Invisible Information Transmission System of Visible Light Based on Interleaved Code

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Abstract. In this paper, based on the characteristics of display-camera link and the secondary imaging mixing phenomenon caused by the hardware structure in invisible information transmission system, we propose a reasonable display-camera link model. Then by analyzing the application environment and the methods to realize of Interleaved Code(IC), we propose an invisible information transmission system design of visible light based on Interleaved Code under the characteristics of the display-camera link, which uses the complementary frame modulation. This system can well resist the secondary imaging mixing problem. The experiment results are shown to validate the robustness and effectiveness of the proposed designs.

1. Introduction
As a new emerging technology, visible light communication (VLC) [1] has great advantages over traditional radio frequency (RF) communication in terms of communication security, green environmental protection and broadband high speed, attracting more and more attention. In recent years, with the popularization of smartphones equipped with high definition cameras and displays with high resolution, a new technology named optical camera communication (OCC) [2-10] comes into being. Operating in the visible light spectrum and utilizing light emitting diodes (LEDs) or displaying as transmitters and cameras as receivers, OCC provides a convenient communication mode interaction with environment without increasing complexity of the existing hardware. The most common application of display-camera link is using a mobile phone to scan a quick response (QR) code for achieving information. In order to avoid the QR code occupying a certain space on the display screen and disturbing the look and feel of the images or videos, the area occupied by the QR code in the application is small, which also causes a problem of reduced throughput and short communication distance. Visible light implicit imaging communication as a communication method that can solve the above problems and realize information transmission under the condition of no human vision is attracted by more and more researchers [2, 3, 6].

To ensure the integrity of the received signal, the camera frame rate is usually set to twice as much as that of the display refresh rate [2, 6, 8]. In order to achieve the implicit effect, the display refresh rate should not be less than 60Hz, which means that the camera frame rate should be up to 120Fps. In addition, the inherent characteristics of display-camera link can cause a series of unsynchronized problems resulting in the reduction of transmission reliability [11-14]. In [11-12], the authors conduct the preliminary research, coming to conclusion that the link characteristics can cause frame losing and frame mixing problems. In [11], an unsynchronized display-camera system is established. It
compensates frame synchronization by using in-frame color tracking and linear erasure code. In [12], the mixed frame is modeled as a linear superposition of two adjacent frames, and a mixed frame seam detection algorithm is proposed. In [13, 14], the preliminary model and frame synchronization compensation algorithms for display-camera link is proposed. In our previous research, the hardware characteristics of the four imaging directions in the display-camera link are studied, and the maximum likelihood estimation of the mixing factor is derived, and the trend is analyzed. Although the existing literatures has studied and analyzed the secondary imaging mixing phenomenon appearing in the display-camera link, its performance against this phenomenon is poor, and the paper does not solve the impact of this phenomenon on information transmission. In this paper, a system design based on Interlaced Code (IC) is proposed for the secondary imaging mixing phenomenon in the display-camera link. It solves the interference problem caused by the secondary imaging mixing phenomenon at the receiver and improve the reliability of the system for the identification of implicit information detection.

2. System Model
The implicit VLC communication is as shown in Figure 1. Signal is modulated into the carrier video, and then transmitted through optical line-of-sight channel. Meanwhile, the modulated signal visually transparent doesn’t impair user-viewing experience, while can be captured by cameras and recovered by subsequent processing. In this paper, we leverage the complementary frame design and embed signal into the B-channel (Red, Green and Blue channel of a pixel) [7] to ensure better implicit effect.

