Visible-light communication system enabling 73 Mb/s data streaming

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***Abstract* - The hOME Gigabit Access (OMEGA) home-area-network project aims at bridging the gap between home and access network and providing Gb/s connectivity to users. The project considers a combination of various technologies such as radio-frequency and wireless optical links operating at infrared and visible wavelengths. When combined with power-line communications (PLC), this enables a home backbone that meets the project's "without new wires" vision.**

A technology-independent MAC layer will control this network and provide services as well as connectivity to any number of devices the user wishes to connect to in any room of a house/apartment.

In order to make this vision come true, substantial progress had to be achieved in the fields of optical wireless physical layer development and data-link-layer protocol design.

This paper reports an experimental demonstration of an indoor visible-light wireless link including a MAC layer protocol adapted to optical wireless communications systems. The system operates at 84 Mb/s broadcast and was successfully used to transmit three high-definition video streams.

***Index Terms*—Home access network, optical wireless, Visible Light Communication, VLC**

I. Introduction

THE DEPLOYMENT of fiber-to-the-home and ultra-fast broadband will bring data rates of 100's of Mb/s to the home. In order to fully utilize these Home Access Networks (HANs), Gb/s-class connectivity will be required. A European-Community project 'hOME Gigabit Access network' (OMEGA) aims to achieve this by using a variety of wireless techniques together with power-line communications [1] and [2]. As the number and variety of wireless devices grows, such a heterogeneous approach is becoming increasingly important.

Part of the OMEGA project is to investigate optical-wireless (OW) communications. One of the technologies addressed is visible-light communications (VLC) [3], which will be used in a broadcast mode, and the other is a 1 Gb/s line-of-sight infra-red communications (IRC) system. The IRC system is the subject of another paper at this conference, and here we are focusing on the VLC system.

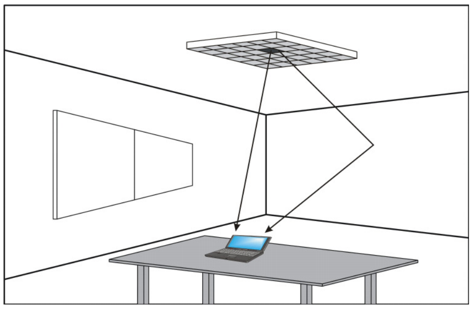

Figure 1: visible-light communications example

Figure 1 shows an example of the VLC transmission system currently being developed. The first prototype achieves data broadcasting at 84 Mb/s transmission rates (73 Mb/s on IP layer) with three High Definition (HD) video signals transmitted (Part II).

The successful demonstration of this VLC link represents a substantial improvement in the state of the art in this area. This VLC demonstrator will, together with the aforementioned IRC system, provide very high connection speed combined with excellent coverage conditions.

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II. VLC SYSTEM DESCRIPTION

A. Overview

The VLC transmission system is depicted in Figure 2. It comprises nine modules and six interfaces. The following part describes the VLC system.

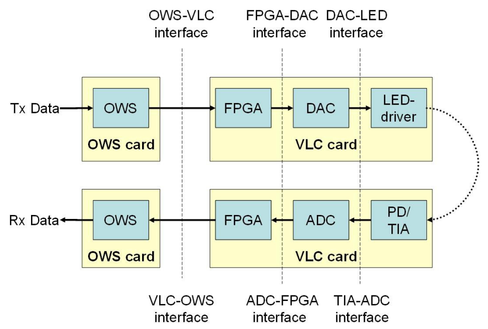

Figure 2: VLC block diagram including interfaces.

While Siemens addresses the development of the analog transmitter (LED driver) and receiver (PD – Photo Diode/TIA – Trans Impedance amplifier), Fraunhofer HHI is responsible for the digital modules, i.e. the transmitter with FPGA (Field Programmable Gate Array) board and DAC (Digital to Analog Converter); and the receiver FPGA and ADC (Analog to Digital Converter). Apside is in charge of the implementation of the Optical Wireless MAC (OWMAC) sublayer in the Optical Wireless Switch (OWS). The optical wireless MAC layer was adapted for the VLC broadcast transmission and was developed by France Telecom. This data link was bandwidth-limited on the transmitter side to around 12 MHz (LED driving circuit), which posed a hurdle for high-speed transmission as targeted by OMEGA (goal: 100 Mb/s). This challenge was overcome with spectrally efficient modulation (discrete multitone, DMT with multi-level quadrature amplitude modulation, M-QAM), and with the intermediate demonstrator presented here we already achieved 84 Mb/s.

B. PHY Layer Description

1) Digital signal processing

Figure 3 presents the digital signal processing at the transmission (Tx on Fig.3a) as well as the reception (Rx on Fig.3b) side. All the clocks are managed by the Digital Clock Management (DSM) system and are shown with dashed lines.

