Simple LCD Transmitter Camera Receiver Data Link

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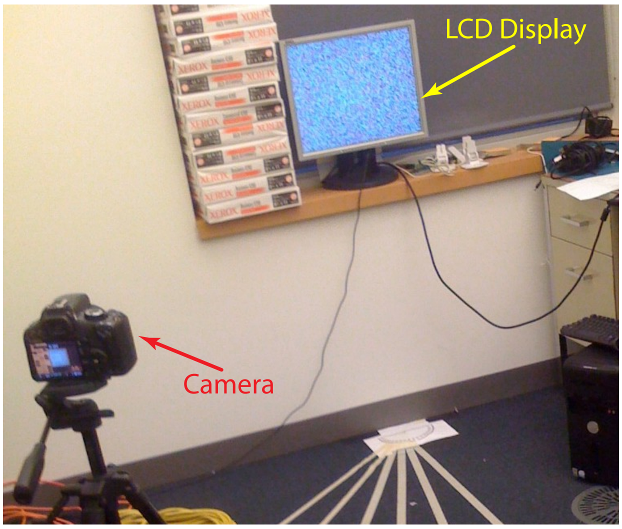

Figure 1: Simple setup with a commodity camera and standard LCD screen.

ABSTRACT

We demonstrate a freespace optical system using a consumer camera and projector in indoor environments using available devices for visual computing. Through design, prototype and experimentation with this commodity hardware, we analyze a practical optical solution as well as the drawbacks for current wireless challenges unmet by classic RF wireless communication. We summarize and introduce some new applications enabled by such similar setups.

1. Introduction

We consider a simple hardware setup using a consumer camera and a standard LCD screen such as the one shown in Figure 1. There are currently many visible light communication (VLC) broadcast configurations exploring the potentials of a data link established using custom freespace optical hardware equipment. This design differs in it's use of a consumer hardware setup and aims to achieve high bit rate as a result.

1.1 Related Work

Komine et. al presented prototypes and a fundamental framework for transmission of white LED light in [4, 5]. More recently, Little et. al [6] build an indoor wireless lighting system also employing OOK time modulation. This class of works represent an effort to demonstrate visible light data transfer systems using classic temporal techniques. QR Codes, Data Matrix Codes, Shot Codes and EZ Codes are examples of popular 2D barcodes which encode information to be transmitted visually. These modes of 2D visual information transmission already conform to ISO standards developed [2, 3, 1] to utilize 2D encoding and decoding of visual information.

1.2 Contributions and Limitations

Our implementation of a display and camera provides high bit rate transfer of up to 30Mbps using a single link where the transmitting LCD screen is a standard Dell 24 inch plasma screen and the receiving camera is a Canon Rebel SLR with standard feature settings. Here we summarize the fundamental contributions and limitations of this work:

Contributions:

- We build an end-to-end transmit and receive prototype system using a standard Dell 24" LCD display as the transmitter, and a commodity Cannon SLR camera as the receiver where the total oversampling rate is 1 pix to 4 pix x 4pix. The bitrate per frame demonstrated in this work is 4.96Mbits per frame with an uncoded average BER of 10%.
- This is an assertion of a channel model for a pixel-to-pixel communication system based on an actual implemented system
- Based on the observed channel properties, we propose several application scenarios that make use of the visible light channel.

The limitations of this approach are the same as any existing visible light link approach. One primary goal of this work is to characterize key benefits to using a visible light transmitter to receiver pair.

Limitations:

- Line of sight is required between the transmitter and the receiver.
- End-to-end visible communication poses new problems, such as geometric angular effects and resampling issues, which potentially call for new algorithms and protocols.
- Performance of visible light systems is ultimately determined by hardware. Key performance enhancements are determined by hardware which

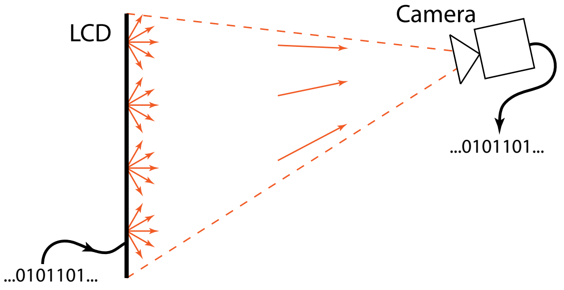

Figure 2: An LCD and a camera used for communication in our Netpix system. The LCD displays images corresponding to the input binary data; the camera captures a photo of the display and decodes the images to recover the data.