**Figure 1. Demonstration of the unobtrusive VLC communication [[5]].**

In the display-camera link, due to the rolling shutter characteristics of the CMOS camera and the line refreshing characteristics of the display, the display can able to respectively refresh the pixels of two adjacent frames when exposing a certain pixel. Then, the pixel information actually received by the camera is a mixture between the two adjacent frame pixels, so a new phenomenon called secondary imaging mixture [11,12,15,16] appears. In order to facilitate the analysis, display-camera link is modeled under the assumption of the optical axes of the transmitter and the receiver aligned. So, the received frame $\tilde{y}_k(i,j)$ can be written as,

$$\tilde{y}_k(i,j) = \sum_{l=1}^{L} G\delta(i,j,d,\theta) T_{k,l}(i,j) y_{k,f,t}'(i,j) + n_k(i,j)$$

$$y_{k,f,t}'(i,j) = \frac{1}{M'} y_{k,f,t} \left( \frac{i'}{M'}, \frac{j'}{M'} \right)$$

$$\sum_{l=1}^{L} T_{k,l}(i,j) = T_k$$

$$y_{k,f,t}(i',j') = y_{(k,j)+l}(i',j')$$

where $\tilde{y}_k(i,j)$ is the received frame mixed by $L$ adjacent original frames, the number $L$ is related to the transceiver refresh rate and the transceiver relative refresh direction, and $G$ is the lens responsiveness. Attenuation factor $0 \leq \delta(i,j,d,\theta) \leq 1$ represents attenuation of signal, which is a
function of spatial location \((i,j)\) and capturing distance \(d\) and angle \(\theta\), is the exposure duration of CMOS, \(0 \leq T_{ij}(i,j) \leq T_e\) is the exposure time for pixel \((i,j)\) in the \(l\)-th frame among \(L\) adjacent original frames. \(T\) is time-delay factor introduced by frame losing, \(y_{k,l,r}(i',j')\) is the \(l\)-th frame in \(L\) adjacent original frames with \(T\) frames lost before. \(y_{k,l,r}(i',j')\) is the image of the transmitted image on the imager plane due solely to geometric optics. \(M'\) denotes the magnification predicted by geometrical optics of the imaging system from the transmitter plane to the imager plane [17]. \(n_k(i,j)\) is modeled as zero-mean additive Gaussian white noise with variance of \(\sigma^2\).

As mentioned before, the existing commercial displays mostly adopt the synchronization technology promising the frame losing probability extremely low, thus the impact caused by frame losing can be overlooked. Assuming the image on the imager plane and the transmitted image are the same in size, \(M'\) equals to 1. So, the display-camera link model can be further simplified as,

\[
\tilde{y}_k(i,j) = \sum_{l=1}^{L} G\delta(i,j,d,\theta) \frac{T_{ij}(i,j)}{T_e} y_{k,l}(i,j) + n_k(i,j) 
\]

Since the refresh direction of the display and the camera are the same, the received frame can be considered as a mixture of two adjacent transmitted frames. Therefore, the link model in this case can be expressed as,

\[
\tilde{y}_k(i,j) = \sum_{l=1}^{L} G\delta(i,j,d,\theta) \left[ 1 - \frac{T_{ij}(i,j)}{T_e} \right] y_{k,1}(i,j) + \frac{T_{ij}(i,j)}{T_e} y_{k,2}(i,j) + n_k(i,j) 
\]

Defining mixing factor \(\lambda_k(i,j)\), the link model can be rewritten as,

\[
\tilde{y}_k(i,j) = G\delta(i,j,d,\theta) \left[ 1 - \lambda_k(i,j) \right] y_{k,1}(i,j) + \lambda_k(i,j) y_{k,2}(i,j) + n_k(i,j) 
\]

3. System Design

In this section, due to its simplicity and practicability, the complementary frame design has been widely used in the existing research. So we also discuss our work based on complementary frame design [3, 5-8, 10].

