Connecting Networks of Toys and Smartphones with Visible Light Communication

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\textbf{ABSTRACT}

Light Emitting Diodes (LEDs) are low-cost and energy efficient. They are replacing incandescent bulbs as 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 (VLC) systems. LEDs have been also extensively used in consumer electronics such as in 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 they are not already embedded) enables the low-cost implementation of a wireless communication interface with VLC. The paper reports about experience with several prototypes of practical VLC systems.

1. \textbf{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. LEDs are today replacing incandescent light bulbs as 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 exist many alternatives to implement short-range wireless communication for toys, such as infrared or uncensored radio communication. 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]. But 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 the traditional illumination with wireless communication and networking. Besides technical, economical, 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 the wide range of products with various operating systems. We explore such heterogeneous VLC systems (LED networks, flashlights, and cameras) to enrich the story telling and play patterns of connected toys. As we aim at examining the landscape, we investigate proof-of-concepts prototypes without the impediments of existing standards.

2. USE CASES
There is a growing interest in toys that are wirelessly connected with each other, to computers, or smartphones. VLC has been so far 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 (a thousand bits per second) at short communication ranges (three meters), 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 some of the scenarios.

2-A. 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 the 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 that communication will be only available when lights are on, and not during daylight when lights are usually switched off, short and nearly invisible light pulses with a pulse-position modulation can be applied. This concept is already proposed in IEEE 802.15.7 [5][6].

2-B. LED-TO-LED COMMUNICATION NETWORKS FOR TOYS
A 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 an 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 backlights can be used to exchange data when pointed towards each other. Depending on the car’s positions, the toys might react in a different way. 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.

2-C. INTERACTIVE FASHION AND FABRICS
Embedding LEDs into clothes has been done before and has been often demonstrated. Illuminated fashion is well established for entertainment and in safety applications. LED-based transceivers can be used to enrich the experience design towards interactivity: For example, a shirt with VLC-enabled LEDs is able to not only show patterns and to transmit data, but also to 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 this 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.

2-D. TOYS WITHOUT RADIO EMISSION

Not everyone is willing to accept exposure to a radio emitter embedded in a toy, because of the perception that radio emission might be harmful. There is no consensus about how harmful a long-term exposure to a low power electromagnetic field could be but free space optics using visible light or infrared however 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 is forbidden, for example, inside hospitals or aircrafts 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.

2-E. 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 for 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 only by pointing a flashlight towards a toy, the toy can be reconfigured so that its play pattern can evolve over time. The LED-to-Smartphone communication can be used to transmit location markers for augmented reality, or let the phone play some sounds during playing. Since users can see where the light is directed, and therefore also the communication is directed to, eavesdropping can be avoided by letting the user control the direction of the light beam.

3. 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 the 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 the Smartphone-to-LED communication, which uses a phone’s flashlight LED to communicate to the devices. Devices receive with the LEDs, but will not transmit back any data or acknowledgements. 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 acknowledgements only when they are combined with each other. For the toy and consumer electronics scenarios described earlier, it is important that the system is based on a low-cost approach and that, ideally, 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 to 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 at the phones) to explore lowest-cost solutions. Figure 2 depicts a heterogeneous low-complex VLC system with its three communication modes.

3-A. LED-TO-LED COMMUNICATION

An LED in a toy is used as data transmitter and receiver in a 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 in 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).

3-B. 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 milliseconds is transmitted. A bit 0 is encoded into the pulse duration of 310 milliseconds. 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 four bits.

3-C. 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 bit 0 or bit 1, 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 thirty Frames Per Second (FPS). The Nyquist criterion dictates 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 ten Hertz 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 four bits per 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 (such as 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 (one to two seconds), 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: The first reason is that there is no synchronization between the LED and the camera; the second reason is that 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 with Fourier transform) shows a peak at a frequency that depends on the blinking fre-
quency 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 fre-
quency (it 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 separated 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].

3-D. SECURITY, PRIVACY, RELIABILITY

Traditional security features like network authentication or address handling are possible but not always needed in
applications of connected toys. Further, 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 location coordinates, or photos taken with the toy, and in such
cases the system would require the appropriate privacy protection. Toy networks might also carry control data
from or to game consoles, which should operate reliably with low latency.

4. PRACTICAL EXPERIENCE

The building blocks described in the previous sections can be combined to form a system that interconnects differ-
ent 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 (see
Table 1 for 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 the 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 Figure 2 is used to demonstrate the practical use of VLC. We report on a nu-
mer of experiences that involve all the building blocks previously described. The goal is to investigate the challeng-
es of building proof-of-concept VLC prototypes.

The experiments were organized in three parts following the same order as the description in Section 2. In every
experiment, we use the average Packet Delivery Ratio (PDR) as performance indicator. PDR is an indicator of the
quality of the system; it is equal to the percentage of transmitted packets that are received. When PDR is
100 percent, the receiver has received all packets. In every measurement the transmitter transmits hundred pack-
ets, and each measurement is repeated several times. All measurements were conducted in an indoor environment
in presence of both incandescent light and indirect sunlight interference.

