Connecting Networks of Toys and Smartphones with Visible Light Communication

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Abstract

Light emitting diodes are low-cost and energy-efficient. They are replacing incandescent bulbs as the primary source of illumination in residential and public environments. The brightness of LEDs can be modulated at a high rate, which enables the combination of illumination and wireless communication, imperceptible to humans. Such systems using LEDs as transceivers are called visible light communication systems. LEDs have also been extensively used in consumer electronics such as toys and smartphones, but primarily for reasons other than communication. We show various use cases of devices connected with VLC. Since LEDs can also be used as light receivers in VLC systems, adding microcontrollers to devices (if not already embedded) enables low-cost implementation of a wireless communication interface with VLC. This article reports on experience with several prototypes of practical VLC systems.

Visible Light Communication for Toys

Connecting interactive toys with light emitting diodes (LEDs) as transmitters and receivers is an approach known to be low-cost and energy-efficient. Such visible light communication (VLC) systems can also be connected to smartphones with the help of a phone's flashlight LED and camera. Today, LEDs are replacing incandescent light bulbs as the primary source of illumination, and this development potentially makes VLC widely available and gives toy designers many new options to enrich the play experience. To build a VLC transceiver, an LED's brightness can be modulated at high rates with the help of software-defined protocols.

There are many alternatives to implement short-range wireless communication for toys, such as infrared or unlicensed radio communications. However, today's wide availability of LEDs has paved the way for a new way of communication: free-space optical communication with visible light. Hardware components such as LEDs or photodiodes and energy-efficient embedded microcontroller systems are the base of such VLC systems. Simple software-defined communication protocols running on the microcontrollers are sufficient for building low-bit-rate VLC systems.

The idea of VLC has a long history through time. Communication with light was used in the early 1880s with the invention of the photophone [1]. However, although the first prototype was demonstrated more than 130 years ago, and infrared systems have been used for decades, VLC remained largely unexplored. Today, with LEDs being applied everywhere, VLC is a creative approach for merging traditional illumination with wireless communications and networking. Besides technical, economic, and efficiency benefits, the major appealing characteristic of VLC is that it takes advantage of existing infrastructure and hardware components: VLC systems extend the capabilities of existing illumination (light bulbs, consumer electronics) to become sources of light as well as communication interfaces. In addition, VLC emissions do not interfere with radio spectrum, hence offering a path to escape the limitations imposed by radio spectrum shortage and overcrowding.

In this article, opportunities for applying VLC to provide communication between toys are elaborated. The use of LEDs as transceivers (LED-to-LED communication for networks of toys [2]), with focus on the simplicity of this wireless interface, is evaluated. Toys are often equipped with LEDs and microcontrollers for their experience design. As LEDs can be used as light emitters and also as light receivers [3, 4], all components required for a complete wireless communication interface are already available. Typical 8-bit microcontrollers used in consumer electronics allow LEDs to operate through a simple yet adequate communication protocol. To extend the reach of such toy networks (e.g., to provide connectivity to the Internet or for interactive experience designs), we discuss how to use visible light to connect the LED-to-LED network of toys with a smartphone's onboard flashlight and camera. We use the term smartphone to refer to a wide range of products with various operating systems. We explore such heterogeneous VLC systems (LED networks, flashlights,

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and cameras) to enrich the storytelling and play patterns of connected toys. As we aim to examine the landscape, we investigate proof-of-concepts prototypes without the impediments of existing standards.

USE CASES

There is a growing interest in toys that are wirelessly connected with each other, and to computers or smartphones. So far, VLC has been mainly considered as a replacement of radio communication to provide Internet access, but other creative use case scenarios, especially in the domain of toys, have not been seriously considered. Many toy applications require only a moderate bit rate (1000 b/s) at short communication ranges (3 m), which can be reached with LED-to-LED networking, or by means of VLC in general. Some example use case scenarios are introduced in the following sections. Figure 1 illustrates a couple of the scenarios.

Figure 1. VLC use cases (© Disney): Users can interact with toys using a smartphone's flashlight as the VLC source and the camera as the receiver. Toys transmit and receive packets with LEDs.