Digital signal processing was implemented on a Virtex-5 FPGA board. The serial input from the OWS card was first mapped to a 16-QAM symbol stream and saved in FIFO memory. In order to obtain a real-valued signal at the output of the IFFT module, a conjugate symmetry was applied to QAM symbols. The system generated 7 modulated subcarriers within a bandwidth of 25.5 MHz. A 16-point (I)FFT blocks were used for the generation and demodulation of the signal. Since the subcarriers were modulated with the same modulation order and the signal bandwidth significantly exceeded the bandwidth of the analogue driving circuit, power pre-equalization was performed to enable similar transmission quality over all subcarriers. Based on the measured frequency characteristic of the analogue system, power of the DMT symbol was distributed among the subcarriers (without changing the total value), so that all result in similar SNR (over 25.5 MHz bandwidth). After IFFT, a 1-sample long cyclic prefix (CP) was added, and the signal was fed into a DAC (12-bit resolution). The DAC operated at 102 MHz, enforcing oversampling, pushing away the aliasing spectra and ensure successful synchronization.

The modules for OFDM demodulation were basically the same ones as in the transmitter, but in reverse order. The optical signal was captured by a photo-detector and converted into a voltage before arriving at the ADC (12-bit resolution and 102 MHz sampling rate). In the FPGA the cyclic prefix was removed and a 32-FFT performed (32-point FFT was needed to correspond to the ADC speed, for successful demodulation). For proper detection and demodulation, the Rx also included channel estimation and one-tap equalization in the frequency domain. Channel estimation was performed with help of a training sequence sent once at the beginning of transmission. After equalization, QAM symbols are de-mapped and a serial bit stream sent to the Rx OWS card.

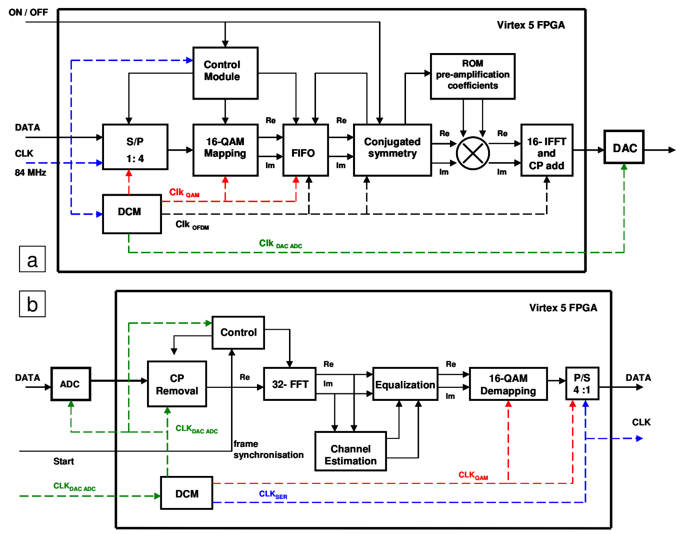

Figure 3: Digital signal processing blocks at a) Tx and b) Rx side. DCM=Digital Clock Management.

A periodically repeated training sequence (after a block of data), forward error correction, and signal-based synchronization are planned to be implemented in the final demonstrator. In the current version, bit- and frame- synchronization were achieved via a clock signal provided over a cable.

2) Analogue front ends

The analogue transmitter consisted of a driving circuit (trans-conductance amplifier, TCA) and a commercial high-power LED luminary [4]. In order to keep the overall complexity of the VLC prototype low, a 6-chip high power version from Osram was chosen (OSTAR E3B). The LED modules were directly mounted onto a heat sink integrated into the circuit board. A factory-designed spherical lens and an optical diffuser were mounted on top of the LED, converting the emission from the rectangular LED module into a diffuse circular light spot. The divergence angle of the emitted radiation was 76° at half power.

The driving circuit was based on a two-stage amplifier topology. A DSL chip was used for voltage amplification in the first stage and a class-AB amplifier based on bipolar-junction transistors for current amplification in the second stage. The driving circuit is discussed in more detail elsewhere in the literature [5]. The driving circuit linearly amplified the AC signal from the DAC and transformed it into an electrical current. After amplification, the signal was combined with a DC bias by means of an on-circuit bias T, and fed to the LED, which in turn emited a modulated optical signal through a wireless channel.

The analogue receiver consisted of an imaging optics (concentrator lens), a colour filter, a photodiode, a two stage trans-impedance amplifier, and a band-pass filter.

The signal strength at the receiver input depended on the illumination level. Table 1 shows the calculation for a best case and a worst case scenario.

