E-paper Display with Li-Fi Integrated on a 1D-Dimming Front-Light Unit

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Abstract
This work integrates Li-Fi into an e-paper's front light unit (FLU), especially multi-input and multi-output (MIMO) Li-Fi on a 1D-dimming FLU. A 5.76-kbps rate with unaffected pictures is experimentally verified on an e-reader with a global FLU. MIMO Li-Fi is verified using an in-house designed 1D-dimming FLU for a fourfold rate.

Author Keywords
Visible light communication, Li-Fi, E-paper, Front light unit.

1. Introduction

The emerging Internet of Things (IoTs) demands the integration of multiple functions. For example, our previous study [1] achieved integrated display and communication (IDAC), which performs normal display and visible light communication (VLC, *a.k.a.* Li-Fi) simultaneously on a mini-LED LCD by modulating the backlight. The many backlight segments brought by mini-LEDs are controlled independently, not only for precise local dimming but also for multiple transmitters in Li-Fi. Thus, high dynamic range display and high-capacity data transmission are obtained. A CMOS camera acts as a multi-channel receiver at the receiver side, forming a multiple input, multiple output (MIMO) communication system. Such IDAC systems adopting an ordinary LCD and a camera open new possibilities for IoTs. For example, public information displays deliver real-time information to passersby via visible light.

Besides LCDs, the reflective e-paper display is even more promising for IoTs due to its low power consumption, eye-friendly reading experience, and flexibility. Extensive applications are expected for e-paper displays, such as e-readers, digital signage, and wearable fabric displays [2-3]. Noticeably, high-end e-papers are also equipped with visible sources, i.e., front light units (FLUs). A FLU provides additional illumination under low ambient lights, essential to all-condition-operated e-papers. As shown in Fig. 1, a FLU usually comprises an LED bar and a light guide plate (LGP) for uniform light distribution.

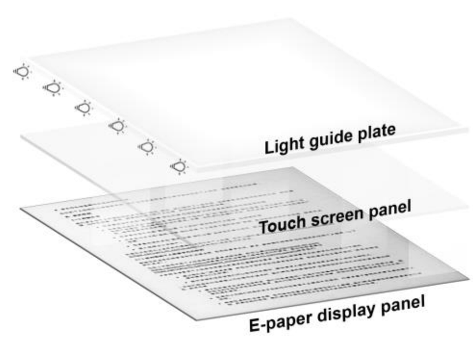

Fig. 1. An e-paper display with a front light unit.

Inspired by the IDAC concept based on LCDs, this study, for the first time to our knowledge, proposes integrating Li-Fi into e-papers with the help of FLUs, enabling bifunctional e-papers, i.e., simultaneous display and communication. First, on the transmitter (Tx) side, we address the problem of embedding a bit stream into a FLU while the display function is unaffected. On the received (Rx) side, an ordinary CMOS camera is adopted, considering cameras are ubiquitous in IoTs. Despite the camera's low frame rate, the inherent rolling shutter effect is exploited to convert a signal of a high temporal frequency to a picture with a high spatial frequency, facilitating image processing-based demodulation. Furthermore, we introduce MIMO into e-paper-based Li-Fi. Underlying the MIMO Li-Fi is a 1D-dimming FLU with an in-house designed LGP (2D dimming is impractical due to the edge-lit FLU). By independently controlling plural LED segments, the communication rate is multiplied, in addition to the well-known benefit of low power consumption and higher contrast brought by dimming [4-7]. At the receiver side (Rx), the CMOS image sensor is also divided into independent regions in the direction orthogonal to how the shutter rolls. In this manner, a MIMO Li-Fi system is built. Simulation and experiments are conducted to verify the display and Li-Fi functions. When the FLU is used as one transmitter without 1D-dimming, a data rate of 5.76 kbps is verified. Next, an LGP is designed for 1D dimming, enabling MIMO with a fourfold rate of 23.04 kbps, as well as better contrast and power saving.

