculate that further research will improve the protocol's efficiency, making it more suitable for widespread adoption[1].

Two parameters that show promise in this regard are the sample duration (which defines the amount of time spent measuring light for each sample) and the number of samples-per-bit (which determines how many "light-seen" samples are used to interpret each incoming bit). These parameters directly control the data transfer rate; by defining these parameters as 100μs per sample and 10 samples per bit, respectively, the LEDcomm specification has a fixed maximum data transfer rate of 250 baud. Unfortunately, adjusting the parameters to increase the data transfer rate will eventually result in an unacceptable bit error rate. The proposed experiment (below) will be used to determine if (and to what degree) the manipulation of these parameters will yield an improvement in the efficiency of the LEDcomm protocol.

4.1.1 Hypothesis

If increasing the sampling frequency and decreasing the number of sampless per bit represent an improvement in the protocol's efficiency, then there will be an improvement in data transfer rate, without any statistically significant increase in error rate.

4.2 Implementation

Prior to the experiment, two (identical) implementations of the LEDcomm transceiver circuit were implemented on Microchip PIC16F690 microcontrollers. A variety of LEDs were examined for use in the transceivers, with varying succcess. For data collection, the transceivers used inexpensive red gallium arsenide light emitting diodes with "water-clear" epoxy lenses.

The LEDcomm protocol was implemented in C using the HI-TECH C compiler for 14-bit PIC MCUs. The protocol implementation was designed to accommodate changes to the sampling duration and number of samples per bit at runtime. The transceivers were also configured with several datasets for testing the error rate, including an all-ones, all-zeros, and random/high-entropy dataset. For the purposes of this experiment, the transceiver LEDs were positioned coaxially at a range of approximately 2mm, for minimal noise.

The experiment consisted of independent trials, in which the datasets were transmitted via the LEDcomm protocol from one transceiver to the other. A total of 208 trials were conducted in a parameter sweep with the sample duration varying between 50μs and 200μs per samples with a granularity of 10μs, and the number of samples per bit varying between 3 and 20. For each trial, the received data were compared to the expected data to determine the error rate.

5 Results

5.1 Observations

The data gathered (Figure 2) appear to strongly support the research hypothesis: the protocol operated with a sampling duration of 80μs, at 6 samples per bit, with no discernible increase in error rate. This represents an increase from 250 baud to approximately 520 baud.

Several anomalies in the collected data were noted; most interesting is a trough in the error rate at 6

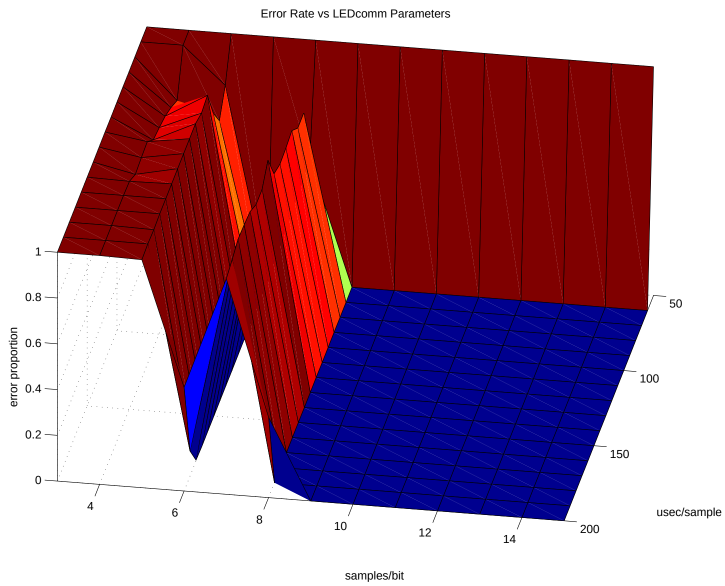

Figure 2: LEDcomm error rates for various parameter values.

samples per bit. A hypothesized cause of this anomaly is integer truncation when dividing the samples-per-bit parameter by three[1]. Additionally, at 6 and 8 samples per bit, there is an increase in error rate as sample duration increases from 180μs to 200μs, possibly due to clock drift between the transceivers.

5.2 Data Analysis

To determine the significance of the recorded variations in error rate, the original experiment design called for correlation coefficients between each of the manipulated parameters and the error rate to be computed for different regions of the parameter sweep. If the parameter changes represented an improvement in protocol efficiency, it was expected that regions of data surrounding the currently specified protocol parameters would show little or no correlation with error rate, and that regions showing strong correlation would only occur after a significant improvement in data transfer rate had been achieved.

However, the data did not present a gradual increase in error rate, as was expected. Instead, a further decrease to either parameter led to a sudden increase from no discernible error to a completely unusable state. In some such cases, the LEDcomm protocol was unable to achieve synchronization (denoted as 100% error in Figure 2); in others, the transceivers synchronized, but suffered nearly 100% error. Consequently, the data are effectively qualitative, and are not suitable for statistical analysis[2].

[1] In the original LEDcomm specification, detecting seven or more light samples represented an incoming "1" bit. In the experimental implementation, a "1" bit was defined as detecting light in more than $\frac{2}{3}$ of the samples for a bit; a "0" bit was defined as detecting light in more than $\frac{1}{3}$ of the samples for a bit, and loss of synchronization was declared if no more than $\frac{1}{3}$ of the samples detected light. Truncation during integer division occurs unless the samples-per-bit parameter is a multiple of three. It is hypothesized that, for small values of this parameter, the truncation error becomes significant.

[2] Quanititative results are expected to be attainable by increasing the dataset size (by several orders of magnitude), and

6 Discussion

6.1 Limitations

Several limitations were encountered during the experiment, most notably the sensitivity of the LEDcomm protocol to several variables not controlled for in this research. While constructing and testing the transceivers, the type of LED used appeared to be more important than discussed in the LEDcomm specification. This experiment did not study the effects of LED luminance, field-of-view, or positioning on error rate.

Ambient lighting also had an effect on error rate; in low light conditions (such as those used to collect the data in Figure 2), a sample duration of $60\mu s$ was sustainable with no discernable error rate. However, reproducing that trial under typical daytime room lighting yielded error rates near 100%.

6.2 Future Work

An obvious avenue of future research is to duplicate this experiment in such a way as to obtain quantitative results (as described above). Other areas to explore are the range and positioning limitations at the improved data rate, and the effect of LED properties such as luminance and variation in wavelength on the LEDcomm error rate.

Lastly, the existence of multicolor LEDs[3] opens the possibility of multichannel LEDcomm as an area of future development.

6.3 Conclusion

The LEDcomm protocol shows promise as a short-range means of exchanging small amounts of data. Much work remains to determine the realistic limits of LEDcomm under typical usage conditions, and in existing circuit designs; however, the results of this experiment indicate that (under some conditions) the original specification can be modified to capture significant improvements in efficiency without degrading communication quality.

Unfortunately, even with these improvements, the range and data rate of LEDcomm are still quite restrictive. Until further improvements can be made, it is unlikely that the LEDcomm protocol will see widespread use.

possibly by reproducing the experiment on a platform capable of finer-grained manipulation of the sample duration. Increasing the dataset size does not seem feasible at the current data rates: a single trial using a 1MiB dataset would take approximately 11.6 hours.

[3]Red, green, and blue LED junctions in a single 5mm epoxy housing

References

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