Light Codes for Fast Two-Way Human-Centric Visual Communication

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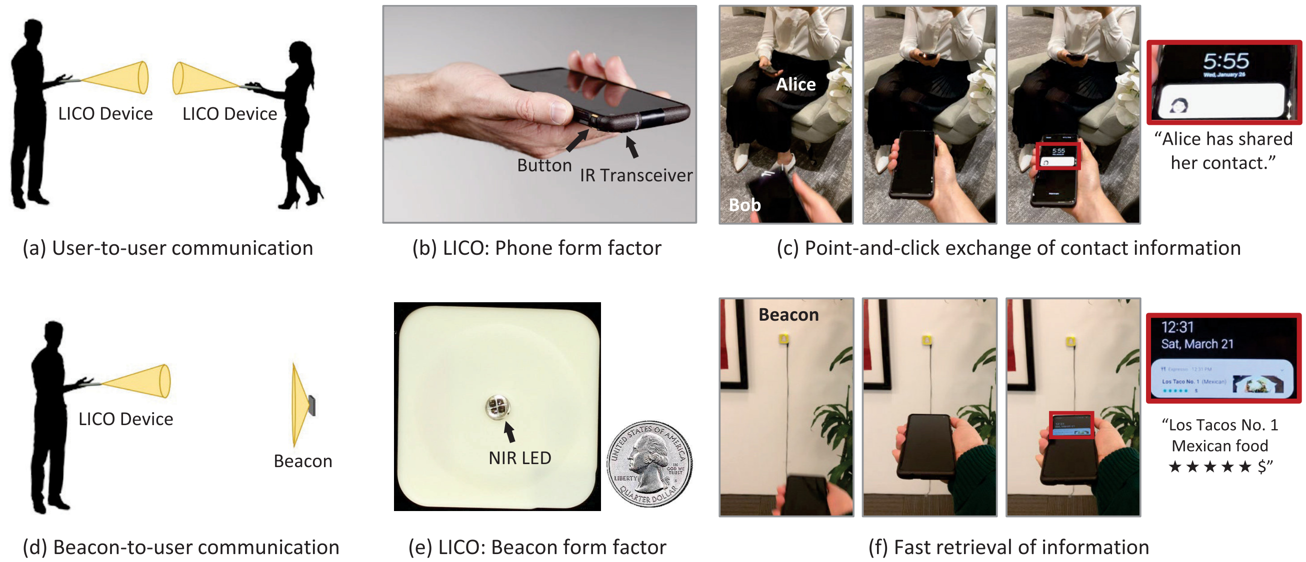

Fig. 1. Light codes. (a) We present Light Codes (LICO), a novel communication modality that enables fast exchange of information among users. (b) A LICO device in a phone case form factor consists of an infrared (IR) transceiver for sending/receiving information as temporal binary codes. (c) Information can be exchanged between two users with a simple 'point-and-click' gesture, leading to a fast and fluid user experience. (d) Light codes can also be used as a beacon, an optical analog to a spatial visual code. (e) A LICO device in a beacon form factor consists of an IR transmitter that emits temporal codes within a 100-degree field of view. (f) Users can read the code instantly by pointing their phone toward the beacon, even in challenging scenarios including motion and strong ambient light.

Visual codes, such as QR codes, are widely used in several applications for conveying information to users. However, user interactions based on spatial codes (e.g., displaying codes on phone screens for exchanging contact information) are often tedious, time consuming, and prone to errors due to image corruptions such as noise, blur, saturation, and perspective distortions. We propose Light Codes (LICO), a novel method for fast and fluid exchange of information among users. Light codes are based on transmitting and receiving temporal codes (instead of spatial) using compact and low-cost transceiver devices. The resulting approach enables seamless and near instantaneous exchange of short messages among users with minimal physical and cognitive effort. We design novel coding techniques, hardware prototypes, and applications that are optimized for human-centric communication, and facilitate fast and fluid user-to-user interactions in various challenging conditions, including a range of distances, motion, and ambient illumination. We evaluate the performance of the proposed methods both via quantitative analysis and user study based comparisons with several existing approaches including display-camera links, Bluetooth, and near-field communication, which show strong preference toward Light Codes in various real-world application scenarios.

CCS Concepts: • **Human-centered computing** → *Interaction devices*; • **Hardware** → Sensor devices and platforms;

Additional Key Words and Phrases: Visual codes, human-centric visual communication, communication protocols

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1 INTRODUCTION

Visual codes, such as QR codes, have proven to be of great utility in our everyday lives. Each code is unique and can be used to access information (menus, product details, etc.) and make connections with other users. Today, the *de facto* procedure for decoding a visual code is to reach for your phone, open the camera app, get close

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	Max. Range	Selectivity	Interaction Time	Power Consumption	Security Risks	Typical Application Scenario
Wi-Fi Direct	30-100 m	Limited	8–12 s	High	High	Data centric; Large amount of data transfer
Bluetooth	~10 m	Limited	6–10 s	Low	High	Data centric; Moderate amount of data transfer
Display-Camera Link	~2 m	High	5–8 s	Low	Low	Human centric; Small amount of data transfer
NFC	~2 cm	High	5–9 s	Low	Minimal	Human centric; Small amount of data transfer
Light Codes	**~3 m**	**High**	**<1 s**	**Low**	**Minimal**	**Human centric; Small amount of data transfer**

Fig. 2. Comparison of various communication modalities for exchanging information. Light codes enable fast exchange of small messages such as QR codes between users while maintaining low power and minimal security risks. The interactions times were estimated from our user study (Section 5.2) conducted to evaluate various modalities.

to the code to ensure it is imaged well, and take a photo. If the code is successfully decoded, the user is taken to the source of the information. These methods, although simple to implement, are prone to errors due to common causes of image degradations, such as occlusions, blur, and perspective distortion. Furthermore, user-to-user communication—imagine two users trying to exchange digital business cards via QR codes on their smartphones—requires users to display their code on their screen and tilt the screen to the other user. These steps considerably reduce the fluidity of user interactions, thus preventing this otherwise powerful technology from gaining widespread traction. Given that visual codes are meant to be purely functional, it would be of great benefit to the consumers and the proprietors of codes to significantly reduce the physical and cognitive effort required to convey and read visual codes.

In this article, we introduce a method for virtually instant detection of visual codes. Our approach is inspired by **Visible Light Communication (VLC)** modalities where information is transmitted via temporally modulated light [Haugen et al. 1986; Lee et al. 2007; Tsonev et al. 2014]. We call the temporal code a *lightcode* and the transceiver a LICO (short for lightcode) device. VLC methods are typically based on high-speed photodiodes [Vucic et al. 2010] that can achieve a high data rate, although in controlled settings. Our goal is different: we aim to design a *human-centric* communication method that facilitates fast and fluid two-way user interactions in uncontrolled consumer settings while potentially sacrificing the data rate. LICO works robustly in challenging scenarios, over a range of distances, orientation differences, motion, and ambient illumination. The proposed method can be either incorporated into a smartphone or embedded in a protective case attached to the phone. The user experience for transmitting or receiving a code is simple, as shown in Figure 1(a–c). LICO can transmit and read a code in a few milliseconds, which for all for practical purposes is instantaneous.

One may wonder if existing methods such as Wi-Fi, Bluetooth, **Near-Field Communication (NFC)**, and RFID may suffice for achieving our goal of instant code exchange. Consider a scenario where two users attending a crowded conference wish to exchange their contact information (e.g., a digital business card) via a code. If this were done using Bluetooth, the users would need to broadcast their codes to all others in their vicinity. To ensure privacy, the users would need to choose each other as recipients of their codes. As we know from existing methods such as iPhone AirDrop, this requires the user to perform several clicks on their phone, as shown later in Figure 3(a). This results from the simple fact that existing modalities do not have high selectivity—that is, they do not allow users to transmit or receive information with a high degree of directionality. Further, these methods cannot be used in places without signal penetration, such as elevators, subways, or highways. NFC, however, works only over short ranges, thereby providing high selectivity and security, but requires close contact and relatively large interaction times (Figure 2) for sharing information, which may not be feasible in several social settings (Figure 3(c)).