HOME NETWORKS

LED-based lights are preferred over incandescent light bulbs because of their longer lifetime and higher energy efficiency. With this trend, more and more devices find their way into the home automation and networking market that can facilitate the rollout of VLC-based solutions. Light sources communicate directly with each other or with devices in their field of view. Identifying a device's location is realized by broadcasting location markers with different lights, as well as light-intensity-based ranging and trilateration. Light bulbs close to each other can form a distribution network that forwards data to a gateway. To avoid the drawback of communication only being available when lights are on and not during the day when lights are usually switched off, short and nearly invisible light pulses with pulse-position modulation can be applied. This concept is already proposed in IEEE 802.15.7 [5, 6].

LED-TO-LED COMMUNICATION NETWORKS FOR TOYS

An LED-to-LED VLC system must provide the necessary networking functionality such as coordinated medium access, network management, and security [3, 7]. LED-to-LED VLC offers appealing support to provide toy-to-toy communication over short ranges. Note that LEDs are widely available in toys. Toy cars equipped with LEDs could exchange data to trigger events when in close proximity. A toy car's front and back lights can be used to exchange data when pointed toward each other. Depending on the car's positions, the toys might react in different ways. For example, they can mimic a discussion if they face each other, or trigger engine, brake, or honking sounds. Collectible toys can identify the status of a collection and indicate that the set is complete by lighting up when the set is put together.

INTERACTIVE FASHION AND FABRICS

Embedding LEDs into clothes has been done before and often demonstrated. Illuminated clothing is well established for entertainment and in safety applications. LED-based transceivers can be used to enrich the experience design toward interactivity. For example, a shirt with VLC-enabled LEDs is able to not only show patterns and transmit data, but also receive data packets from many directions. Each individual LED can serve as a transceiver. For example, as soon as one of the LEDs receives a packet, a visible light pattern can begin to flow over the shirt, starting from the LED that received the packet first. While dancing together or shaking hands, light could be passed from one person's shirt to another person's shirt. It is easy to imagine a wide variety of novel experience designs with interactive transceiver LEDs in fashion.

TOYS WITHOUT RADIO EMISSION

Free space optics using visible light or infrared has always been regarded as non-intrusive and safe. This view is also reflected by the fact that use of VLC or infrared communication is often permitted in places where radio communication is forbidden (e.g., inside hospitals or aircraft during takeoff and landing). Contrary to infrared, the human eye reacts to visible light and closes its iris upon strong incoming light to protect the eye against unwanted exposure. This could be an important benefit of VLC over infrared.

TOY COMMUNICATION WITH SMARTPHONES

LEDs can also receive data from LED flashlights of a phone and transmit back to a phone's camera. Figure 1 illustrates example use cases. The achievable data rate in both directions is on the order of a few bits per second, which is enough for many toy applications. Using a smartphone's flashlight to trigger events in toys does not require a high channel capacity, but could already add a new play experience. Transmitting short status indicators back to the camera might take a few seconds, which is acceptable. The main advantage of VLC in such scenarios is the ease of use: without any authentication, and by only pointing a flashlight toward a toy, the toy can be reconfigured so that its play pattern can evolve over time. LED-to-smartphone communication can be used to transmit location markers for augmented reality or let the phone play some sounds while playing. Since users can see where the light is directed, and therefore also where the communication is directed, eavesdropping can be avoided by letting the user control the direction of the light beam.