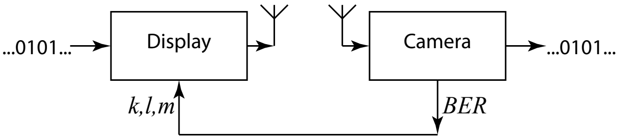

Figure 3: A feedback system allows for better adjustment and fine tuning of parameters between the transmitter and receiver. The correctly exposed parameters result in a system which may be adjusted depending on the number of users.

we limit ourselves to by using off-the-shelf equipment.

2. System Overview

We build on a simple understanding of a channel model and propose a communication system that uses a camera and a LCD display to communicate using visible light. We describe the main components of our transmitter and receiver chain.

2.1 Transmitter

The transmitter proposed considers a transmitter scenario such as the one depicted in Figure 2. We are interested in the bitrates received at each one of the cameras, with respect to angle and distance as related to users in a physical space.

We consider a scenario where incoming bits are first compressed. These bits may be split into several frames to guarantee independence. Next, forward error correction is placed to protect the bits through a lossy channel. An additional block in this chain creates a feedback system to determine how these protection bits must be placed in physical space.

Figure 4 shows a block diagram for a system with multiple receive cameras, and a single transmitting display. We consider the details of the exposed parameters and how they are related to the results.

Parameter k determines how bits are placed in time depending on the temporal coherence of the channel. Parameter m determines how bits are placed depending on where users are in physical space. Considering the need for these two parameters, we send two calibration frames before placing bits sequentially in the data frames. A system with feedback such as that in Figure 3 determines how often calibration frames are sent. The evaluation from the complete receive chain determines how these parameters k and m are set depending on the environment.

The first calibration frame sent is a frame `cornercal_frame` consisting of four corner markers. The second calibration frame sent is a frame `sampoints_frame` consisting of a grid containing all sampling points in the next few data frames. Following these two frames are data frames containing all information.

2.2 Receiver

The high level receive system block diagram is shown in Figure 5. It is split into two sections where many of the preprocessing elements are reminiscient of traditional image processing. The postprocessing elements are more reminiscient of RF design blocks. Here we explain the role of each component.

Spatial Tracking: The purpose of spatial tracking is to determine where in the scene the data is located. We search for the corners using a modified fast corner algorithm [7]. As there might be several corners in the scene, each of the corner candidates using the fast corner detector is compared to a large quadrilateral generated from the second frame. This is done in the system using a function `find_corners` which takes as input the incoming frame `imin` and the sampled frames `cornercal_frame` and `sampoints_frame`.

The quadrilateral from the second frame is obtained by repeatedly blurring and lowpassing the second sampling frame and then converting to a high-contrast black and white image. The square is found by discovering all white regions in the scene and calculating a “square score” given by:

$$\left(\frac{\min\left(\sqrt{\text{area}}, \frac{\text{perimeter}}{4}\right)}{\max\left(\sqrt{\text{area}}, \frac{\text{perimeter}}{4}\right)}\right)^2$$

All distances are calculated from the corner candidates in the first frame to the centroid of the square found in the next frame. The four corners with distances closest to each other are considered the corner calibration points for this block. The brightest pixel point associated with these corner calibration points are considered the corners for this round.