In contrast, LICO enables seamless exchange of codes using a gesture that is analogous to a handshake but without any physical contact. Since LICO uses optical transmission and reception, it only needs a pre-designed aperture to ensure that the transmission and reception only take place within a cone. Such a conical **Field of View (FOV)** is what makes other everyday devices, such as TV remotes, easy to use. TV remotes are designed for one-way interaction with a fixed receiver; however, we optimize the underlying communication technique and the device for two-way interaction in uncontrolled user interface scenarios. To exchange codes, as shown in Figures 1 and 3(d), both users roughly point their phones toward each other and press a button. While the button is pressed (for a fraction of a second), the codes are exchanged. All this happens without the users having to even unlock their phones, and without worrying about interference from thousands of concurrent interactions going on in the conference. Once the exchange has taken place, the users can later decide whether or not to to accept a received code. Another application for LICO is as a beacon (see Figure 1(d–f)) that continuously transmits a code within a wide FOV. The beacon is an optical analog to a spatial visual code. A user can read the code by pointing their phone in the rough direction of the beacon and pressing a button to instantly read the code and obtain product information, read menus, and so forth from several feet away, without unlocking their phones.

The goal of LICO is to enable fluid and low-latency interactions, without requiring global infrastructure to perform arbitration among users. A key challenge in such uncontrolled human-to-human interaction is interference between different devices. We design a temporal stochastic coding scheme that enables efficient communication while preventing cross-talk and self-transmissions. The communication scheme is inspired by classical shared medium access communication protocols such as **Time-Division Multiplexed Access (TDMA)** [Miao et al. 2016] and ALOHA [Abramson 1985; Martin 2005; Metcalfe and Boggs 1976]. In comparison to these methods, the proposed scheme avoids the need to perform explicit handshake among devices, thus lowering latency and system complexity, albeit at the expense of lower overall bandwidth. As a result, LICO enables exchange of short messages between human users with minimal physical and cognitive effort. We demonstrate the effectiveness of LICO via hardware prototypes in two different form factors—a smartphone case form factor and a beacon—for several applications, including sharing contact and digital content, and accessing information (see Figure 13). We evaluate the performance of the proposed methods via quantitative comparisons, as well as user studies that show preference of users in various real-world scenarios.

Limitations and Scope. LICO requires emitting light and needs additional power as compared to passive approaches based on spatial QR codes. Furthermore, LICO requires dedicated devices which are not currently available off-the-shelf, whereas several existing techniques are already integrated into consumer smartphones. Fortunately, the cost, weight, size, and power consumption of LICO devices are relatively low (for the transceiver, about $3, 77 mg, $3.1 \times 8.5 \times 2.5$ mm (H, L, W), 73.5 mW [Vishay Semiconductors 2022]), thus opening up the possibility of consumer adoption in the future. The proposed approach is not meant to replace or directly compete with conventional modalities such as QR codes and NFC, which have been optimized over several years, and can produce useful experiences. Instead, our goal is to explore and analyze a novel modality, which complements existing methods (e.g., QR codes may be used during the day, and beacon/LICO may work well in the dark) and could lead to fast and fluid user interactions in a broad range of real-world consumer applications. This article should be seen just as a first step toward that goal.

2 RELATED WORK

In the following, we briefly review several existing human-centric communication techniques. For a more comprehensive review of prior art, see the supplementary report. Figure 2 summarizes several modalities, including the proposed Light Codes, across several dimensions that are critical for a smooth user experience.[1] Figure 3 illustrates a typical user interaction for exchanging contact information (e.g., "friending") using different methods. Typically, methods with higher selectivity result in interactions that are less physically and mentally demanding, and require overall lower interaction time.

Wi-Fi. Radio wave based communication methods such as Wi-Fi can achieve a high data rate over long distances. However, Wi-Fi-based communication does not have directionality, resulting in low selectivity. Due to the lack of selectivity, Wi-Fi-based inter-device communication often requires manually selecting and authenticating the device to communicate with. This reduces the overall fluidity of the user experience. Wi-Fi also has high power consumption (2–20 Watts), which is an important consideration in mobile devices.

[1] The numbers in the table are for reference only; some numbers could change depending on available power and experience of the users with different applications. Whenever possible, we used actual measurements (e.g., NFC range and connection times from iPhone and Samsung phones).

Bluetooth. Bluetooth is a wireless technology used for connecting two devices and exchanging data. In contrast to Wi-Fi where two devices need to connect to an access point, Bluetooth can directly build a connection between two devices. Although Bluetooth has lower data rate (≈1/10 of Wi-Fi) and smaller range (~10 m), the power consumption is also considerably lower than that of Wi-Fi. Since Bluetooth is also based on radio waves which do not have strong directionality, Bluetooth devices have a wide communication cone leading to limited selectivity, as well as potential security risks such as cyber-flashing where a user can receive unwanted data.

Li-Fi. Li-Fi is a communication technology that uses laser beams or LED sources for transmitting information [Haugen et al. 1986; Tsonev et al. 2014], and high-speed photodiodes as receivers [Vucic et al. 2010]. These techniques, also referred to as VLC [Lee et al. 2007], while capable of achieving high data rates in controlled settings, are not applicable in the human-to-human communication and consumer scenarios because they require near perfect alignment of the transmitter and the receiver.

Receivers using hemispherical lenses [Barry and Kahn 1995] have been explored for non-directed **Infrared (IR)** communication systems [Otte et al. 2013] that do not require precise alignment between transmitter and receiver (e.g., television remote controls). These systems use IR protocols such as Sony SIRC [Sony 2022], the Phillips RC5 (Manchester encoding), and the NEC IR protocol (pulse distance encoding) [DigiKey 2022]. These protocols and devices are typically meant for one-way communication. An interesting future direction is to adapt these methods for two-way interactions.

Display-Camera Links. A special case of Li-Fi is where the light source is a display. Data is transmitted typically by displaying a code (e.g., a QR code) on the display and capturing an image by a receiver camera. Various codes have been considered, including frequency domain spatial coding [Perli et al. 2010], color codes [Hao et al. 2012], and spatial-temporal codes [Hu et al. 2014; Jo et al. 2016; Langlotz and Bimber 2007]. An important class of display-camera communication methods are those based on steganography [Baluja 2017; Tancik et al. 2020], where the goal is to make the displayed code imperceptible to humans [Jo et al. 2016; Nguyen et al. 2016; Tran et al. 2021; Wengrowski and Dana 2019; Yuan et al. 2012]. Although display-camera links can provide directional communication in consumer devices, their range is limited due to imaging degradations such as perspective distortion [Wengrowski and Dana 2019], motion blur, and ambient illumination [Perli et al. 2010]. Furthermore, display-camera-based interaction often requires users to clear their display (to pull up the code) and tilt their screen to the other user. These steps increase the overall interaction time (see Figure 3(b)).

Near-Field Communication. NFC is a set of protocols for very short distance (<2 cm) data transfer between two devices [Coskun et al. 2013; Paus 2007]. Similar to LICO, NFC methods are typically optimized for transferring a small amount of data. NFC works only for a very short range, thus requiring close contact and large interaction times (see Figure 2) for sharing information, which may not be desirable in human-centric application scenarios (see Figure 3(c)). In contrast, the proposed system enables fast communication and fluid user interactions across a range of distances while maintaining low power requirements and minimal security risks.

3 LIGHT CODE COMMUNICATION MODEL

Each LICO device consists of a light source (Transmitter) that emits temporal light codes and a sensor (Receiver) that captures the codes emitted by other devices. Consider a scenario where two users *Alice* and *Bob* wish to connect and exchange information via their LICO devices. Both users press the buttons on their respective devices to initiate the communication. When the buttons are pressed, the transmitters emit temporally coded light within an illumination cone, as illustrated in Figure 4. For successful transmission, the devices must have the following:

- *Temporal overlap*: Both devices must be switched on for an overlapping duration of time.
- *Angular overlap*: The communication cones of the devices must intersect.