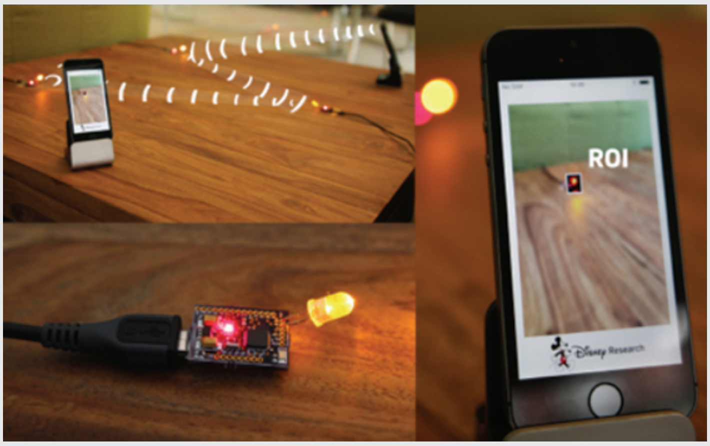

Figure 2. Photographs showing different parts of the integrated system: top left: a view of the overall experimental setup from the top; bottom left: a microcontroller with an LED able to act as a transceiver; right: a smartphone running an application developed for experimental tests.

SYSTEM DESIGN

System aspects and software components for the realization of three VLC communication modes determine the overall design of VLC systems. For the application area discussed here, we identify three communication modes, and a heterogeneous approach that supports all modes is required. The first communication mode is LED-to-LED communication, in which two or more devices equipped with microcontrollers and LEDs exchange data using visible light and a software-defined protocol. LEDs are used to transmit and receive data [7]. The protocol enables acknowledged transmissions in all directions. The second mode is smartphone-to-LED communication, which uses a phone's flashlight LED to communicate with the devices. Devices receive with the LEDs, but will not transmit back any data or acknowledgments. The third mode is the LED-to-camera communication mode, in which a phone's camera receives packets from a device's LED. Modes two and three support two-way communication with acknowledgments only when they are combined with each other. For the toy and consumer electronics scenarios described earlier, it is important that the system be based on a low-cost approach, and ideally that the three modes can coexist with each other.

The IEEE 802.15.7 standard defines its own physical (PHY) and medium access control (MAC) layers for VLC. The standard includes three different PHY layers with different data rates that do not interoperate. To build a VLC system that is compliant with the IEEE standard, a certain level of complexity is already required. We developed systems that differ from the VLC standard to keep our approach simple, software-defined, and based on hardware components readily available (microcontroller and LED transceivers in the toys, flashlight LEDs and cameras on the phones) to explore lowest-cost solutions. Figure 2 depicts a heterogeneous low-complex VLC system with its three communication modes.

LED-TO-LED COMMUNICATION

An LED in a toy is used as a data transmitter and receiver in slotted half-duplex mode so that the same LED does not transmit and receive at the same time. LEDs of different toys have to synchronize their light patterns. The necessary protocols for synchronization and communication can all be implemented in software. LED-to-LED communication is therefore low-cost, and the implementation is of low complexity. It has been shown to be robust enough to support small networks of devices all communicating with each other [7]. The achievable system throughput is on the order of several hundreds of bits per second at distances on the order of a few meters, with an 8-bit 16 MHz microcontroller [7]. Sensitivity (for larger distance) and system clock (for increased throughput) can be improved with more sophisticated microcontrollers (more precise clocks and analog-to-digital converters).

SMARTPHONE-TO-LED COMMUNICATION WITH THE FLASHLIGHT LED

Modern smartphones are equipped with cameras and flashlights. The flashlight can operate to blink at given frequencies. We experimentally found out that the flashlight frequency can be up to 50 Hz with today's smartphones. However, the frequency is not constant over time because the flashlight is controlled by the operating system, and depending on the process scheduling, the flashlight's light pattern deviates significantly from the intended pattern.

In the implementation, every information bit is mapped to light pulses with different durations. To transmit a bit 1, a pulse with the duration of 250 ms is transmitted. A bit 0 is encoded into a pulse duration of 310 ms. These values are two possible combinations of values that match the timing restriction of existing smartphones.

The receiving part is implemented in software running on a microcontroller attached to an LED. The program collects readings from an analog-to-digital converter (ADC) that measures the remaining voltage over the LED and decodes the voltage measurements into meaningful bits by detecting the duration of received pulses. In the prototype, the packet size is 4 bits.