2. Method

Fig. 2 shows the general principle of the proposed e-paper integrated with Li-Fi. The display panel normally presents pictures; meanwhile, the FLU is modulated at a high frequency, invisible to human eyes. A specific modulation algorithm is applied to the FLU to carry bit streams. On the Rx side, a rolling-shutter camera takes pictures by exposing the CMOS sensor row by row at a scanning speed of several thousand Hertz. When the FLU's modulation frequency is comparable to the shutter's scanning speed, light-dark stripes are recorded in a picture, as Fig. 2(a) shows. Thus, with the help of the rolling shutter effect, an image frame can carry many more data bits than that limited by the low frame rate. If further segmenting the FLU and independently embedding data bits in these segments, the camera will receive 2D stripes whose columns correspond to the segments, as Fig. 2(b) shows. MIMO Li-Fi is built this way, and the 1D dimming improves display quality.

Three critical problems must be addressed to accomplish the above proposal: (i) modulation algorithm regarding both the bit streams and image content [8]; (ii) acquisition and demodulation approach using a rolling-shutter camera; (iii) LGP design for a light spread function (LSF) not diffusing excessively; otherwise, light from different FLU segments completely merges to eliminate independent transmission.

The following sections discuss specific work by adopting a commercial e-paper display (an e-reader from XIAOMI with a 7.8-inch electrophoretic panel from E Ink and a FLU).

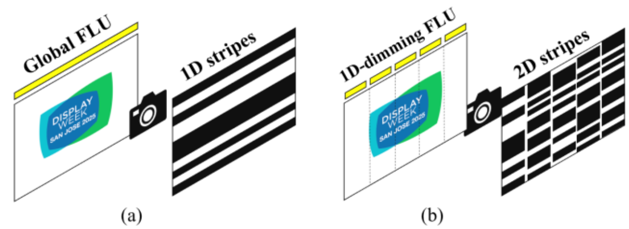

Fig. 2. Data bits captured as stripes by a rolling-shutter camera: (a) a global FLU; (b) a 1D-dimming FLU.

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2.1 Modulation

Two signals are inputted into the proposed e-paper: bit streams for Li-Fi and images for display. First, like local dimming in LCDs, a specific algorithm obtains the dimming level of each FLU segment according to the image content (one segment for the global FLU). Here, we select the maximum method (dimming level = maximum grayscale) to avoid the clipping artifact as much as possible, which is well-known in LCD local dimming. Next, the bit streams after serial-parallel transformation are modulated based on the dimming levels and sent to the FLU. Image grayscales are compensated and transmitted to the display panel.

Several modulation algorithms with dimming control are available for Li-Fi. Here, we adopt the mature multi-pulse position modulation (MPPM). In MPPM, a symbol is divided into m time slots. Depending on the dimming level γ, 10γ time slots transmit optical pulses. We set m to ten and the range of γ to 0.1~0.9. Different positions of the emitted pulses represent different symbols, so the symbol number is given in Eq. (1). Thus, the bit number every symbol can transmit is $\lfloor \log_2 C \rfloor$. Each packet is transmitted three times to ensure a picture frame can acquire at least one packet.

$$C = \binom{10}{10\gamma} \tag{1}$$

2.2 Light guide plate (LGP) for 1D dimming

This study operates the FLU in the global and 1D modes, respectively, as Figs. 2(a) and (b) show. The FLU in the commercial e-reader is directly used for the global mode. On the other hand, an LGP is designed in-house for the 1D mode.

Ideally, the 1D-dimming FLU provides illumination in the form of perfect bands. However, like the role the light spread function (LSF) plays in local dimming backlights, the LGP also spreads the light from each FLU segment. This study designs an LGP, which provides uniform full-on illumination and moderately confines the illumination of a single segment within a band-shaped region. Not very severe light spreading can help distinguish rolling-shutter patterns in the horizontal direction.

Table 1 shows the primary specifications of the LGP. LED bars are placed on all four edges of the LGP for better light manipulation. The two LED bars on the short edges provide background DC brightness, while the long sides act as controllable segments. The light-guiding dots are designed to be lenticulars for high coupling efficiency [6]. The dot pattern is optimized using LightTools. Fig. 3(a) shows the LGP model. Figs. 3(b) and (c) show the full-on illumination and single segment's LSF. The simulated LSF plays a conventional role in grayscale compensation. More importantly, it tells the receiver how to recognize each segment for the image processing-based demodulation.