3.1 Self-Transmission Due to Cross-Talk and Reflections

The communication model described previously assumes that the sensor on a LICO device receives light codes only from a different device. However, cross-talk between a LICO device's own source and sensor, as well as retro-reflection of a transmitted code by the surrounding scene, may result in *self-transmission*—that is, a sensor may receive the illumination code emitted by its own light source. Such self-transmission may corrupt the true received code, leading to large, systematic errors. Example scenarios in which self-transmission can occur include (1) light being bounced within the enclosure or the optics, then returning to the receiver; (2) light reflecting back when a user directs it toward a wall, floor, or ceiling; and (3) light also being reflected back from a human body when a user points it toward another user.

Temporal Synchronization. It is possible to prevent self-transmission by ensuring that a LICO device does not transmit and receive at the same time. One way to achieve this is via TDMA, a widely used scheme for facilitating multi-user access of shared communication channels [Miao et al. 2016]. This can be implemented by dividing the total ON time into shorter time blocks, as shown in Figure 5. The two devices are assigned different blocks during which they transmit to avoid cross-talk. Applying TDMA directly for light code communication will require either a central arbitration authority (e.g., base stations for synchronizing timing across different users) or high-speed temporal synchronization of devices, which may not be possible in the uncontrolled user interface scenario considered here. Is it possible to implement a TDMA-like approach without synchronization?

Stochastic Transmission. Our key idea is to leverage stochasticity to avoid central arbitration or explicit synchronization. Stochasticity is utilized in several shared-medium access communication protocols. For example, ALOHA [Abramson 1985, 2009] is a classical shared-medium communication protocol used in mobile wireless networks [Pahlavan and Levesque 1994; Stavenow 1984], Ethernet [Martin 2005; Metcalfe and Boggs 1976], and modern satellite networks [Abramson 1990]. These classical approaches employ a 'stochastic backoff' strategy, where a transmitter, in the case of a clash, waits for a random amount of time before re-transmitting. This approach requires repeated acknowledgments from the receiver before making a decision to re-transmit, which could increase latency, and thus is non-ideal in a user interface setting. See the supplementary report for a detailed discussion on stochastic communication protocols in the communication literature.

Instead of waiting to decide whether to re-transmit when there is a collision, we take a different *feedback-free* approach. We propose a stochastic coding scheme that divides the ON time of a device into multiple time blocks. In our implementation, each block is approximately 10 ms long (details in Section 4). In each block, the device transmits independently with a fixed probability p_t *without waiting for feedback*. To avoid self-transmission as discussed earlier, the source and the sensor on a LICO device take turns transmitting and receiving (i.e., if the device transmits in a block, its sensor is switched off). Conversely, if the device is not transmitting in a block, then it is in the listening mode so that the sensor is on and receives light. Since each device transmits independently in each block with a probability p_t, no explicit 'handshake' is required between devices. Since the approach is stochastic, without explicit synchronization or feedback, there may still be clashes when both devices are transmitting. In this scenario, since both sensors are switched OFF, none of the devices receives the transmitted codes.

The proposed approach is simpler; requires no synchronization or feedback,[2] albeit at the cost of lower data rate and bandwidth; and thus is ideally suited for user-centric applications which require transmitting only short messages but where simplicity and lower latency are at a premium.

3.2 What Is the Optimal ON Probability?

The performance of the proposed stochastic approach is determined by the block ON probability p_t. The choice of p_t presents a tradeoff. If p_t is too high, although each device transmits more frequently, there will be more clashes and none of the sensors will receive the transmitted codes, as described previously. However, a low p_t may lead to fewer clashes, but the devices incur a longer "dead time" during which no signals are transmitted. This raises a natural question: What is the optimal p_t?

Probability of Successful Transmission. Consider two LICO devices trying to communicate with each other using the preceding stochastic transmission scheme. Let W be the temporal overlap window when both devices are switched ON. We assume that the entire code that a device needs to communicate can be fit in a single block. Furthermore, we also assume that the devices can successfully communicate even if one code is successfully transmitted (i.e., even if transmission during one block is successful). Therefore, in the proposed stochastic transmission approach, each device repeatedly transmits its code multiple times. In the following, we derive

[2]LICO is feedback free at the low-level communication protocol level but requires a single positive feedback at the user level (i.e., when both users have successfully exchanged information).

Fig. 3. Visual comparison of different methods for exchanging digital contact information. (a) Wi-Fi and Bluetooth have limited selectivity, thus requiring users to choose each other as recipients of transmitted codes, resulting in cognitive effort and latency. (b) Display-camera links require users to adjust the camera to avoid image artifacts for receiving the code, reducing the overall fluidity of user experience. (c) NFC-based methods require close contact among users, which may not be feasible/desirable in several social scenarios. (d) In comparison, light codes enable seamless and near instantaneous exchange of codes between users. The thick red lines along the time axis indicate the key bottleneck of each method. Note that the time for other methods is measured from two users who are already familiar with all steps and start the process from "ready" state (the phone is unlocked and is in the contact sharing app).

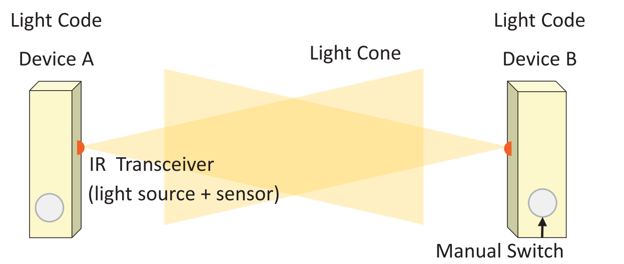

Fig. 4. LICO devices communicate by pointing at each other. When the users press the buttons on their respective devices, the transmitters emit temporal codes within a light cone. If the light cone of a device intersects with the sensor of the other device, information is exchanged in a short duration of time (< 1 second).

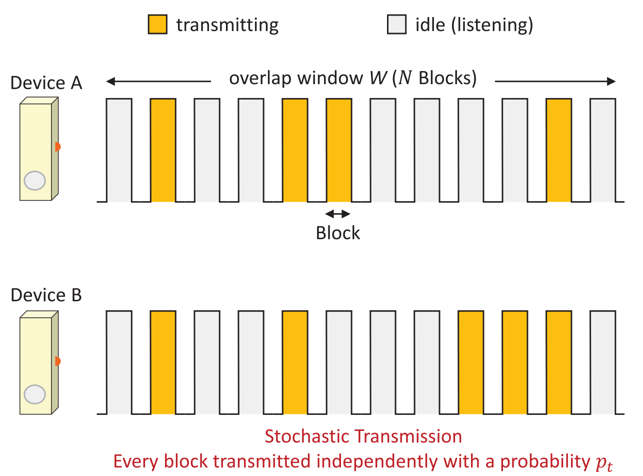

Fig. 5. Light code communication protocol. LICO devices communicate by transmitting codes in temporal blocks. Each block is 10 ms long and contains the entire code to be transmitted. To avoid self-transmission, the source and the sensor on a LICO device take turns transmitting and receiving (i.e., if the device transmits in a block, its sensor is switched off). To address the lack of synchronization between devices, we propose a stochastic protocol where in each block the device transmits with a probability p_t; each devices repeatedly transmits its code multiple times over the temporal overlap window W. Since each device transmits independently in each block with a probability p_t, no explicit synchronization is required between devices.

the probability of successful transmission during the entire duration of the overlap window. For ease of analysis, we assume the devices are identical.

