Poster Abstract:
Supporting Heterogeneous LCD/Camera Links

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***Abstract*—Visible light communication over LCD/camera links offers a potential complement to traditional RF communication technology such as WiFi or cellular networks. However, the heterogeneity in receivers (e.g., mobile phone cameras) presents a challenge because the receivers differ widely in resolution, distance to the transmitter (LCD), and other factors, and therefore they differ in channel quality. We are researching a communication scheme in which each receiver can decode as much data from an LCD's transmission as the receiver's channel supports. The core idea is to encode the payload into an image's frequency representation rather than directly into pixels. We have successfully transmitted data using a prototype implementation and are currently investigating appropriate channel models.**

I. INTRODUCTION

Encoding data in optical displays offers a flexible, accessible and powerful method for communicating data. Devices containing cameras are ubiquitous and (with the installation of appropriate software) are equipped to receive optical transmissions, without requiring specialised hardware. Visible light communication links from LCD screens to cameras are a potential complement to traditional RF communication. Such links are inherently directional and thus less interference prone, which facilitates spatial reuse without contention problems. Visible light also avoids the problem of radio's crowded and limited spectrum.

A major challenge in LCD/camera communication arises from the heterogeneity in the receivers' channels. Current smartphone cameras differ widely in resolution and picture quality. Additional factors, such as distance to the transmitting LCD, perspective transform, lighting and focus all affect the quality of the receiver's image. Consequently, the receivers' channels differ considerably from one another.

In this work we address the question of how a transmitter can accommodate multiple receivers each with a different channel quality. Our approach is based on the insight that poor channel conditions often are limited to certain frequency ranges in an image's frequency representation. For example, an unfocused, blurred image mostly misses fine details (high frequencies), whereas the image's core features (low frequencies) remain unaffected. Therefore, we propose that data should be encoded into the frequency representation of the transmitted image, rather than encoding it directly into pixels. We envision that this approach will allow a receiver with a good channel to decode all data, whereas a receiver with a bad channel will still be able to decode the low frequencies, i.e., the leading bytes of the transmitted data. The better a receiver's channel, the more data it can decode. In contrast, when data is encoded directly into pixels (as is the case for QR codes, for example), receivers receive either all data or none.

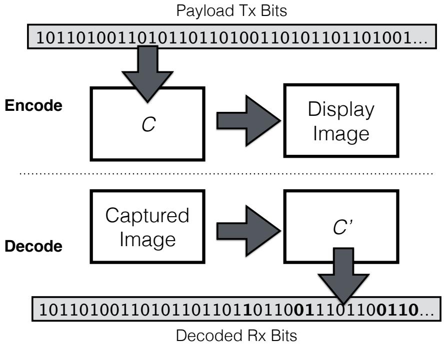

Fig. 1: Overview of the TX and RX flow. The complex matrix C is received with noise C', causing some bits to be decoded incorrectly (bold).

Many recent visible light communication schemes for LCD/camera links focus on barcode or QR code based transmissions [1], [2]. Our approach shares similarities with PixNet [4], which also encodes data in the frequency domain of an image. In contrast to PixNet, we do not focus on high-quality photo cameras with optical zoom, but on more prevalent smartphone cameras. Furthermore, we plan to address a range of channel distortions and incorporate an erasure code in our communication scheme to ensure that each receiver makes the best use of its channel capacity.

In this poster abstract, we outline our approach, describe an initial experiment, and give an overview of our plans for further investigation.

II. APPROACH

We briefly describe the TX and RX processes, which are visually summarized in Fig. 1. Our approach is similar to orthogonal frequency division multiplexing (OFDM) in the sense that we transmit symbols over the different orthogonal frequencies of an image's frequency representation.

Transmission. The sender converts the payload bit sequence to be transmitted into a sequence of *complex symbols* using a suitable modulation scheme, e.g., QPSK. Next, the sender populates a two-dimensional *complex matrix C* with the complex symbols. The symbols are arranged in order of increasing distance from the matrix' center. The sender then applies an inverse Fourier transform to the matrix and yields a real-valued matrix that can be displayed as a grayscale image. Note that from the construction it follows that the frequency components of the image are determined by the bits to be transmitted. More specifically, the first payload bits determine the lowest frequency components and later bits correspond to higher frequencies. Lower frequencies are visible as larger artefacts in the encoded image, while high-frequency components are fine-grained details (that only high-quality receivers may capture).