Table 1. Specifications of the LGP for 1D dimming

Parameters	Value
Diagonal size	7.8 inch
Active area	140 mm (W) by 200 mm (H)
LED number	10 (W) and 16 (H)
FLU segment number	8
LED size	2mm by 3mm

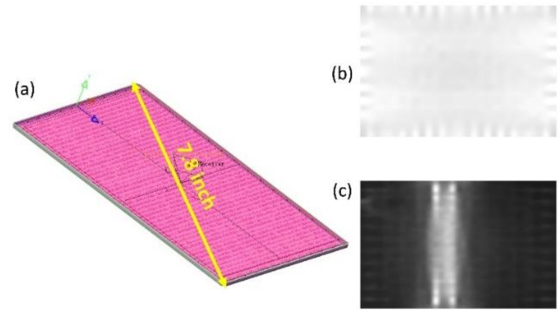


Fig. 3. (a) The LGP model; (b) simulated full-on illumination; (c) LSF produced by one of the eight segments.

2.3 Signal acquisition and demodulation

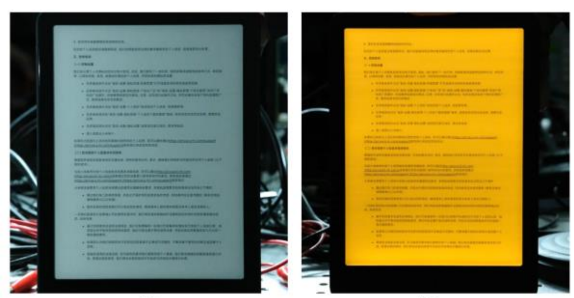
On the Rx side, the camera with a rolling shutter captures stripes overlapping normal pictures. Partition detection, packet identification, threshold determination, and MPPM demodulation are performed to retrieve the data bits from image frames. A neural network-based demodulation algorithm from our previous work [1] can recognize individual data bits represented by only five-pixel-width stripes. This study directly adopts the pipeline in [1].

3. Results

3.1 Global mode FLU

The XIAOMI e-reader with the FLU is used to verify the global mode experimentally. The FLU is driven by an external arbitrary waveform generator (AWG), which sends modulated symbols with a time slot frequency of 17 kHz. A commercial camera (Fujifilm X-S10) is used as the receiver.

For verification of the display performance, the camera's shutter is set to 1/60 s to imitate human eyes and then captures the e-reader, as Fig. 4 shows. As seen, although the FLU is modulated with Li-Fi signals, it can still be normally watched, as the modulation frequency is high enough.



(a) (b)

Fig. 4. The e-reader captured by the camera with a 1/60 s shutter, verifying an unaffected display function: (a) front light off (ambient light mode); (b) the warm front light on.

The shutter speed is changed to 1/20000 s to match the modulation frequency, then the Li-Fi performance is verified. Fig. 5 shows acquired pictures corresponding to three data rates of 1.44 kbps, 2.88 kbps, and 5.76 kbps. The data rate directly determines the stripe width, while a higher rate produces an increased bit error rate (BER) because narrower stipes induce stronger crosstalk. The current experiment achieves a BER satisfying the forward error correction under the data rate of 5.76 kbps. We consider it the Li-Fi speed of the global mode in this study. Nevertheless, the stripes in Fig. 5(a) are still easily distinguished, suggesting a higher data rate in the future with more advanced image processing.