Without loss of generality, let us consider the probability that Device A successfully transmits to Device B in a given overlap window. Device A transmits with a probability p_t in every block. In general, since the devices are not synchronized, the temporal boundaries of the blocks may not be aligned across devices, as shown in Figure 6. Therefore, with high probability, any given block of a device will overlap with two blocks of another device. For a transmitted block to be received, Device B should not be transmitting in two neighboring blocks that overlap with the transmitted block. Thus, the probability p^b_{suc} that transmission is

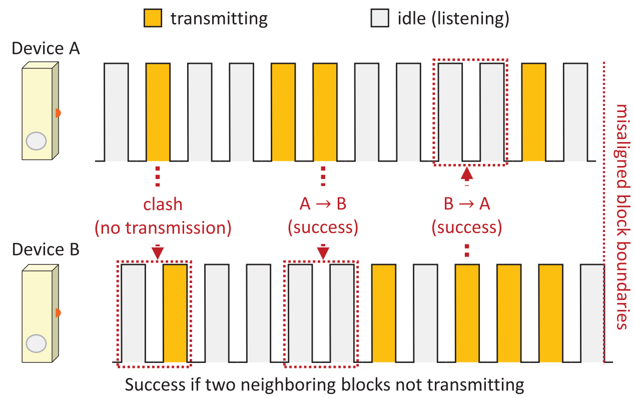

Fig. 6. Asynchronous transmission and probability of success. Since two devices are not synchronized, the temporal boundaries of the blocks may not be aligned across devices. Therefore, with high probability, any given block of a device will overlap with two blocks of another device. For a transmitted block to be received, Device B should not be transmitting in two neighboring blocks that overlap with the transmitted block.

successful in a single block (i.e., only Device A is transmitting during that block) is

$$p^b_{suc} = p_t \,(1 - p_t)^2 \,. \tag{1}$$

Effect of Channel Noise. Even if a transmitted code is received, it may be decoded incorrectly due to various non-idealities in the optics and electronics and sensor noise. To model these effects, we assume that a received code is successfully decoded only with a probability p_n. In the ideal case, $p_n = 1$. Then, the probability p^b_{suc} that transmission is successful in a single block is given as

$$p^b_{suc} = p_t \,(1 - p_t)^2 \, p_n. \tag{2}$$

Suppose the overlap window W is divided into N temporal blocks, as shown in Figure 5. Then, the overall probability of successful transmission in W is given by the probability that at least one block is successfully transmitted and decoded:

$$p_{suc} = 1 - \left(1 - p_t \,(1 - p_t)^2 \, p_n\right)^N . \tag{3}$$

Optimal Transmission Strategy. To find the optimal transmission strategy, we aim to find the transmission probability p_t such that p_{suc} (Equation (3)) is maximized. To this end, we use the first derivative test, setting $\frac{\partial p_{suc}}{\partial p_t} = 0$. Solving for the resulting equation, we get the optimal transmission probability:

$$\boxed{p_t^{opt} = \frac{1}{3}.} \tag{4}$$

The preceding equation is the key mathematical result of the article. It tells us that the optimal transmission probability is independent of the channel noise p_n and the window size in terms of the number of blocks N. To validate this result, we perform Monte Carlo simulations of the proposed stochastic coding scheme (see the supplementary report for details). Figure 7 plots p_{suc} vs. p_t, for different values of N and p_n. As can be observed, the simulated values of p_{suc} closely match the theoretical values.[3] As predicted

[3]There is a discrepancy between the simulated and analytical values due to the approximate nature of the expression in Equation (3). This is because the derivation assumes

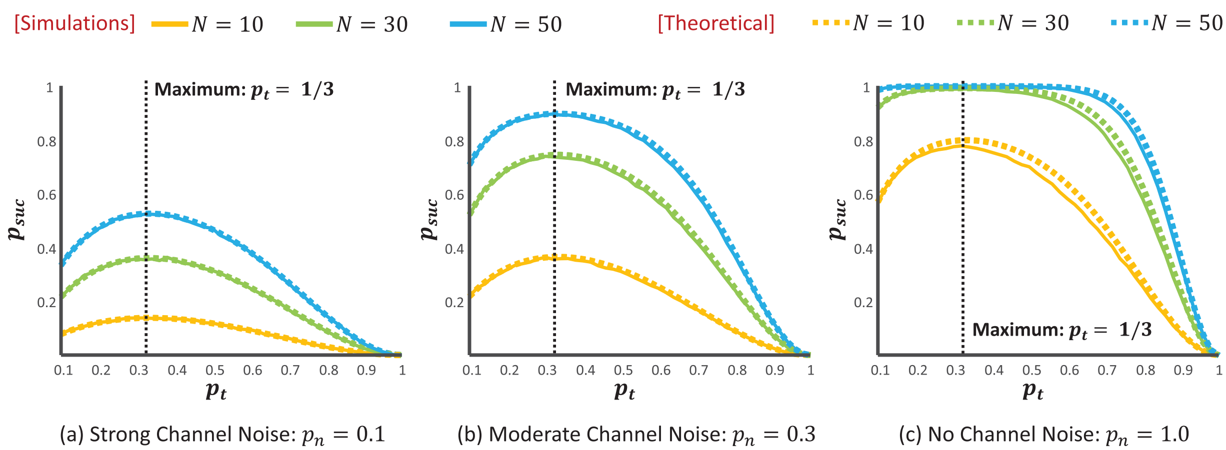

Fig. 7. Optimal transmission probability for a stochastic transmission scheme. We perform Monte Carlo simulations to verify the performance of the proposed stochastic coding scheme. (a–c) Plots of p_{suc} vs. p_t, for different values of N and channel noise p_n. The simulated values of p_{suc} closely match the theoretical values. As predicted by theory (Section 3.2), the optimal ON probability $p_t^{opt} = \frac{1}{3}$ across all parameter settings.

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Implications. The preceding result has useful practical implications. The optimal transmission strategy is to simply transmit with a fixed probability $p_t = \frac{1}{3}$, regardless of the noise, window size, and other hardware device characteristics. The probability of successful transmission is given by substituting Equations (4) in (3):

$$\boxed{p_{suc}^{opt} = 1 - \left(1 - \frac{4}{27} p_n\right)^N.} \tag{5}$$

Figure 8 plots p_{suc}^{opt} vs. N for different levels of channel noise. Since the transmission scheme is stochastic, the longer the overlap window (large N), the higher the probability of successful transmission.

How Long Should the Transmission Window Be? An important practical consideration is the duration for which the devices must be switched ON for successful transmission of the message. Let χ be the minimum desired probability of successful transmission. Let N_{min} be the minimum number of transmission blocks needed in the overlap window W for successful transmission of the code with probability χ (i.e., $p_{suc} = \chi$). Then, from Equation (3),

$$\chi = 1 - \left(1 - p_t \left(1 - p_t\right)^2 p_n\right)^{N_{min}}. \tag{6}$$

After rearrangement, we get the following expression for N_{min} in terms of χ, the desired minimum probability of success:

$$N_{min} = \frac{\log\left(1 - \chi\right)}{\log\left(1 - p_n p_t \left(1 - p_t\right)^2\right)}. \tag{7}$$

Assuming optimal transmission probability $p_t^{opt} = \frac{1}{3}$, we get the following expression for the minimum number of transmission blocks needed for successful transmission of the message with probability χ:

$$\boxed{N_{min}^{opt} = \frac{\log\left(1 - \chi\right)}{\log\left(1 - \frac{4}{27} p_n\right)}.} \tag{8}$$

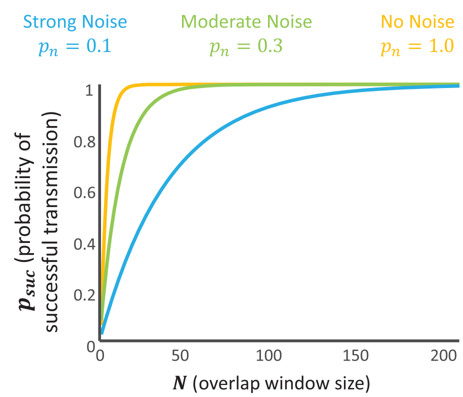


Fig. 8. Success probability p_{suc}^{opt} vs. the window size N. Since the proposed transmission protocol is stochastic, the longer the overlap window (large N), the higher the probability of successful transmission.

