Productization Experiences of G.vlc (ITU) based LiFi System for high Speed Indoor Wireless Access

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The number of Internet-connected mobile devices are increasing rapidly. HD video streaming and accessing cloud-based services are the main user activities consuming data capacity. Most of this data traffic is generated in indoors environment. This demand for video and cloud-based data is expected to grow exponentially and is a strong motivator for the adoption of new spectrum, including the use of optical wireless media. Visible light communication (VLC) commercially known as LiFi (Light Fidelity) is getting adopted by the industry as a complementary wireless access technology to offload the WiFi data traffic. From the first market responses we also learn that the unique properties of the light propagation are seen as a compelling alternative to the increasingly congested radio waves. In fact, the exponential growth of the number of wireless users led to a continuous shrinking of wireless cell sizes, from several kilometers, to microcells, and now to very small cells that cover just a few rooms or a few meters as femtocells. While operators and IT departments struggle to handle higher user densities, with each user demanding higher rates and with the growth of wirelessly connected IoT devices, the property that light does not travel across walls and stays inside a room comes as a great advantage. It allows reuse of the same entire spectrum in every room. Moreover, it avoids interference, that currently limits the user experience that WiFi dramatically deteriorates in crowded areas, subject to the contention-based access protocols.

The ITU standard G.VLC offers a solution for the Physical layer using adaptively bit-loaded OFDM modulation that is suitable for various light sources, including illumination power LEDs (both visible and Infrared), or in future VCSELs and other lasers [1]. The ITU standard also offers a MAC layer that can guarantee a Quality of Service (QoS) by placing users signals on a TDMA grid, which is in contrast to most wireless radio standards that use contention-based random access with back-off procedures to allow retransmissions after unavoidable message collisions. Most of the research on VLC focuses on increasing the data rate through the commercial LEDs employing advanced modulation techniques such as OFDM and multi-PAM [2]. Little is known about the complete practical implementable LiFi architecture and standardization activities. Here, we demonstrate a commercial prototype for practical LiFi system that incorporates the complete system architecture, network signal distribution and ITU-T G.VLC implementation. We demonstrate the PHY rate of maximum 250 Mbps for downlink and 200 Mbps for uplink direction with a wide coverage area of about 35m^2 at standard ceiling desk height of 240cm.
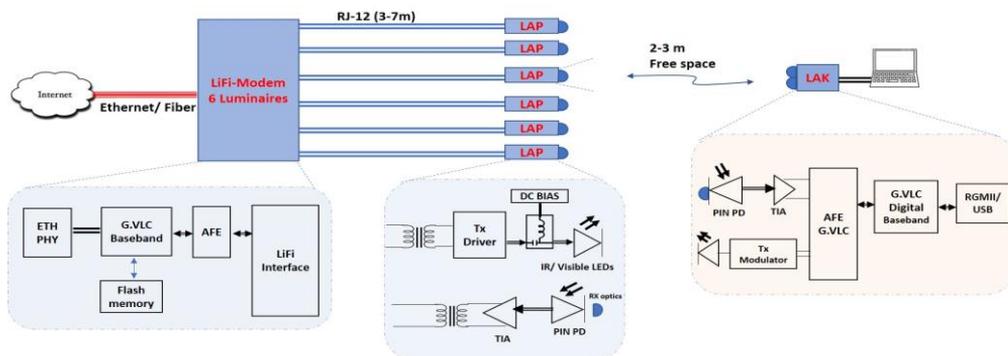
LiFi Architecture

Fig. 1. LiFi system architecture, LAP: LiFi Access Point; LAK: LiFi Access Key

Fig.1 shows the complete LiFi system architecture. The system comprises of LiFi-Modem (LM), LiFi-Access Point (LAP) and LiFi Access Key (LAK). The LM is connected to either GbE (Gigabit Ethernet) or fiber network. The LM consists of ETH-PHY (chip) that directly feeds GbE signal to the G.vlc baseband module. The baseband module is a system on chip (SoC) that implements ITU-T G.VLC (G.9991) standard [3]. G.vlc recommendation is the derivative of G.hn (G.9960) standard which was developed for next generation home network technology. The PHY layer of G.vlc uses DMT modulation and configurable baseband bandwidth of 50-200 MHZ with 512 subcarriers. The individual sub-carriers are modulated with multiple QAM levels with maximum of 12-bits/subcarrier and employ adaptive bit loading based on channel estimation.