LED-TO-SMARTPHONE COMMUNICATION WITH THE CAMERA

A link from an LED to a smartphone can be built using the phone's camera. The general idea behind detecting bits through a camera is to associate an LED's blinking frequencies to a 0 or 1 bit, depending on the frequency. The phone's software identifies the frequencies; therefore, the camera must capture several consecutive frames. A picture of an LED taken with a camera contains the LED and the surrounding environment. However, only a portion of the picture conveys useful information. We call this portion of a frame the region of interest (ROI). To achieve a high signal-to-noise ratio (SNR), it is important that the ROI includes the LED and discards the surrounding portion of the frame. Since the ROI fills only a portion of every frame, it is possible to decode bits from multiple LEDs placed in front of one camera as long as there is only one LED per ROI. Although in this article we focus on communication involving only a single LED, the extension to multiple LEDs is straightforward.

Most cameras integrated into smartphones can sample at a maximum rate of 30 fps. The Nyquist criterion dictates that the maximum detectable intensity variation frequency with a camera is 15 Hz with 30 fps. We analyze two possible methods of operation to detect bits transmitted by an LED: the *Blink* method and the *Aliasing* method. In the Blink method, the LED flickers at rates visible to the human eye (around 10 Hz in our implementation), whereas in the Aliasing method, the LED is modulated at high rates such that the LED is perceived as constantly turned on. Both methods are implemented to receive small packets with the size of 4 b/packet.

The Aliasing method takes advantage of the aliasing artifacts that arise when the camera's sampling rate is slower than half the blinking rate of the LED. Examples of aliasing distortion appear when an object moves fast in front of a camera (e.g., the wheel of a car or the rotor blade of a helicopter) creating unwanted visible effects. The implementation of the LED-to-camera system exploits the aliasing artifacts. The camera takes several consecutive pictures over a capture time window (1–2 s) and stores the average light present inside every ROI in a vector. The vector of measurements contains values that are different from each other for at least two reasons: first, there is no synchronization between the LED and the camera; second, the blinking frequency of the LED is higher than the capture frequency of the camera. Since the LED blinks with constant frequency for an interval at least as long as the capture window, the frequency representation of the vector of measurements (obtained by Fourier transform) shows a peak at a frequency that depends on the blinking frequency of the LED. In the prototype implementation, two different blinking frequencies are used, one to encode bit 1 and another to encode bit 0. This is a slow process, but improvements are possible. For example, synchronizing transmitter and receiver, or using additional blinking frequencies should increase the system throughput.

An alternative way to decode bits exploits the fact that most cameras in smartphones cannot take an instantaneous picture. Instead, they use a fixed exposure time to capture an image. If the transmitting LED blinks with high frequency (goes on and off one or several times during the capture time) in front of the camera, the LED creates a predictable distortion in every image, called the *electronic rolling shutter effect* [8]. As a consequence of the rolling shutter effect, which depends on the blinking frequency of the LED, the image presents several vertical stripes. The rolling shutter effect is efficient and robust; however, it allows the camera to capture only the transmission of a single light source and requires a large ROI. In contrast, the aliasing method described above uses small ROIs to enable the reception of multiple LEDs (on the same transmitting device or separate sources) transmitting at the same time. In this article we analyze the communication using a single and small ROI. A technique for higher data transmission rates has already been investigated in [9].

Communication mode	**LED-to-LED**
Processor	Atmel Microcontroller
Clock	16 MHz
LED blinking frequency	1 MHz
LED type (transmit and receive)	Red — 5 mm
Packet size	Up to 255 bytes
ADC resolution	10 bits
Encoding	Pulse position [7]
Realistic data rate	8 kb/s
Communication mode	**Smartphone-to-LED**
Processor	ARMv7
Clock	1300 MHz
LED type (transmit)	White bright flashlight
LED type (receive)	Red — 5 mm
LED blinking frequency	50 Hz (software limited)
Packet size	4 bits
Encoding	Pulse duration
Realistic data rate	2 b/s
Communication mode	**LED-to-smartphone**
Camera type	8 megapixels
Sampling rate of the camera	30 fps
LED type (transmit)	Red — 5 mm
Packet size	4 bits
Encoding (blinking)	Pulse duration
Encoding (aliasing)	Frequency shifting
Realistic data rate (blinking)	1 b/s
Realistic data rate (aliasing)	0.5 b/s

Table 1. System parameters.