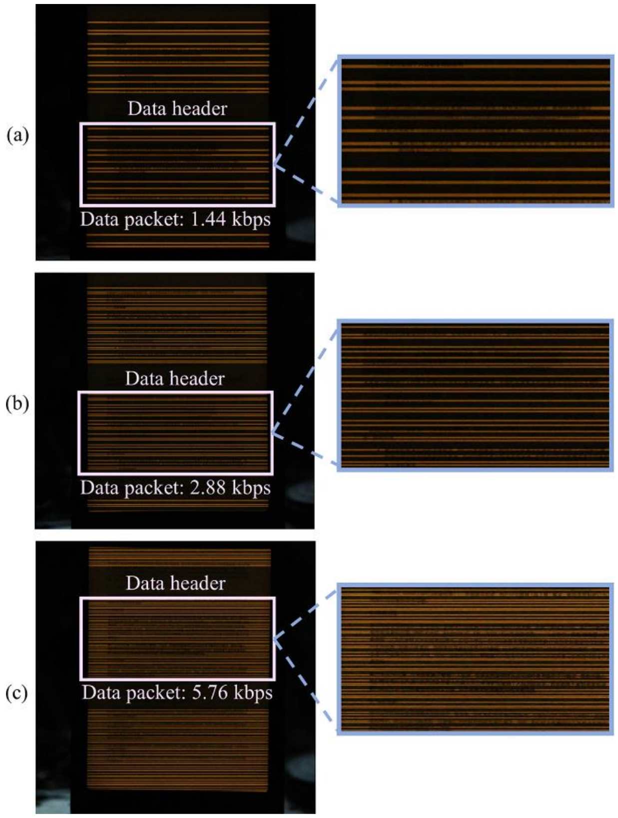


Fig. 5. The rolling-shutter patterns acquired by the camera: (a) 1.44 kbps, (b) 2.88 kbps, (c) 5.76 kbps.

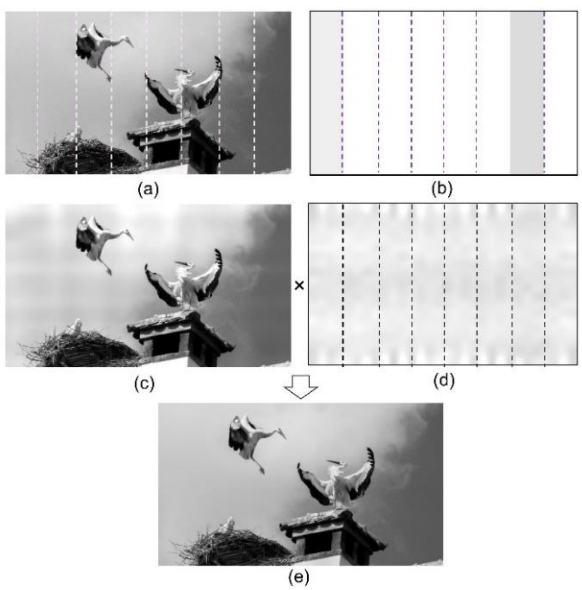


Fig. 6. 1D-dimming pipeline: (a) an input image; (b) the dimming level map; (c) compensated grayscales; (d) the actual front light distribution; (e) the output image.

3.1 1D-dimming mode FLU

While the LGP is under fabrication, to be reported in the full text, we first verify the 1D-dimming mode through simulation using LightTools. We adopt a sample image shown in Fig. 6(a). The image is divided into eight columns to get the dimming level map using the maximum dimming algorithm, as Fig. 6(b) shows. The corresponding brightness levels are assigned to LEDs in the FLU segments, then the actual front light distribution is simulated, as Fig. 6(d) shows. Grayscales are compensated according to the front light distribution, as shown in Fig. 6(c). Finally, the compensated grayscales are converted into reflectance using the Gamma curve, then multiplied with the front light distribution to obtain an output image, as shown in Fig. 6(e). With 1D dimming, the power saving and contrast of the e-paper are expected to be improved. Nevertheless, the improvement must be significantly lower than local dimming, limited by the absence of direct-lit FLUs.

For the VLC performance, we synthesize rolling-shutter patterns with the LSF of the FLU segments. The simulation method of rolling-shutter patterns is from [1] (noise and the time-domain low-pass effect considered). The LSFs are extracted from LightTools simulation, as shown in Fig. 7(a), where the individual LSFs are well confined in band-shaped regions. Fig. 7(b) shows synthetic images on the e-paper's entire screen when four of these segments are turned on alone. Note a high-pass filter has removed the DC brightness provided by the LED bars on the short edges.

Finally, we perform two simulation tasks to examine the crosstalk when multiple FLU segments simultaneously work as Li-Fi transmitters. (i) All-transmitter mode: all eight segments act as transmitters to produce rolling-shutter stripes. (ii) Interlaced mode: four are used as transmitters, and the other four only provide background DC illumination. Figs. 8(a) and (b) show the two modes. The all-transmitter mode produces substantial crosstalk against demodulation, while the interlaced mode provides clear data packets. Therefore, under the current LGP design, we consider four independent Li-Fi inputs available, indicating a fourfold data rate of 23.04 kbps.