The digital G.vlc signal is fed to the Analog Front-End (AFE) for digital to analog conversion, and then is further applied to the LiFi interface. The LiFi interface comprises of linear drivers with matching network, providing connectivity to, in our case up to six LAPs via RJ12 STP cable, to multicast the same signal via multiple LAPs. The LAP is a ceiling unit comprises of LED drivers (modulator) and IR-LEDs for the downlink transmitter and photodiode with transimpedance amplifier for the uplink receiver. The G.VLC signal is directly modulated on the IR-LED (850nm) via a bias-tee. The LAK is a mobile terminal module connected to the PC via a USB interface. It incorporates the whole optical frontend and digital baseband for both downlink and uplink direction. The modulated light-wave signal from the ceiling transmitter is received by the lensed Si-photodiode (Φ = 14mm) and transimpedance amplifier has 60 dB gain within LAK. The AC output signal from the TIA is directly coupled to the G.vlc chipset with Automatic Gain Control (AGC), analog to digital converter and digital baseband modem, and then it is fed to USB interface via SGMII bus. For the uplink direction an IR LED (940nm) is used to have full duplex communication link. The transmitted optical power in free space for both uplink and downlink are below the eye safety limit with 40% margin. One LM can be connected up-to six LAPs (bi-directional SIMO configuration), extending the total coverage of the system with flexibility. A total of sixteen LAK can be connected simultaneously to the LM within the coverage zone of six LAP.

While G.vlc is in principle not limited to LEDs and can also support future laser-based transceivers, our productization was up to now restricted to LEDs. Yet, our evaluations of the LED power consumption and response suggest that the VLC channel, where illumination thus a DC bias is already available, can be modeled as a channel where the

extra consumed power in the LED is proportional to the variance, thus the power of the modulated data. This leads to a different point of views as many studies in literature where the optical power is seen as a constraint. In fact, according to such optical power limited papers, LiFi comes for free, while according to our practical experience, the power consumption of LiFi even in VLC remains an aspect that requires further investigation.

Various modulator topologies have been studied in literature to modulate the LED current at high speed [4]. For our practical design we test two topologies, including Bias-T and series transistor topology. In various studies, mostly a power amplifier with 50-ohm output is connected via a Bias-T to modulate the LEDs, this is not appropriate and may not work properly for a LED based LiFi products, because of very low impedance of LED (0.5-1 Ohm). Yet in matching impedances, we learned to challenge the common RF practice that the load impedance should be conjugate to the output impedance of the driver. The theory of impedance matching was developed by posing the question: "given an output impedance Z_{TX} of a power source, which load Z_L extracts the maximum power". Yet, the optimization in LiFi is not about maximum power extraction, but about the most energy efficient operation of the driver [5]. We saw that the Bias-T with a low impedance power amplifier would be capable of actively pulling out electron hole pairs, thereby speeding up the fall-time of the LED response. However, a Bias-T topology requires bulky inductances and decoupling capacitors, which causes DC wondering effect. Contrary to our expectation the series transistor gives a flatter frequency response, but the series transistor requires a proper biasing control to minimize the power losses.