Figure 9 plots N_{min}^{opt} as a function of channel noise p_n, for various levels of desired success probabilities. Even for relatively strong channel noise $p_n = 0.5$, successful transmission can be achieved with a high probability (>0.99) using less than 100 blocks. In practice, as we demonstrate via our hardware prototypes (Section 5), LICO devices require fewer than 20 blocks for successful transmission across a wide range of operating conditions, including orientation differences, ambient illumination, and distances of up to 6 feet.

4 HARDWARE PROTOTYPING AND IMPLEMENTATION

We developed hardware prototypes of LICO devices to demonstrate and evaluate their performance in various application

independence of the probability of neighboring pairs of blocks being switched OFF. This results in a gap in the simulated and analytical values of p_{suc}, especially for p_t values around 0.5, due to the assumption of independence being violated. In our experiments, the maximum difference in the simulated and analytical values of p_{suc} is 0.05. Despite this bias, the optimal transmission probability p_t^{opt} remains $\frac{1}{3}$.

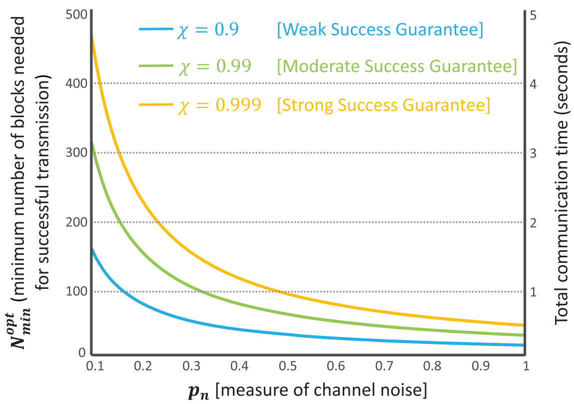


Fig. 9. Minimum window length N_{min}^{opt} required for successful transmission. Plot of the N_{min}^{opt} and time for successful communication vs. channel noise p_n, for various levels of desired success probabilities. Even for relatively strong channel noise $p_n = 0.5$, successful transmission can be achieved with a high probability (>0.99) using less than 100 blocks. In practice, as we demonstrate via our hardware prototypes (Section 5), LICO devices require fewer than 20 blocks for successful transmission across a wide range of operating conditions.

scenarios. A LICO device consists of an IR transceiver module (Vishay Semiconductors, part number TFDU4301 [Vishay Semiconductors 2022]) operating in wavelengths of 850 to 900 nm. The transceiver can transmit and receive temporal binary codes at data rates from 9.6 to 115.2 kbit/s; in our implementation, we operate the device at 57.6 kbit/s. The size of the module is 8.5×2.5×3.1 (L × W × H in millimeters). The illumination and sensing cone angle of the transceiver is approximately 50 degrees. The overall LICO circuit board also consists of a microcontroller for programming the transceiver, an LED indicator light, and an LED driver, as shown in Figure 10(a).

The transceiver is programmed to transmit temporal binary codes consisting of 176 bits, and an additional 16 error correcting bits based on CRC polynomial error correction [Peterson and Brown 1961]. Therefore, each information packet (data block) consists of a total of 192 bits, which is sent repeatedly until successful transmission. Each data block is 10 ms long, with approximately 4 ms of active transmission time and 6 ms of dead time needed to demarcate two consecutive transmissions for error correction.

LICO Device: Phone Form Factor. To facilitate two-way user-to-user communication, we develop a LICO device (based on the circuit board as described previously) in the form factor of a phone case. The color LED indicates the status of the device; a red light indicates that the transceiver is sending and receiving the data, and a green light means a code has been successfully received after passing error checking. An easy-to-access button is placed on the top right side of the phone case; a user can simply press the button to start transmitting and receiving the light code without unlocking the phone, as shown in Figure 10(b). A USB-C male plug, a female plug, and a USB hub chip are used to draw the power from the phone. The power consumption is 73.5 mW. Assuming each friending exchange takes approximately 1 second, the total energy consumption is approximately 73.5 mJ, which corresponds to $1.8{\times}10^{-4}$% of a 3,000-mAh battery. Therefore, a LICO device can be used to make approximately 500,000 communication exchanges on a full battery (assuming no other battery usage). The cost of the transceiver is about US$3. In terms of scalability and manufacturability, the LICO circuit board follows a standard IR transceiver design [Vishay Semiconductors 2022]), making it amenable to consumer device integration in the future. For example, several flagship Android phones, including Xiaomi 12 Pro, Honor V40, and Huawei P50 Pro, are equipped with an IR emitter. By replacing the emitter with a standard transceiver, LICO could be implemented on them. Additionally, the LICO device can be seamlessly integrated into a phone case,[4] effectively becoming a hardware accessory for the phone, similar to an NFC tag [Dot 2022].

LICO Device: Beacon Form Factor. We also develop LICO devices that can act as a *beacon* for one-way communication, as shown in Figure 10(c). A beacon continuously transmits the code within a fixed FOV. A user can read the code by pointing their phone in the approximate direction of the beacon and pressing the button on their device. The design of a beacon should consider its range, FOV, power, and eye safety. The current prototype is similar to a sticky note in size and consists of an LED (100-degree FOV, 850 nm, part number OSRAM LZ4-40R608-0000), a microcontroller (same as the one used in the phone case form factor), an LED driver (part number FemtoBuck COM-12716), and a voltage converter (DROK buck converter). The range of the beacon is determined by the power and duty cycle of the LED, which in turn decide the eye safety distance. We used 5.25 Watts for the LED with a duty cycle of 50% (4-ms emitting code + 6-ms dead time), making the eye safety distance to be 59 mm [International Electrotechnical Commission 2006]. The time to successfully receive a code also depends on the duty cycle; in our implementation, a user can get the code within half a second for a distance of up to 6 m.

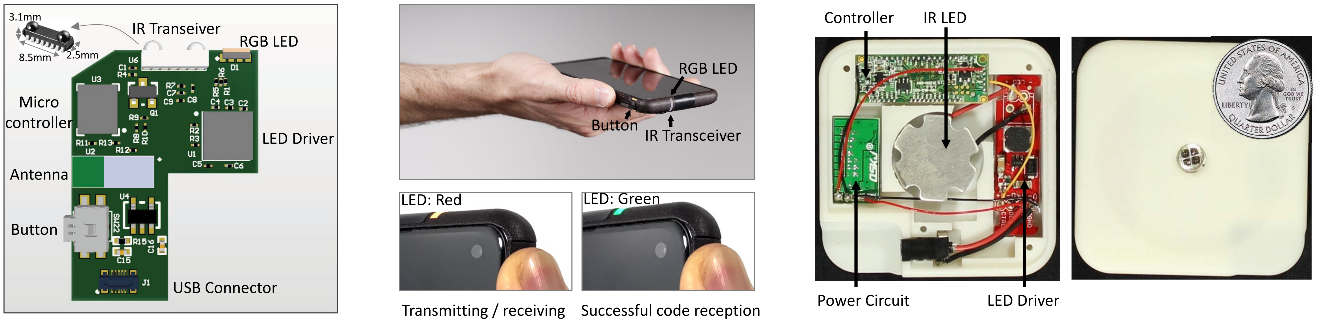
5 EVALUATION AND COMPARISONS

5.1 Quantitative Evaluation of LICO Devices

We evaluate the data communication performance of the proposed Light Codes method by using two prototype devices, as shown in Figure 11(a). Each device is equipped with a transceiver (similar to the LICO device with a phone form factor as shown in Figure 10), and can both transmit and receive data. Each device has an LED light that indicates successful reception of the transmitted light code.