Security, Privacy, Reliability

Traditional security features like network authentication and address handling are possible but not always needed in applications of connected toys. Furthermore, there is also minor demand for data security, because less sensitive data is transmitted over a network of toys compared to typical Internet traffic. With more sophisticated toys, however, the transmitted data might include the history of the toy's location coordinates or photos taken with the toy, and in such cases the system would require appropriate privacy protection. Toy networks might also carry control data from or to game consoles, which should operate reliably with low latency.

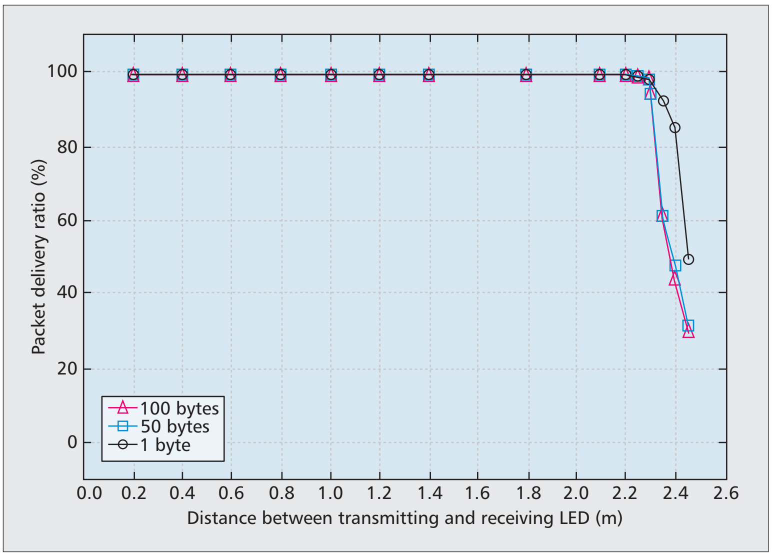

Figure 3. LED-to-LED communication mode: packet delivery ratio over distance for two communicating LEDs; throughput: up to 8 kb/s. Results are shown for distances of up to 2.5 m and for packet sizes of 1, 50, and 100 bytes. The communication protocol described in [7] is used for the data exchange.

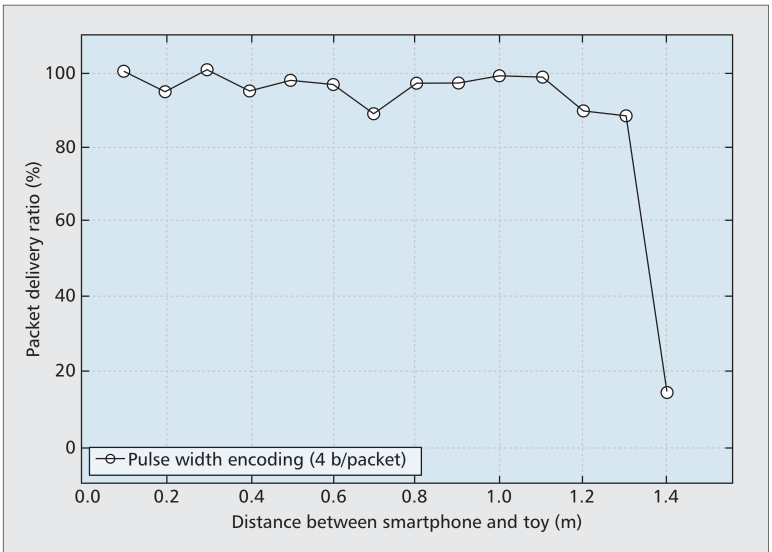

Figure 4. Smartphone-to-LED communication mode: packet delivery ratio over distance for a flashlight communicating to a toy; throughput: up to 2 b/s. Results are shown for distances of up to 1.5 m. The flashlight speed limits the throughput.