3.1. Complementary Frame Design IC-Based System Design

Complementary frame design to visually hide embedded data in display-camera VLC is based on the following simple idea. A two-dimensional (2D) data pattern is added to one frame and then subtracted from the next frame. So the basic complementary frame design is as follows,

\[
\begin{align*}
\forall k, L & \quad y_k(i,j) = V_k(i,j) + d_k(i,j) \\
\forall k, L & \quad d_k(i,j) = (-1)^{q_{\frac{i}{H}} \frac{j}{L}} \Delta
\end{align*}
\]

where \(V_k(i,j)\) is the \(k\)-th original frame, \(d_k(i,j)\) is the embedded signal, \(y_k(i,j)\) is the displayed frame, \(H\) and \(L\) represent the frame resolution, and the coordinate range of the pixel of the transmitting end is \(1 \leq i \leq H, 1 \leq j \leq L\). The information factor \(q\) is the corresponding element in the information matrix \(Q_{\frac{i}{H}}\). The elements in the information matrix \(Q\) are all 1 or -1, and they are mapped by a
sequence of 0, 1 bit of length $Q_xQ_y$, 0 and 1 are respectively mapped to -1 and 1. $[\cdot]$ is round up operation, $\Delta$ represents signal embedding intensity in B-channel.

In receiver, the embedded signal is recovered from the difference between adjacent camera-captured frames (difference frame decision) under perfect frame synchronization condition with no frame losing and no frame mixing,

$$\tilde{d}_k(i,j) = \frac{1}{2}(\tilde{y}_{2k-1}(i,j) - \tilde{y}_{2k}(i,j))$$

$$= \frac{1}{2}(y_{2k-1}(i,j) - y_{2k}(i,j))$$

$$= d_k(i,j)$$

(6)

3.2. IC-Based System Design

In the display-camera link when information is transmitted, there are about 2.5 consecutive seconds in each 15 seconds, which is a serious mixture and the mixing factor is around 0.5, so that the information at the receiver cannot be recovered well, and the error performance of the system is reduced. We can think of this secondary imaging mixing phenomenon as a kind of periodic deep fading, which can lead to long burst errors. The most common coding technique for solving burst errors is Interleaving Code, which can separate such long burst errors in time. Therefore, we introduce interleaved coding technology into implicit imaging communication to improve system performance.

3.2.1. Interleaving Code Technique. Interleaved code is a channel modification technology, which is essentially a time diversity technique that can correct long burst errors or multiple burst errors. Through the interleaving technique, the burst error channel can be converted into a statistically independent error channel, so that long burst errors are broken up in time, and long burst errors are evenly distributed over the entire time axis. Therefore, the long burst error is converted into a short burst error and there is less error code in one codeword. The burst error can be solved by further using common channel coding techniques.

The principle of the interleaved code is as shown in Figure 2, assuming that the original transmission information of the channel is a codeword $A'$, and $A' = (a_{11}, a_{12}, \cdots, a_{1m}, a_{21}, a_{22}, \cdots, a_{2n}, a_{m1}, a_{m2}, \cdots, a_{mn})$. The interleaver is designed as an array memory which is written in row-wise and read out in column-wise. The interleaver is used to read the code array into the interleaver first by row, and then read into the channel for transmission by column. The receiver first needs to deinterleave the information transmitted by the channel, and the deinterleaver works exactly the opposite of the interleaver. The deinterleaver is still an array memory, which is written in column-wise and read out in row-wise. After deinterleaving, we can decode the transmitted information.

Common interleaved code has packet interleaved code and convolutional interleaved code. In this paper, we use packet interleaved code to design the system. The packet interleaved code arranges the encoded data in a matrix of $m$ (interleaver of degree) row and $n$ (length of one codeword) columns, and the interleaved code matrix $A'$ of the codeword $A$ can be expressed as

$$A = \begin{bmatrix}
a_{11} & a_{12} & \cdots & a_{1n} \\
a_{21} & a_{22} & \cdots & a_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
a_{m1} & a_{m2} & \cdots & a_{mn}
\end{bmatrix}$$

(7)

Each line codeword is a row code or sub code of the interleaved code matrix, and is transmitted in columns in order from left to right in the transmission.
3.2.2. System Design. RS code has strong ability to correct burst errors, and RS code has matured and is widely used in practice. Therefore, in our system design, we adopt reed-solomon (RS) code and interleaved code to solve long burst errors introduced by secondary imaging mixing.