Performance as a Function of Distance and Angle. We evaluated the performance of light codes as the distance d between two devices was varied. The angle between the two devices was held constant at 0 degrees. Each experiment consisted of switching on both devices, and each device attempting to transmit its code to the other device, while simultaneously listening. For each distance d, we measure the total time for successful transmission of the code (contact time), for different transmission probabilities p_t. Figure 11(b) plots the contact times as a function of p_t for various inter-device distances. Each measurement was repeated 200 times and averaged to mitigate noise. Although there is residual

[4]A total of 79% of smartphone users have cases to protect their phones in the United States [Statista 2019].



(a) LICO Device Circuit Schematic (b) LICO Device: Phone Form Factor (c) LICO Device: Beacon Form Factor

Fig. 10. Light code device hardware implementation. (a) A LICO device consists of an IR transceiver module. The transceiver transmits and receives temporal binary codes at 57.6 kbit/s. The illumination and sensing cone angle of the transceiver is approximately 50 degrees. The circuit board also consists of a microcontroller for programming the transceiver, an LED indicator light, and an LED driver. (b) A LICO device in a phone case form factor consists of a color LED that indicates the status of the device; a red light indicates that the transceiver is sending and receiving the data, and a green light means a code has been successfully received after passing error checking. An easy-to-access button is placed on the top right side of the phone case; a user can simply press the button to start transmitting and receiving the light code without unlocking the phone. (c) A LICO device in a beacon form factor consists of an LED, a microcontroller (same as the one used in the phone case form factor), and an LED driver. A beacon continuously transmits the code within a fixed FOV. A user can read the code by pointing their phone in the approximate direction of the beacon and pressing the button on their device.

noise in the timing measurements due to limitations of the timing circuitry, we observe that the minimum contact time (highest transmission success probability) is achieved at $p_t^{opt} \approx \frac{1}{3}$ for every d, as predicted by the theoretical model derived in Section 3. Even for inter-device distances of more than 5 feet, the codes are successfully transmitted in approximately 100 ms (10 blocks).

In the second experiment, we varied the angle θ between the two devices (see Figure 11(a)) while keeping the distance at 3 feet. Figure 11(c) plots the contact times as a function of p_t for various θ values. Each measurement was repeated 200 times and averaged. As earlier, we observe that the minimum contact time is achieved at $p_t^{opt} \approx \frac{1}{3}$ for every θ, consistent with the theoretical model. The codes are successfully transmitted in approximately 120 ms even for oblique angles $\theta = 45^\circ$, indicating that the proposed techniques and device can be used in uncontrolled user-to-user communication scenarios.

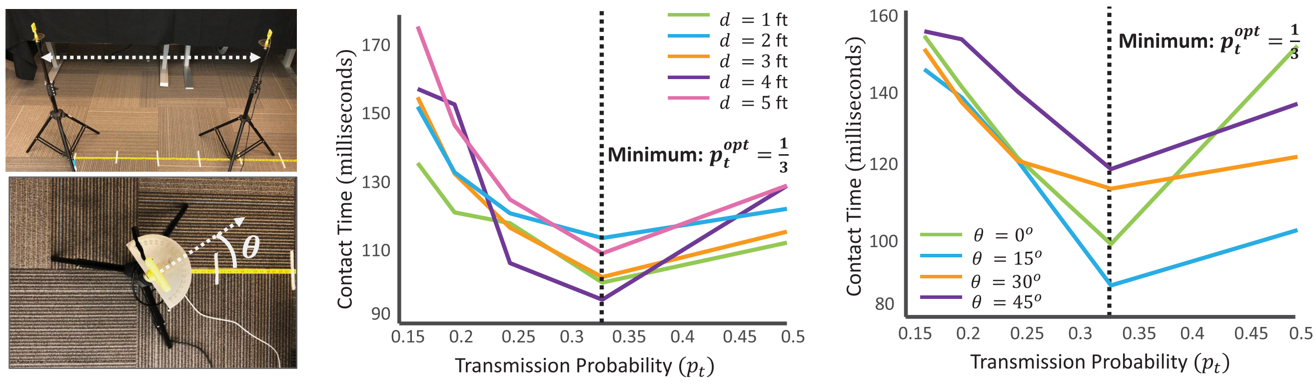
5.2 User Study Based Comparisons

The primary intended applications for LICO-based techniques and devices are user centric. Therefore, we also evaluated their performance in real-world settings via user studies, where light codes were compared to existing methods for the task of exchanging contact information (e.g., a digital business card) or friending someone on a social media app. Existing technologies that are used for these applications include Bluetooth, NFC, and display-camera links via QR codes. For simplicity, we did not develop new apps but used existing functionalities for contact sharing that almost every phone is equipped with. For example, several phones have built-in methods that use QR codes and Bluetooth for sharing contact and establishing connection between devices (e.g., Nearby Share for Android phones and AirDrop for iPhones).

For comparisons, we selected the following four methods, all running on the same Samsung S10e phones to avoid any bias, and the detailed steps of exchanging contact information between two users for each method are shown in Figure 3:

(1) Bluetooth represents a category of methods with long range and no or weak directionality. In our study, we used the Nearby Share feature available on the Samsung phones. Due to lack of selectivity, Alice's phone discovered several phones in the environment, requiring her to select Bob's phone manually before sharing the information.
(2) *Display-camera link*: A user displays a QR code on their screen; the code points to the contact information that the user wants to share. Another user then initiates their camera, which automatically detects and decodes the QR code (see the second row of Figure 3), thus receiving the contact information.
(3) *Near-field communication*: We attached Popl sticker tags [Amazon 2022] to the phones. Our experimental Samsung phones were equipped with an NFC reader. Users exchange information by unlocking their phone and touching their phone to the other user's tag (see the third row of Figure 3).
(4) *Light Codes*: We used prototype LICO devices with the phone case form factor. The received light code is transferred to the phone via the phone's USB port, where it is parsed and the received information is stored.

User Study Design. The reason LICO achieves seamless user interactions is twofold: (1) it uses a dedicated device and thus can skip steps like unlocking the phone and clicking on the app, and (2) the technique involves a natural gesture and enables simultaneous two-way communication. To ensure a fair comparison, we attempted to remove the influence of factor (1) (LICO using a dedicated device) by having all other methods in a "ready" state (phone was unlocked, the friending app was already opened, or, in the case of a QR code, the code was already displayed). Although likely not perfect, these steps were taken to attempt to decouple the effect of the dedicated device so that users could fairly compare the fluency and overall experience of different methods. Finally, the same amount of data was transmitted using each modality.



(a) Experimental Setup to Evaluate LICO Devices

(b) Contact Time vs. Distance (d) between Devices

(c) Contact Time vs. Angle (θ) between Devices

Fig. 11. Empirical evaluation of LICO devices. (a) We evaluate the data communication performance of Light Codes by using two prototype devices as the distance d and angle θ between them is varied. (b) The average contact time (time for successful transmission) vs. transmission probability p_t for various inter-device distances. The angle between the two devices was held constant at 0 degrees. The minimum contact time (highest transmission success probability) is achieved at $p_t^{opt} \approx \frac{1}{3}$ for every d, as predicted by the theoretical model derived in Section 3. Even for inter-device distances of more than 5 feet, the codes are successfully transmitted in approximately 100 ms (10 blocks). (c) The average contact time vs. p_t for various θ values, with the distance fixed at 3 feet. The codes are successfully transmitted in approximately 120 ms even for oblique angles $\theta = 45°$.