Practical Experience

The building blocks described in the previous sections can be combined to form a system that interconnects different VLC devices with different modes. We now provide a brief performance analysis, and describe experiences with our VLC testbed.

Figure 2 shows a complete VLC system that involves smartphones and microcontrollers connected to LEDs (Table 1 shows system parameters). Figure 2 (bottom left) shows one of the microcontrollers with an LED that is used for bidirectional LED-to-LED communication. Figure 2 (top left) depicts the complete experimental setup: several smartphones and microcontrollers are facing each other to exchange VLC data. Figure 2 (right) offers a view of the smartphone application that was developed for practical experience. The application augments the camera view with the ROI and buttons to trigger the transmission of VLC data packets using the flashlight.

The experimental setup depicted in Fig. 2 is used to demonstrate the practical use of VLC. We report on a number of experiences that involve all the building blocks previously described. The goal is to investigate the challenges of building proof-of-concept VLC prototypes.

The experiments were organized in three parts following the same order as the description earlier. In every experiment, we use the average packet delivery ratio (PDR) as the performance indicator. The PDR is an indicator of the quality of the system; it is equal to the percentage of transmitted packets received. When PDR is 100 percent, the receiver has received all packets. In every measurement the transmitter transmits 100 packets, and each measurement is repeated several times. All measurements were conducted in an indoor environment in the presence of both incandescent light and indirect sunlight interference.

Figure 3 shows the PDR of the LED-to-LED communication mode for varying distances between the transmitter and the receiver. It illustrates that two devices can communicate over a distance of 2 m very efficiently (PDR is 100 percent). Every data packet is acknowledged (ACK). If no ACK is received within a protocol-dependent timeout interval, the same data packet is transmitted again. This step is repeated up to a maximum of three times before the packet is discarded and counted as lost. The figure shows the performance for three different packet sizes. In the experiment, the transmitter and receiver are in line of sight and face each other. Depending on the type and field of view of the used LEDs, if the relative angle between transmitter and receiver increases, the PDR decreases because the LED's received signal strength decreases. This effect can be mitigated using lenses or LEDs with different cases and shapes, and a broader field of view.

Figure 4 shows the PDR of the smartphone-to-LED communication mode. The result is plotted for a packet size of 4 bits for different distances. Phone and LED positions are fixed during the experiment, and they are in line of sight of each other. When the microcontroller decodes a packet from the flashlight, it confirms the reception with an ACK (LED-to-smartphone camera). One packet is considered received if the smartphone receives the ACK. The ACK is transmitted using the Blinking method for the LED-to-camera mode (not Aliasing).

Figure 5 shows the performance of the LED-to-camera mode. We investigate the performance of one LED transmitting to one smartphone. The LED repeatedly transmits a packet of a length of 4 bits. The figure shows results for both the Blink and Aliasing methods. Both methods show similar performance and outperform the smartphone-to-LED mode (using the flashlight) in terms of achievable distance. The camera of the smartphone used for these experiments is very sensitive to the red light of the transmitting LED. However, since we consider an ROI with constant size, the sensitivity of the camera decreases with the distance and angle from the LED. The major challenge of this mode is the efficiency of the signal processing algorithm. For the experiments described in this article, we implemented a receiving algorithm using a publicly available computer vision library. Another challenge is false bit detection due to camera motion when capturing consecutive frames. To limit this effect, we use the built-in accelerometer and gyroscope to stop the bit recognition algorithm as soon as the phone moves.

Intensive use of the camera and the flashlight results in unwanted high power drain of the phone's battery. We also note an increase in the phone's temperature due to the heavy computation. Keeping the application running for 30 minutes drains a fully charged battery with our algorithms, which are not optimized for low energy consumption. Thus, this type of communication requires optimization and is useful when communication is needed only sporadically over short time periods.