Interleaver of degree is a very important parameter in interleaved code, so it needs to be determined in our system design. If a row code \((n,k)\) that can handle burst errors of length \(b \leq \frac{n-k}{2}\), then it can be combined with an interleaver of degree \(m\) to create an interleaved \((mn,mk)\) block code that can handle bursts of length \(l\), which can be expressed as

\[
l = mb
\]

So, the interleaver of degree can be calculated by,

\[
m \geq \left\lceil \frac{r \times F_i \times t \times K}{b} \right\rceil
\]

where \(t\) is the continuous error time, \(r\) is the display refresh rate, \(F_i\) is the probability of continuous long error bits, \(K\) is the parameter in complementary design.

Our system design based on interleaved code is shown as Figure 3. Firstly, at the transmitter, the data is RS encoded by the channel encoder. Then the RS-encoded data is interleaved by the interleaver and subjected to the complementary frame modulation. After that, the modulated frames are pushed by the display and transmitted through the optical channel. At the receiver, the received frames are captured by the camera and then subjected to different frame decision demodulation. Then deinterleave the data demodulated by different frame decision, and finally decode the data by channel decoder, and the transmitted information can be obtained.

4. Experiment Results and Analysis
In order to test the performance of the proposed systems, prototype systems are set up under laboratory conditions to carry out experiments.
4.1. Experiment Parameters Setup

In our experiments, we leverage an off-the-shelf 27-inch liquid crystal display (LCD) monitor (PHILIPS-272G5DYEB) with resolution of 1920*1080 as transmitter. At receiver, we capture videos of resolution 1920*1080 by using an Apple Iphone6s smartphone. The display refresh rate and camera frame rate are both set to 60. The hardware configurations are shown in the Table 1.

| Transceiver | Type                  | Resolution    | Frame rate/FPS |
|-------------|-----------------------|---------------|----------------|
| Transmitter | PHILIPS-272G5DYEB(27inch) | 1920*1080    | 60             |
| Receiver    | Apple Iphone6s        | 1920*1080    | 60             |

Experiment conditions are shown in the Table 2. In the IC-based system design, the RS (15, 9) code is adopted by taking the decoding complexity, coding redundancy and error correction performance into account. The parameters in equation (9) are shown in Table 3, so the interleaver of degree is set to 10 in our experiments.

| Parameter                              | Value                        |
|----------------------------------------|------------------------------|
| Embedding intensity                    | {1, 2, 3, 4, 5, 6, 7, 8}     |
| Diversity-multiplexing (Block number) | 24*40                        |
| Distance/cm                            | 110                          |
| Angle/degree                           | 0                            |
| Illumination intensity/lux             | 100-200                      |

4.2. Analysis of Experiment Results

In the same experiment environment, the invisible information transmission system based on interleaved code and the system without interleaved code are tested respectively, and the error performance of the two systems under the same information embedding strength is compared. Experiment results is shown as Figure 4.

It can be seen from Figure 4 that the error performance of the invisible information transmission system based on interleaved code increases with the increase of the embedding strength, and the error performance of this system based on interleaved code is better than that without interleaved code. And when the embedding intensity is about 8, the BER is close to 10^-4, which indicates that the invisible information transmission system designed in this paper increases the complexity of the system, but the reliability of the system is improved and the information can be transmitted effectively.

5. Conclusions

In this paper, we firstly presented a reasonable model of the display-camera link based on its characteristics. From our analysis, we can see the characteristics of the display-camera link can lead to secondary imaging mixing phenomena, and we further simplified the display-camera link model with the same refresh rate for both the display and the camera. Next, based on the characteristics of the secondary imaging mixing phenomenon in the display-camera link model, we proposed a system
design of the invisible information transmission based on interleaved code, which can improve the reliability and validity of the system. Finally, we constructed the system under experiment conditions and test performance of the system. The experiment results show that the proposed system design can effectively reduce the impact of secondary imaging mixing phenomena and greatly improve the BER performance of the system.

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