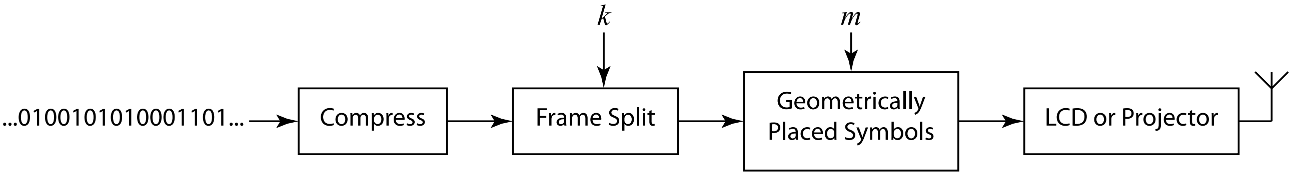

Figure 4: The transmit chain is designed for a scenario where a single screen might be transmitting information with many onlooking receivers. The transmit chain carries properties similar to that of a RF transmit chain with additional parameters for adjusting frame split, forward error correction and awareness of users in physical space.

Homography: Once the scene is found, the perspective scene may be restored using well known techniques for recovering perspective projections. This is done in the system using a function `frame_recover`. A transfer function is formed using the corners from `find_corners` and a homogeneous inversion may be performed from the formed matrix C.

All the following frames are cropped using corners found from `find_corners` and the transform coordinates fround from `frame_recover`. These are passed through the rest of the receive chain until another dark calibration frame is found.

Timing Recovery: Timing recovery is done by detecting all dots from `sampoints_frame`. `sampoints_frame` recovers the image by adaptively equalizing the entiring image and then passing it through a high-contrast filter wth contrast limits of 0.2. This is then converted to a high-contrast black and white image. The centroids of each one of these points are found using standard logic functions.

These points are assumed to be contained on a near perfect grid. The points of this mesh are reordered as such. This mesh is interpolated by an upsampling factor of 4 to allow for localized timing offset. Here, a match filter from the grid length is used as a kernel for the image. The convolved image is used to find the optimal sampling points.

Sampling: Sampling is done from the result of the timing recovery frame where all maximum values corresponding to a region within a found grid point is sampled. `Sampling` takes as input an incoming color image and slices the image into three slices and considers each slice with grayscale levels. As a result of the interference discussed, each slice is adaptively equalized followed by high contrast adjustment. The result is sampled with sampling points found in the timing recovery.

In reporting the BER of the system, the recovered frames are compared to the random frames sent.

3. Hardware Overview

In this work, we use only commodity hardware to achieve a high-bit rate link and make no modifications. As discussed in future work, there are many prototypes in development out of the scope of this work which would allow a much more powerful platform. We provide in detail the specifications of the truly off-the-shelf equipment we choose.

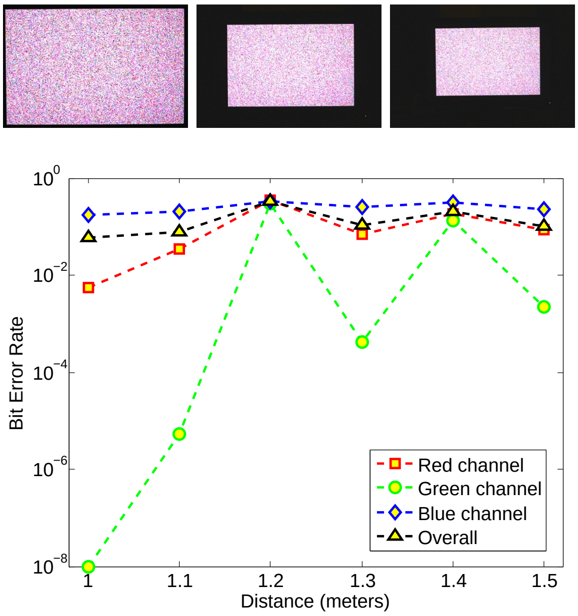

Figure 6: BER with respect to distance between the camera and display for encoding in all three color channels for a 1599x1035 pixel transmit block.

In these experiments, we choose a standard Dell Ultra Sharp 24" wide screen flat display with 1920x1200 resolution. The screen contains an anti-glare coating. These screens cost approximately $350 today. A n x n array of these standard displays simulate a higher resolution "transmitter" displays available in the future.

We use the "Canon Rebel XS" camera to capture transmitted images. These cameras likewise cost approximately $500. The sensor resolution is approximately 10 megapixels. The lens is a standard 50mm lens with $f/8$ aperture size.