	Result	
Parameter	**Worst case**	**Best case**
Illumination level at desk: 200…1000lx	200 lx	1000 lx
Conversion photometry → opt. radiation: ~200 lm/W	1 µW/mm²	5 µW/mm²
Concentrator gain	1	3
Blue portion of LED-spectrum usable for high speed data transmission: 10…50%	0.1 µW/mm²	7.5 µW/mm²
Responsivity Si-PIN diodes with ideal QE @ 460 nm: 0.25…0.35 A/W	25 nA/mm²	2.6 µA/mm²
Signal modulation: 10…100%	2.5 nA/mm²	2.6 µA/mm²
Required detector area assuming a sensitivity of the TIA of 0.07 µApp @ 35 MHz BW (e.g. MAX3657)	28 mm²	0.026 mm²

Table 1: Link budget calculation

As presented in Table 1, the effective detection area has to be in the range of 30 mm² to cover the worst case receiving conditions. The performance of the lens packaged Hamamatsu Si-PIN diode (S6968) is very close to an optimized theoretical design. An active area of 25 mm² and an optical gain of 4.4 at 70° FOV lead to an effective aperture size of 110 mm², which well exceeds the predicted requirement.

In order to achieve maximum modulation bandwidth for high speed data transmission, it was necessary to remove the slow yellow portion from the spectrum [6]. A customized blue filter was designed (Berliner Glas) to meet the requirements of the filter design in terms of cut off wavelength, absorption loss and filter slope.

The trans-impedance stage after the photodiode achieved a 3-dB bandwidth of 45 MHz at 12 kV/A gain, and a noise-equivalent voltage of 0,23 nV/Hz$^{1/2}$ by the use of the low noise op-amp OPA657 from Texas Instruments. All components were mounted in a cage with an aperture window, and a mechanical fixture for the wavelength filter as well as signal interface to the ADC stage (see Figure 4).

Figure 4: Receiver Board (left) and housing (right).

III. OPTICAL WIRELESS MAC LAYER

A. General overview

The MAC data communication protocol sub-layer is a part of the data link layer (layer 2) specified in the seven-layer OSI model. It provides addressing and channel-access-control mechanisms for terminals or network nodes to communicate within a multipoint network. Different access methods have been used in wire-line, radio or optical wireless communications. One approach is based on multiplexing by, e.g., wavelength-division multiplexing (WDM) [7] or space-division multiplexing (SDM) [8]. The second approach relies on electrical multiplexing techniques, such as time-division multiple access (TDMA) [9], frequency-division multiple-access (FDMA) and code-division multiple-access (CDMA) [10].

For optical wireless communications, there are several IrDA point-to-point protocols [11] and [12]. When it comes to multi-access protocols it is worth mentioning, that the an IEEE 802.11

infrared PHY standard was developed in 1993 for 1 to 2 Mbps throughputs, but it has not been commercially exploited. Currently, the task Group IEEE 802.15.7 is working on a VLC standard for point-to-point and point-to-multipoint links [13].

One of the well-established MAC protocols for wired communications is the Ethernet protocol (IEEE 802.3). But the direct conversion of fiber-based Ethernet to an analogue optical wireless version may not be suitable due to bandwidth efficiency and quality-of-service concerns (QoS) [14] and [15]. In conclusion, a key challenge for an optical wireless network system is the development of a well adapted MAC layer.

The proposed optical-wireless media-access control (OWMAC) protocol requires the following features provided by the physical layer (PHY), such as: frame transmission and reception, PPDU (PLCP Protocol Data Unit) and PLCP (Physical Layer Convergence Protocol) header. Figure 5 shows the structure of a physical frame.

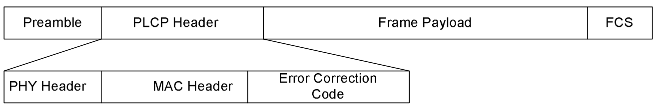

Figure 5: PHY Frame Structure

The PLCP header includes MAC and PHY headers with an error-correction code (ECC), similar to the UWB-ECMA (ultra-wide band - European computer manufacturer's association) standard [16]. The reason is to protect the Acknowledgement frame; to make sure that when station A receives a frame with no error; the corresponding acknowledgement sent by this station A will be correctly decoded or corrected, avoiding retransmission as much as possible. For the OW system, one of the most efficient ECCs is Reed-Solomon [17], for instance RS (255, 239, 16). The frame payload, followed by the frame-check sequence (FCS) closes the physical frame structure.

The OWMAC protocol is based on TDMA (time-division multiple access), and multi-sector transmission. The basic timing structure for frame exchange is a super frame with Time Slots (TSs).

TDMA was chosen because it is a simple way to avoid collision and retransmission that ensures data transmission availability in accordance with Quality of Service (QoS) parameters. Each device can reserve a time slot, and advertises the reservation in a beacon frame, preventing other stations from using the medium during the reserved time slot. TDMA also prevents the use of admission control mechanisms and RTS/CTS (ready to send / clear to send) frames, which consume bandwidth. For instance, the RTS/CTS mechanism is used by 802.11.