The G.9991 standard allows either DCO-OFDM modulation, thus with a DC bias, or the unipolar ACO-OFDM. In a preface to our productization we analyzed the potential benefits of ACO-OFDM. We concluded that for VLC, the extra power consumption above illumination could jeopardize energy efficiency regulations on the electrical-input-power-to-lumen-output efficacy of the lighting system. We present the performance of the first commercial LiFi system with coverage of two LAPs (placed at 0cm and 240 cm) vs achievable gross data-rate in Fig. 2a ('blue •' represents theoretical and 'red ◊'represents the measured capacity). The PHY rate of maximum 250 Mbps is achieved with single LAP covering ~6m² yielding the total system coverage of 36 m² at 240cm ceiling height. The areas where the light-waves overlap (in between the LAPs) contribute to the higher SNR thanks to the constructive interference and point to multicasting configuration, hence achieving seamless coverage between two APs. The maximum achievable throughput C of a G.vlc that selects the strongest signal out of a set $i \in \{0, 1 ..\}$ of ceiling units is given by
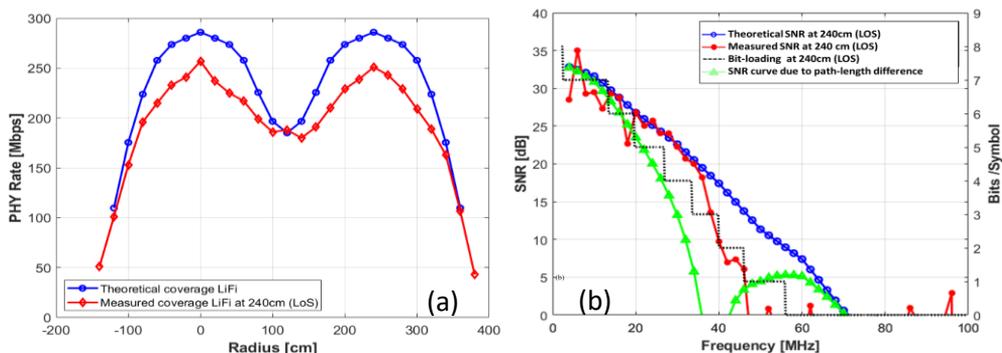

Fig. 2 a) LiFi system coverage vs PHY rate at 240cm ceiling height; b) SNR vs frequency for LoS at 240cm (red •), bit-loading ('black --') at 240cm, theoretical SNR ('blue o') and SNR due to the path length difference ('green Δ')

$$C = \max_i \int_{BW} \left\lfloor \log\left(1 + \frac{P(f)|H_i(f)|^2}{N_0}\right) \right\rfloor df \qquad (1)$$

It is the integral over all bandwidth BW , of the received power, subject to a channel and LED attenuation $H_i(f)$, and, for G.vlc, a uniform, thus constant power spectral density. The floor function reflects that only an integer number of bits can be loaded on all subcarriers. Fig. 2a ('blue •') compare these theoretical maxima with measured performance. If multiple light sources cooperate by emitting the same signal, the receiver power is increased and hence the SNR, which yields in high capacity.

One advantage of the OFDM modulation is that it allows a frequency-dependent number of bits per subcarrier. As the LED may be seen as the first order low pass filter, with a gentle roll off caused by the LED junction capacitance and the dynamic LED resistance make it very suitable channel for bit-loading the subcarriers. The Fig.2b illustrates the measured SNR as a function of frequency at 240 cm in direct LOS. A max of 33dB and min 6.5dB SNR is achieved. The adaptive bit-loading allow to efficiently exploit the useful SNR on subcarriers. (see Fig. 2b 'black --'). The subcarriers that have SNR < 6.5dB (minimum BPSK) is left un-modulated. The theoretical SNR for the same system configuration (at 240cm) is presented ('blue o'). The big difference in SNR after 35Mhz is mainly due to the distortion occurs induced by LED non-linearities. The OFDM also allows the emission of signals from multiple emitters, even with the risk that the multiple wireless propagation paths differ essentially in length. In a single carrier system, e.g., OOK or PAM, this would lead to inter symbol interference and loss of performance if not compensated in an adaptive equalizer. In the case of two Line of Sight (LoS) signals emitted by two adjacent LAPs and received by single LAK, will lead to a periodic series of notches in frequency domain that only attenuates portion of the spectrum (loss only few subcarriers). The signal from multiple light sources only have equal strength causes the cancellation of some frequencies (subcarriers) occurs right in the middle between two light emitters (see Fig. 2b 'green Δ'), in practice these may be wired up with different cable lengths between LAPs, thus resulting in wave cancellation effects.

In future, we plan to demonstrate the feasibility to exploit full distributed MIMO capabilities, that is, to adopt spatial multiplexing of multiple streams, there getting the sum of the individual throughputs.

Conclusions

In this paper, we highlights the experiences to use ITU-T G.6991 (aka G.vlc) standard in productization of first commercial LiFi system for indoor broadband wireless access, we achieved gross data-rate of 350 Mbps downlink and 250 Mbps uplink with wide coverage of 36 m^2 at 240 cm standard ceiling desk height.

References

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