4. Results

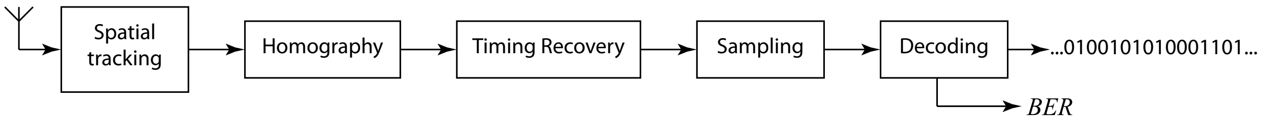

Figure 5: The receive chain design is the most computationally heavy portion of the design. This block diagram gives a high level overview, the details are discussed in the text.

Using the transmit chain and receive chain described in Section 2, we carry out several experiments which demonstrate the performance of the Netpix system. While the system design is based on ideal assumptions about the nature of the optical channel, the actual performance of the system is stressed under many parameters which are exposed to the highest layer. There are two goals in these experiments. The first is to establish the performance of the system. The second is to develop a channel model thus giving fundamental insight into the nature of a pixel to pixel system.

Figure 6 reports BER with respect to distance for encoding in all color channels for a 4.96Mbits/frame/screen in a n x n array of cameras and screens where $n = 3$. With a shutter rate of 1/30 seconds, this gives an aggregate throughput of 1.34 Gb/s. Here, the total transmit size of each frame is 1599 x 1035 pixels. In this experiment, the array setup is such that each camera is exactly in front of each display.

Here, we determine when the goodput is 1.34Gb/s - BER*1.34Gb/s. Despite large bit errors, the overall goodput for a 3 x 3 camera/display array is still very high ($\approx$ 1Gb/s). These transmit frames were generated with 1 bit of information contained in each slice of red, green and blue.

While it is interesting to consider the circumstances under which a very high speed link works, we would also like to understand how these pixels might behave under other constraints. Figure 7 is a 1599 x 1035 pixel board with bits of symbol size 4. The symbol size is the number of pixels on the display that each bit occupies. Here, we consider the results with no color and how this might eliminate errors. Here, at 1m, there are 0 errors and a sharp jump at 1.1m.

Figure 7 reports BER when using only the black and white channels. This reports only 1/3 the throughput. These results decoded using the same receive chain however result in much lower BER. This suggests a considerable effect from neighboring color bands.

Angle evaluation is done using a square black and white checkerboard carrying a throughput of 7.86Mbits. Figure 8 shows BER as a function of different viewing angles. A viewing angle of 30 degrees may cover significant area within a room.

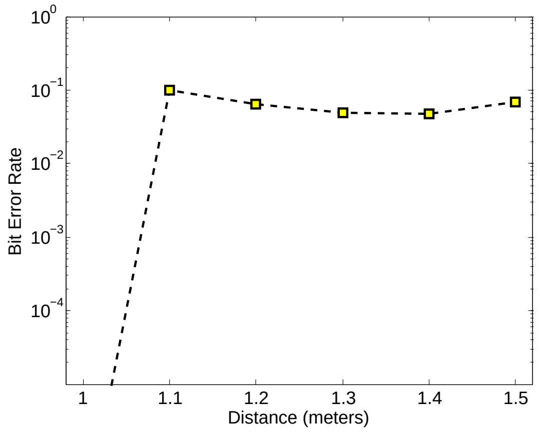

Figure 7: BER with respect to distance between the camera and display for encoding in black and white. This eliminates the effects of color interference and reports BER purely as a result of what is observed at the sensor.