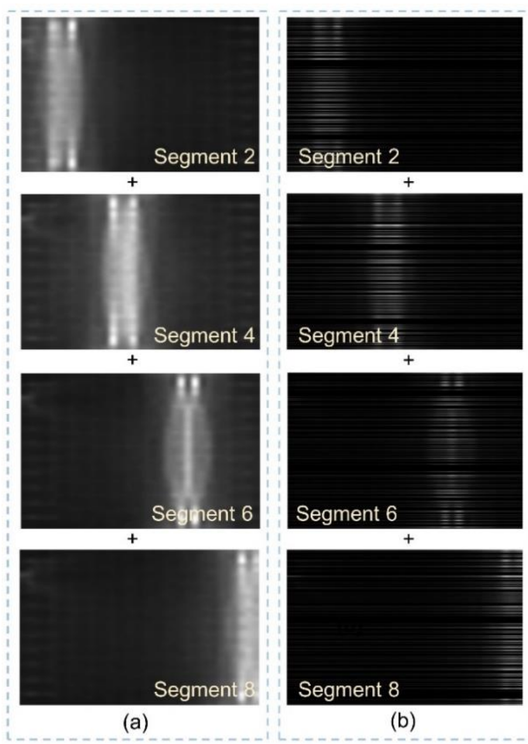


Fig. 7. (a) LSFs of four FLU segments tuned on alone. (b) Synthetic rolling-shutter patterns applied to the segments.

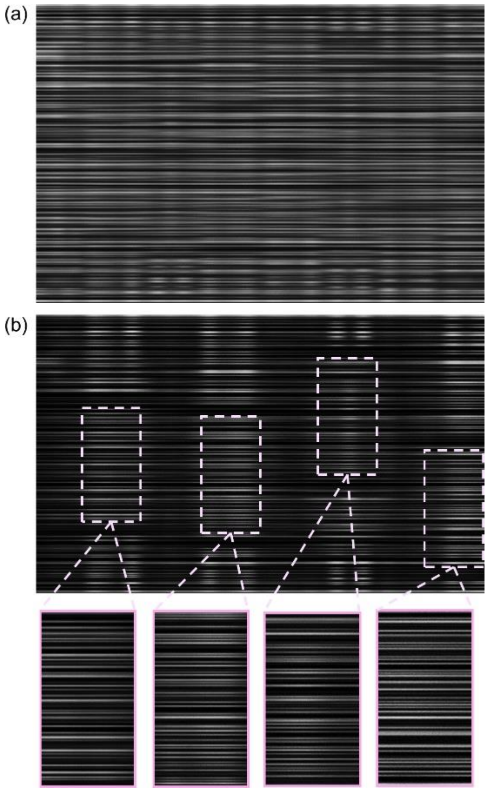


Fig. 8. Synthetic rolling-shutter patterns of (a) the all-transmitter mode and (b) the interlaced mode.

4. Discussion

In the above 1D mode study, the number of independent Li-Fi transmitters is limited by the light spreading of individual FLU segments. Nevertheless, note that a large room exists for LGP optimization. Studies on local dimming based on edge-lit have reported that 1D backlights can be considerably localized in bands [6]. The potential number of independent Li-Fi transmitters must be much larger than four. This study should provide a pioneering concept of MIMO Li-Fi integrated into 1D dimming.

Other potential approaches to faster Li-Fi include using fewer pixel rows to represent a time slot of MPPM symbols. For example, our previous study [1] used five rows for one symbol with the help of neural networks, whereas this study uses ten, suggesting the possibility of doubling the rate to 46.08 kbps. Another possibility is using orthogonal polarization light for interlaced FLU segments, along with a polarization-sensitive receiver. Taking advantage of polarization can quickly eliminate the crosstalk between adjacent FLU segments.

5. Conclusion

This study proposed a bifunctional e-paper integrating the normal display function and Li-Fi for the first time. Li-Fi integrated on a global FLU was experimentally verified with a data rate of 5.76 kbps. Next, an LGP was designed in simulation for 1D dimming, enabling MIMO Li-Fi with a fourfold rate of 23.04 kbps. This study likes to initialize the concept of e-paper integrated with Li-Fi, while much potential exists for data rate improvement.

6. References

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