The OWMAC protocol was developed to accommodate link adaptation from 128 Mb/s to 1024 Mb/s and multi-sector coverage with half duplex or full duplex transmission. The goal of our efforts was to facilitate robust communication using either IRC for full duplex high-data rate line-of-sight links or VLC for broadcast coverage at lower data rates. If there is no data to send/receive, only a part of the frame is sent which makes power savings up to 98% possible.

To meet constraints set by numerous services and security levels, the protocol is also able to handle meshed or star topology, with unicast, broadcast, and multicast traffic. It also integrates functions such as an emergency message even in the case of saturation traffic and Quality of Services (QoS) parameters.

B. Adapted VLC OWMAC Frame

The MAC sublayer was first specified for a general optical-wireless channel and then adapted for the VLC broadcast transmission. The abbreviated data frame is a shorter version of the OWMAC standard [17] data frame that assumes that the original source and ultimate destination of the frame are the transmitting and recipient devices, respectively.

The format of the abbreviated VLC frame is modifying for the only downlink traffic; the OWMAC destination address is the broadcast address 0xffff.

The OWMAC protocol implementation was achieved on the OWS card. This OWS card was based on a Xilinx board (ML510) and on an interface card adapted to IRC and VLC PHY modules. The ML510 board is a complete embedded development platform for the FPGA Virtex 5. For our application, not all elements of this platform were used. Two 10/100/1000 Ethernet RJ45 connectors were used for this application. The Ethernet frames from the application computer are encapsulated in OWMAC broadcast format. These OWMAC frames can be monitored and analyzed by a frame analyzer. This frame analyzer was developed by France Telecom and Apside and works in the Wireshark environment.

IV. EXPERIMENTAL RESULTS

The block-diagram representation of the VLC prototype is shown in Figure 7. Transmission of three HD video streams (3x20 Mbps) was achieved by modulating a single LED. The achieved data rate was 84 Mb/s (around 73 Mbps on IP layer without error).

On the emission side, videos are hosted by a video server and at the reception side, each video is shown on a separate lap-top computer. The distance of the wireless link is 1.2 meter. This relatively short distance is a consequence of several factors. First, due to the lack of FEC, a very low bit-error ratio was required. Secondly, the demonstrator involved only one LED luminary, which has a relatively large emission angle. To achieve the needed PHY link quality for video transmission, we needed to include extra optic (lens) which would provide enough optical power at the receiver.

The next demonstrator will be based on 16 luminaries and include FEC, so that a successful video transmission can be expected over typical indoor distances and without any extra optics.

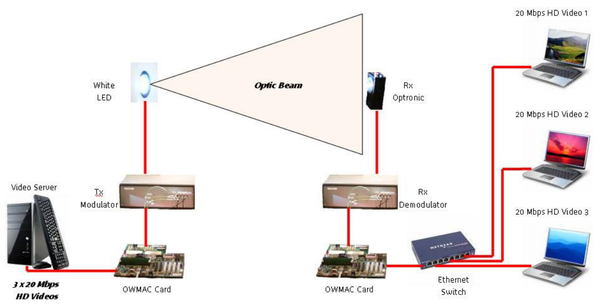

Figure 7: VLC prototype version 1

A picture of the current demonstrator is provided in Figure 8. On the left side, there is the LED transmitter (white box) with lens, then the OWMAC board and the modulation box (grey box). On the right side, we can see the reception module (black box) connected to the demodulator module (grey box) then connected to the OWMAC board and the PCs

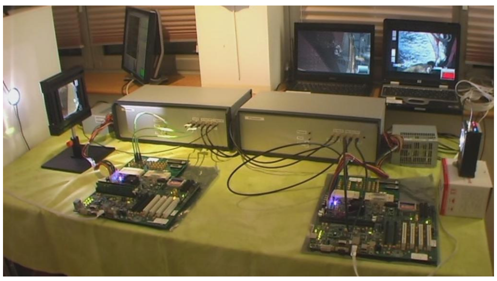

Figure 8: VLC V1 complete prototype

V. Conclusion and Perspectives

This paper reports an experimental demonstration of an indoor VLC link including a new MAC sublayer protocol for optical wireless systems. The VLC demonstrator operates at 84 Mb/s (around 71 Mb/s at the IP layer). This high data rate was used to transmit three HD videos (3x20 Mbps) in parallel. The next version will be able to transmit up to 100 Mbps in a 10 m^2 coverage area. This will be achieved by modulating multiple LED luminaries in lock step. The OWMAC protocol proposed is able to manage VLC communication for broadcast coverage and is also intended to support robust IRC in full-duplex high-data-rate line-of-sight links.

Acknowledgements

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