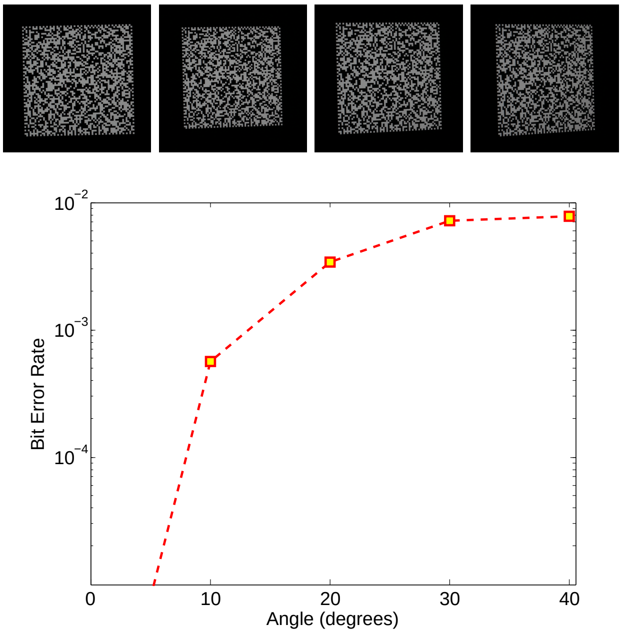

Figure 8: BER with respect to angle between the camera and display for encoding in black and white. Angle increases in the photos from left to right (0, 10, 20, and 30 degrees).

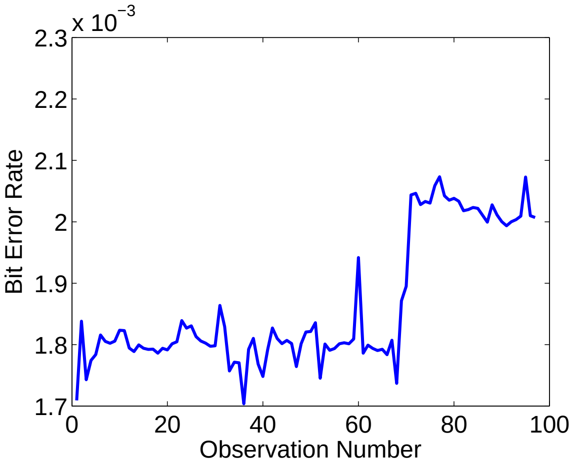

Figure 9: Coherence plots showing how BER changes with respect to time. This experimental plot suggests the presence of a stochastic channel in practice. We further explain the nature of this channel in the text.

Figure 9 shows that although the channel model for these results are analytical, the resulting bit errors still have randomness. We can see this effect in both angle and time.

Figure 10 shows BER as a function of the symbol size. As the symbol size increases, the chance for neighbors interfering decreases thus reducing the BER.

5. Conclusion

We present a wireless optical system built with commodity hardware which may be used for many network scenarios. Depending on the application and needs of the network, there are many modifications to be made which will ultimately result in significantly higher bit rates. We are currently in the process of developing such a hardware platform. Even with current commodity off-the shelf hardware, we obtain very high bit-rates. As the consumer world strives to develop the newest form factors for projectors and cameras, visual communication systems such as the one proposed in this work will allow users to use a new set of networking components capable of delivering high bit-rate wireless links.

6. References

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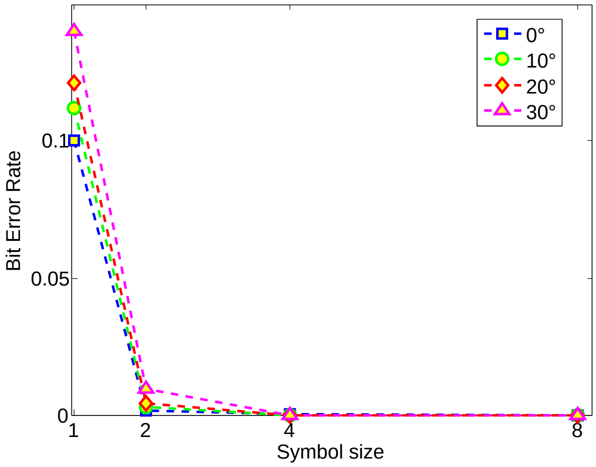

Figure 10: BER vs. symbol size viewed as reported for various angles between the camera and the display. The symbol size is the number of pixels on the display that each bit occupies. The BER falls down significantly as the symbol size goes up. Performance is similar for different angles.