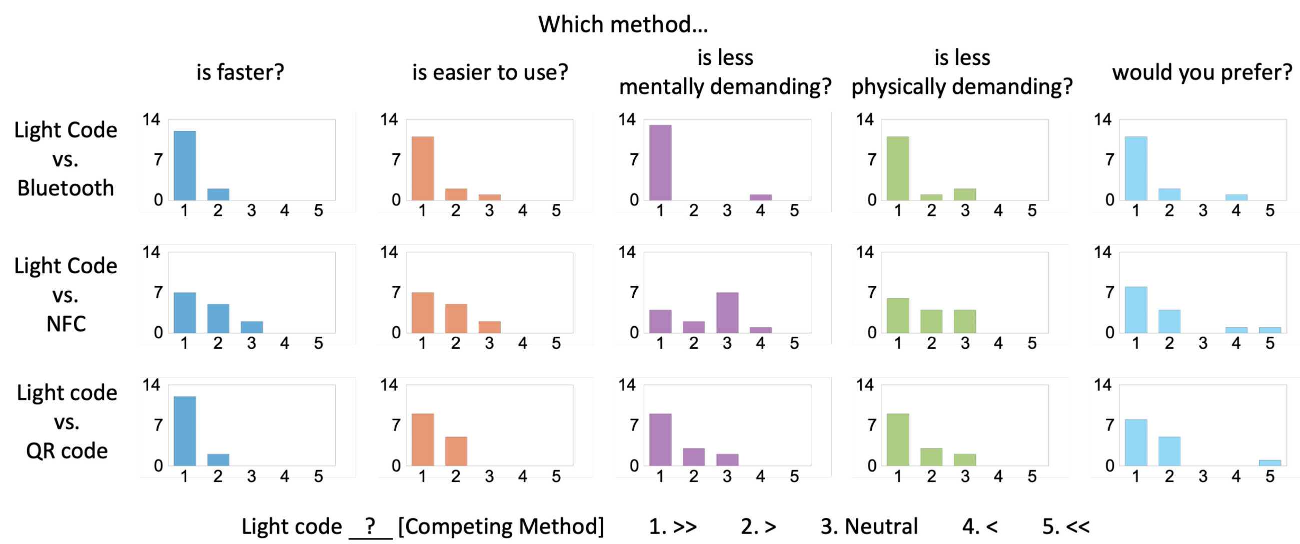


Fig. 12. User study results for 14 participants. When comparing light code to Bluetooth or QR code based display-camera links, a large fraction of users felt that light code is faster and easier to use, is less demanding, and overall preferable. This is because methods typically require several clicks translating into longer interaction time and effort, whereas LICO devices can exchange information via a single press of the button. When comparing light code to NFC, users still demonstrate a preference for light codes, albeit the margin is smaller. This could be explained by the fact that NFC, similar to light codes, does not require many clicks, thus lowering the overall effort. Light code exchange can be two-way simultaneously, whereas other methods are one-way and thus need to be performed twice sequentially if two-way communication is desired.

Before starting the study, the users were asked to familiarize themselves with all four methods by trying them several times and then testing them in a social environment. Pairs of users were then asked to exchange their contact information via all four methods, then answer a questionnaire anonymously. The questionnaire asks the users to compare light codes to Bluetooth, NFC, and display-camera links in terms of speed and ease of use, and their overall preference. Specifically, for each comparison (lightcode vs. Bluetooth, lightcode vs. NFC, lightcode vs. QR code), we asked five questions ((1) Which method is faster? (2) Which method is easier to use? (3) Which method is less mentally demanding? (4) Which method is less physically demanding? (5) Which method would you prefer?) and let users choose a number from 1 to 5 (1 means light code ≫ [competing method], 2 means >, 3 means neutral, 4 means <, and 5 means ≪). There is also a descriptive section for qualitative questions such as what they liked and disliked about light codes.

Potential Sources of Bias. Despite our efforts to ensure impartial comparisons, the possibility of bias persists. For example, first, the user study employed Android Samsung phones, yet some participants were iPhone users. Therefore, despite having been provided with time to familiarize themselves with the study, they might not have felt entirely at ease with the Samsung device. This could potentially have resulted in biases against the other three methods. However, the influence of Light Codes seems less significant due to its minimal operation—a mere single click. Second, the inconsistent behavior of the Bluetooth method—occasionally displaying the partner's device name instantly and other times necessitating a delay—remains unexplained. Third, the placement of the NFC reader on this particular Samsung phone, positioned at the center of the back rather than the top as seen in iPhones, could be perceived as inconvenient. This design quirk can leave users uncertain about where to make adjustments after their initial attempt fails. Fourth, the QR code scanning process ememploying the built-in Samsung camera might not be cutting edge [Nayar et al. 2022; GitHub 2021]. We apprised participants of these potential biases, encouraging them to attempt to segregate these influences during comparisons. For instance, they could carry out the procedures of a method multiple times and then consider the quickest instance as their reference point.

Quantitative Results. Our analysis is based on feedback collected from 14 volunteers. Figure 12 shows the aggregate results for all the questions and comparisons in a tabulated form. When comparing light code to Bluetooth or QR code based display-camera links, a large fraction of users felt that light code is faster and easier to use, is much less demanding, and is considerably preferred overall. When comparing light code to NFC, users still demonstrate a preference for light codes, albeit the margin is smaller. This could be explained by the fact that NFC, similar to light codes, does not require many clicks, thus lowering the overall effort. In summary, light code outperformed existing methods (in some cases by a large margin) across all the questions posed in the user study. This is because existing methods typically require several clicks translating into longer interaction time and effort, whereas LICO devices can exchange information via a single press of the button. Furthermore, light code exchange can be two-way simultaneously, whereas other methods are one-way and thus need to be performed twice sequentially if two-way communication is desired.

Qualitative Feedback. In the following, we provide some qualitative comments from the study. These comments are instructive in understanding the users' preferences, and their likes and dislikes:

—*Light code*: "[R]esponse is very fast"; "just needs a click"; "less possible to send to someone wrongly"; "No need to distinguish different devices"; "It's pointing to the friend to be added, which is more intuitive"; "like handshaking; natural gesture."

—*Bluetooth*: "[T]oo many steps," "too slow," "It is hard to use," "may face the issue that different devices have the same name."

Near-field communication: "NFC is not responsive enough, takes many attempts to succeed." "Touching the other phone is weird." "NFC requires alignment between phones. This is even more challenging for friending multiple people."

QR code: "It takes a long time to show and scan QR code"; "QR code does not look good and is so common that I lose interest in it"; "QR code scanning device (camera) may not work sometimes"; "QR code is fast, but it is still slower than "one click' light code."

Negative Feedback. We also received some negative feedback about light codes, which is instructive in understanding its limitations, including the following sample comments: "QR code is a more mature technology, I trust it more." "I am less concerned about security using QR code. I can clearly see QR code from the screen." "I can share QR code in zoom. QR code can be published in a group chat for multiple people to add." "Light code needs power." "Light code needs additional hardware while other methods are built-in." "Not everyone has the light code hardware."

6 APPLICATIONS AND DEMONSTRATIONS

Light codes can be used in scenarios where a user wants to exchange (or receive) a small amount of data with another user (or a device). This includes a broad set of applications that are similar to that of QR codes but with lower physical and cognitive effort from the user, as well as lower interaction time. We built a simple phone app that controls the LICO device to demonstrate the real-world potential of light codes via several example applications (Figure 13).

(a) Exchanging Digital Business Cards. Figure 13(a) shows two users exchanging contact information by simply pointing their phones toward each other, pressing a button, and immediately receiving the other's information. The time and the location of the interaction is also recorded and saved to the calendar, which becomes a spatial-temporal meeting log.

Light codes can also be used in scenarios where two users wearing AR glasses or smartwatches want to exchange a small code. The small footprint of the transceiver makes it easy to embed in space-constrained wearables. Furthermore, LICO devices require a smooth gesture (Figure 14). In contrast, other methods, such as QR codes, may not be suitable due to limited/no display in these devices.

(b) Sharing Content. Sharing digital content is a frequent form of social interaction between users who share a physical space. A typical user interaction is shown in Figure 13(b). Bob wants to share an image with Alice. The image is uploaded to a server and the app generates a *token*, a code that can be used to retrieve the image. Bob then presses our app's icon, which prompts the LICO device to send the code in a cone. When Alice points her phone toward Bob and presses her LICO device button, she receives the code and can retrieve the image. Another use case for light codes is to initiate the connection and then use a faster but heavier method for data transfer (similar to Bluetooth or NFC for Wi-Fi in iPhone's AirDrop).