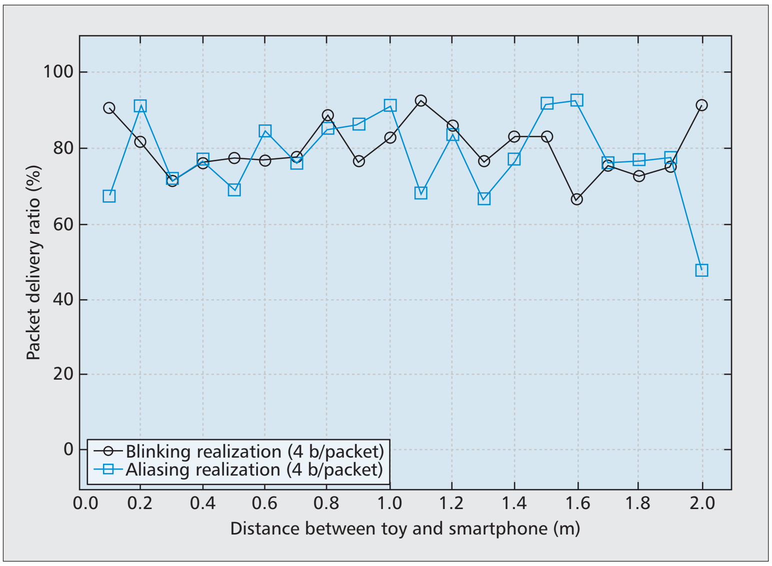

Figure 5. LED-to-smartphone communication mode: PDR over distance for an LED communicating to a camera; throughput: up to 1 b/s. Results are shown for distances of up to 1.5 m. The measurements result in the same packet loss ratio for both methods. However, the throughput is lower for the aliasing method because of the lower data rate (0.5 b/s and 1 b/s, respectively).

Concluding Remarks

Visible light communication is a creative approach to combine illumination, wireless communication, and novel play patterns for connected toys. Since it can be implemented at low cost with components that are available in many toys, VLC facilitates toy networking and, in addition, communication with phones via cameras and flashlights. This is possible without the need for extra hardware. In the future, free space optics (infrared or VLC) can play an interesting role complementing traditional radio communication in consumer electronics. The arrival of IEEE 802.15.7 [6], recent updates of the infrared communication standard IrDA [10], and the evolving lightweight IPv6 networking protocols originally developed at the Internet Engineering Task Force (IETF) for sensor networks and the Internet of Things [5] may provide the means to build such novel connected toys. This might well be referred to as the future Internet of Toys. Many challenging system aspects remain to be addressed. One future research challenge lies in combining the different protocols and standards to create the necessary multimode communication. A system with this combination should remain low-cost (based on, e.g., software-defined protocols as in [7] or duty cycled as in [5]) and should not add unnecessary complexity or resource requirements.

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BIOGRAPHIES

GIORGIO CORBELLINI (giorgio@disneyresearch.com) joined Disney Research, Zürich, Switzerland, as post-doctoral researcher in September 2012. His research activity includes visible light communication, acoustic data communication, RFID, and MAC for wireless networks. He worked with the Commisariat a l'Energie Atomique (CEA), Grenoble, France (2007–2012). He received a Ph.D. in computer science from the University of Grenoble in 2012. He received his M.Sc. and B.Ch. in telecommunication engineering from the University of Rome La Sapienza in 2007 and 2005, respectively.

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STEFAN MANGOLD is senior research scientist at Disney Research, Zurich, and a lecturer at ETH Zürich, Department of Computer Science. Before joining Disney Research, he worked at Swisscom in research, product, and business development, and with Philips Research USA. His research covers many aspects of wireless communication networks and mobile computing, such as wireless protocols and system aspects for connected toys, entertainment parks, and games, with some focus on IEEE 802.11 wireless LAN, VLC, cognitive radio, and cellular networks. Other research interests include mobile computing and mobile application building for studio production and broadcasting.

THOMAS R. GROSS is a professor of computer science at ETH Zurich. He joined Carnegie Mellon University, Pittsburgh, Pennsylvania, in 1984 after receiving a Ph.D. in electrical engineering from Stanford University. In 2000, he became a full professor at ETH Zurich. He is interested in tools, techniques, and abstractions for software construction, and has worked on many aspects of the design, implementation, and programming of computer systems.