Reception. The receiver captures a picture from its camera and extracts the transmitted image. It then applies a Fourier transform to the image and yields a two-dimensional complex matrix C'. It extracts the received complex symbols from the matrix by considering how the symbols are arranged in the matrix. The resulting sequence of complex symbols is finally demodulated to obtain the sender's original bit sequence.

To see how this approach helps with different channel conditions, consider two identical receivers. One is close to the LCD, the other further away. The near receiver captures the displayed image fully and correctly and hence decodes all of the transmitted data. The receiver that is further away from the LCD undersamples the image, and hence loses information stored in high-frequency components. However, the far-away receiver still can decode the beginning of the transmitted bits, as they are represented by low-frequency components. More generally, channel distortions usually only affect certain frequencies. Encoding data in the different frequency components of an image thus lets the receiver still decode data from the unaffected frequencies.

III. INITIAL EXPERIMENTS

We have developed a prototype of the described approach for Android phones. Our initial experiments focus on the general feasibility. We have been able to successfully transmit and receive data using a 24" Samsung SyncMaster SA450 LCD and a Samsung Galaxy S4 smartphone located at a distance of roughly 1 m from the LCD. Quadrature phase-shift keying (QPSK) was used as the modulation scheme, and the transmitted images contained 1 KB of data.

Figure 2 shows the bit error rate of received data as a function of the bit position in the payload for one experiment. In the figure, the bit error rate is smoothed over a window of 32 bytes to ensure a legible plot. Recall that earlier bits are represented by lower frequencies, and later bits by higher frequencies, and hence the plot's x-axis also corresponds to frequency. The plot shows that the bit error rate increases with the frequency. This observation fits with our suggestion that data should be encoded at different frequencies of an image so that even a receiver with a bad channel can receive part of the data. Another implication is that earlier bits (lower frequencies) would require less error correction, or could contain more important data.

In simulation, we have also explored the effect of some channel distortions on phase errors in the received complex symbols. Specifically, we considered the effect of downsampling (idealized approximation of distance), blurring (idealized approximation of incorrect focus), and over-/underexposure of the transmitted image. As we would expect, in the case of downsampling and blurring the phase error increases with frequency. The impact of over-/underexposure on phase errors was comparably moderate, since these affect mostly the intensity of the image, which corresponds to the amplitudes of the image's frequency representation. However, we observed that for extreme over-/underexposure, the introduced phase error was not constant but actually decreased with frequency.

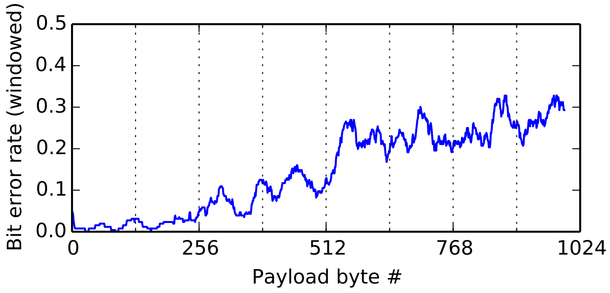

Fig. 2: A receiver's bit error rate over increasing byte positions, which correspond to increasing frequencies by design of the proposed scheme. Thus the plot shows that higher frequencies coincide with higher error rates.

This observation again supports encoding data over different frequencies, because distortions are roughly limited to certain frequency ranges.

IV. CURRENT WORK

We are currently focusing on three aspects: understanding the communication channel, choosing a modulation scheme, and applying coding to deal with errors and erasure.

In the first step, we aim to understand the channel by considering how different distortions affect the frequency representation of an image. Specifically, we are considering distortions that are common in pictures taken with smartphone cameras, e.g., perspective transform, inconsistent lighting, over/underexposure, incorrect focus and lens aberrations. For each of these distortions, we want to understand how they affect the phases and amplitudes of different frequencies in a captured image. We have started this investigation by simulating the distortions digitally to ensure a controlled environment in which we can isolate different effects. We then plan to characterize the channel of actual smartphone cameras. Once we have established a thorough understanding of the channel, we can determine an appropriate modulation scheme to use.

Our communication scheme must deal with transmission errors. We therefore investigate the application use of error correcting codes and erasure codes. We plan to apply error correcting codes in a way that data represented in higher frequencies, which are more error prone, is protected by greater redundancy. Since we are ultimately interested in transmitting data over a series of images, we also explore the use of Fountain codes to deal with occasional data loss [3]. These codes, which are rateless, would allow each receiver to reach the data rate its channel supports.

REFERENCES

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