(c) Synchronizing Media Experiences. Aligning songs between two users for a shared experience is an interesting application. For example, Apple offers this functionality via its AirPods devices [Apple 2022] but requires several steps, thus inhibiting its applicability and adoption. In contrast, light codes offer instantaneous transfer of information, thus improving the fluidity of such an

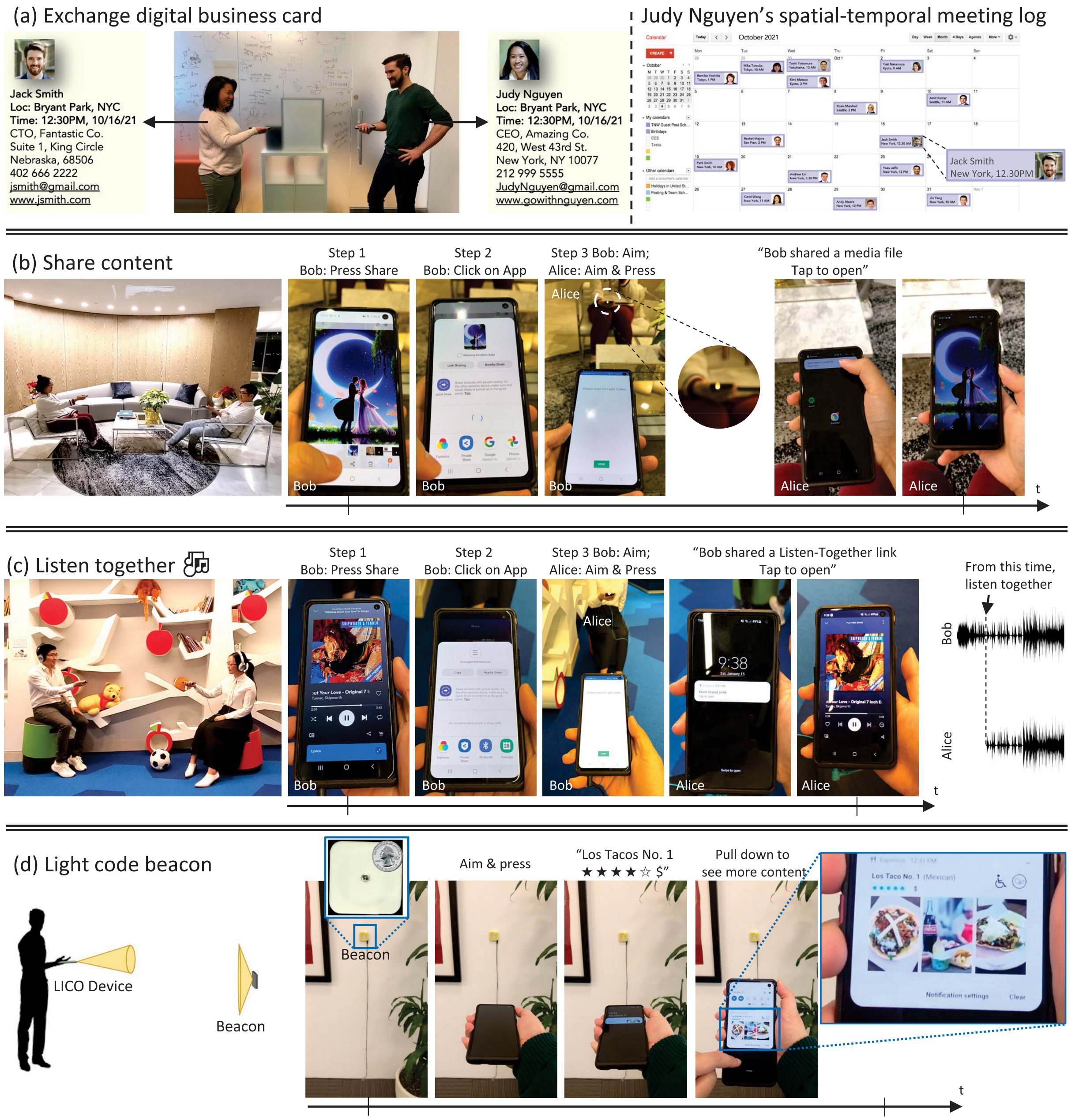


Fig. 13. Applications of light codes. Light codes can be used in scenarios where a user wants to exchange (or receive) a small amount of data (e.g., a QR code). We built a simple phone app that controls the LICO device to demonstrate the real-world potential of light codes via several example applications. (a) Two users exchanging contact information by simply pointing their phones to each other, pressing a button, and immediately receiving the other's information. The time and the location of the interaction is also recorded and saved to the calendar, which becomes a spatial-temporal meeting log. (b) Light codes can be used to initiate and establish connection between two devices for sharing digital content. (c) Aligning songs between two users for a shared experience is an interesting application. Light codes offer instantaneous transfer of information (identification of a song and timestamp), thus improving the fluidity of such an interaction. (d) In the beacon form factor, the LICO device only transmits information (as a code), and can be placed in front of a restaurant, a product, or an exhibit. A user can read the code instantly by pointing their phone in the rough direction of the beacon and pressing their device's button.

interaction, as illustrated in Figure 13(c). The user Bob is listening to a song in Spotify. When he wants to listen this song together with Alice, he simply presses the App icon. When Alice points her phone toward him and presses the button, she receives the name of the song and the current timestamp of the song. The app calls the Spotify API and starts to play the song for Alice at the timestamp (while also compensating for the time lag if any), thereby enabling Alice and Bob to listen to the song together.

(a) AR glass (b) Smartwatch

Fig. 14. Applications of light codes on wearables. Light codes can be used when two users wearing AR glasses or smartwatches want to exchange codes (e.g., making friends). In these wearables, a display-camera link might not be suitable since there may not be an outward-facing display in an AR glass. In a smartwatch, the gesture needed with a display-camera link might be awkward. In contrast, the small footprint of a LICO device and the natural, fluid gesture makes it suitable in these scenarios.

(d) Light Code Beacons. In the beacon form factor, the LICO device only transmits information (as a code), and can be placed in front of a restaurant, a product, or an exhibit. A user can read the code instantly by pointing their phone in the rough direction of the beacon and pressing their device's button, as shown in Figure 13(d). The user can then obtain the product information, restaurant menu and reviews, and so forth from several feet away, without unlocking their phone. In contrast, similar beacons implemented by Bluetooth or Wi-Fi do not have directionality, resulting in users inadvertently receiving unwanted broadcast codes.

7 DISCUSSION AND FUTURE DIRECTIONS

We present Light Codes, a novel communication modality geared toward user-to-user interactions. Light Codes provide a new point in the design space of human-centric communication methods. On the one hand, the proposed techniques are optimized for exchange of short messages. On the other hand, LICO minimizes latency, as well as physical and cognitive effort, thus providing for fast and fluid interactions. Due to these benefits and the low cost, size, and power requirements of LICO devices, these methods could significantly expand the consumer adoption of visual codes based applications such as digital exchange of contact information, user-to-user data transfer via handheld devices, and sharing media experiences.

Multipath Interference. The proposed approach assumes direct line-of-sight communication and may lead to erroneous transmission in the presence of multiple light bounces and multi-path interference in highly cluttered environments. A promising future direction is to design LICO protocols that account for multi-path dispersion [Park and Barry 2004].

Transmitting Longer Messages. LICO is optimized to transmit short messages. The key assumption is that the entire message can be embedded in a single code so that the devices can successfully communicate even if one code is transmitted; the single code is sent repeatedly until successful transmission. An important next step is to extend LICO to handle larger messages, which may either require increasing the length of the slots from 10 ms (likely sub-optimal) or possibly breaking up the message into multiple codes that are transmitted sequentially, which will require designing a multi-code protocol with possible synchronization challenges and performing an analysis of the error rate of the larger message.

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