Figure 3 shows the packet delivery ratio 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 two meters very
efficiently (PDR is equal to 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 max-
imum 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, 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 four 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 four bits. The figure shows results for both methods: Blink method and Aliasing method. 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 a constant 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 the false bit detection due to camera motion during 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.

An intensive use of the camera and the flashlight results in an unwanted high power drain of the phone’s battery.

We also note an increase of the phone’s temperature, because of the heavy computation. Keeping the application running for thirty minutes drains a fully charged battery. We note that running the algorithms that 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.

5. **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, the 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 to complement traditional radio communication in consumer electronics: The arrival of the IEEE 802.15.7 standard [6], recent updates of the infrared communication standard IrDA [10], and the evolving lightweight IPv6 networking protocols originally developed at 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 are to be addressed: One future research challenge lies in combining the different protocols and standards to create the necessary multi-mode communication. A system with this combination should remain low-cost (based on, for example, software-defined protocols as in [7], or duty cycled as in [5]) and should not add unnecessary complexity or resources requirements.
REFERENCES


Figure 1: VLC use cases (© Disney): Users can interact with toys using a smartphone’s flashlight as VLC source and the camera as receiver. Toys transmit and receive packets with LEDs.
Figure 2: Photographs showing different parts of the integrated system: (top left) A view of the overall experimental setup from the top, (bottom left) Microcontroller with LED able to act as transceiver, and (right) smartphone running an application developed for experimental tests.
Figure 3: LED-to-LED communication mode: Packet delivery ratio over distance for two communicating LEDs. Throughput: up to 8 kbit/s). Results are shown for distances of up to 2.5 meters and for packet sizes of 1, 50, and 100 byte. 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 bit/s). Results are shown for distances of up to 1.5 meters. The flashlight speed limits the throughput.
Figure 5: LED-to-Smartphone communication mode: Packet delivery ratio over distance for an LED communicating to a camera. Throughput: up to 1 bit/s). Results are shown for distances of up to 1.5 meters. 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 bit/s and 1 bit/s, resp.).
Table 1: System parameters.

<table>
<thead>
<tr>
<th>Communication Mode</th>
<th>LED-to-LED</th>
<th>Smartphone-to-LED</th>
<th>LED-to-Smartphone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processor</td>
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<td>ARMv7</td>
<td>8 Megapixel</td>
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<tr>
<td>Clock</td>
<td>16 MHz</td>
<td>1300 MHz</td>
<td>30 frame/s</td>
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<tr>
<td>LED blinking frequency</td>
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<td>white bright flash light</td>
<td>30 frame/s</td>
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<td>red - 5 mm</td>
<td>30 frame/s</td>
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<tr>
<td>Packet size</td>
<td>up to 255 byte</td>
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<td>4 bit</td>
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<tr>
<td>Encoding</td>
<td>pulse position, see [7]</td>
<td>pulse duration</td>
<td>pulse duration</td>
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<td>Realistic data rate</td>
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<td>2 bit/s</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Communication Mode</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Camera type</td>
<td>8 Megapixel</td>
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<tr>
<td>Sampling rate of the camera</td>
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<td></td>
<td>0.5 bit/s</td>
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<td>LED type (transmit)</td>
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<td></td>
</tr>
<tr>
<td>Packet size</td>
<td>4 bit</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Encoding (blinking)</td>
<td>pulse duration</td>
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</tr>
<tr>
<td>Encoding (aliasing)</td>
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<tr>
<td>Realistic data rate (blinking)</td>
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</tr>
<tr>
<td>Realistic data rate (aliasing)</td>
<td>0.5 bit/s</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**Biographies**

**Giorgio Corbellini** joined Disney Research, Zürich as post-doc in September 2012. His research activity includes Visible Light Communication, Acoustic Data communication, RFID, and MAC for wireless networks. He worked with the Commissariat a l’Energie Atomique (CEA), Grenoble, France (2007-2012). He received a Ph.D. in Computer Science from the University of Grenoble (INPG) in 2012. He received his MS.c and BCh. in Telecommunication Engineering from the University of Rome La Sapienza in 2007 and 2005, respectively.

**Kaan Akşit** received the B.S. degree in electrical engineering from ITU, Turkey in 2007. He received the M.Sc. degree in electrical power engineering from RWTH, Germany in 2010. He is currently a Ph.D. candidate in electrical engineering at Koç University, Turkey. He works on autostereoscopic displays at Dr. Urey's group. In between February-May 2013, he joined Disney Research at Zürich, Switzerland as an intern under Dr. Corbellini’s guidance in Dr. Mangold's group.

**Stefan Schmid** is a PhD student at Disney Research and ETH Zurich, under the supervision of Dr. Stefan Mangold and Prof. Thomas Gross. His research includes wireless communication protocols, wireless hardware and Visible Light Communication. Currently, he is working on low-cost visible light communication devices. Stefan started his PhD in November 2011. He received a Bachelor’s and Master’s degree in computer science, both from ETH Zurich.

**Stefan Mangold** is Senior Research Scientist at Disney Research, Zurich and 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, games, with some focus on IEEE 802.11 Wireless LAN, visible light communication, 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, Switzerland. He joined Carnegie Mellon University in Pittsburgh, PA, 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.