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Introducing A New Paradigm in Visible Light Communications: Light Distribution With Optical Fibers

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Abstract—This paper introduces a new approach to Visible Light Communications (VLC) by utilizing optical fibers for decorative purposes while investigating their potential in VLC applications. An in-vehicle prototype was developed and tested, consisting of a VLC emitter distributing light through 500 optical fibers on a 1 x 2 meters' surface to a mobile VLC receiver. Experimental results show the concept's viability, achieving a BER below 10^{-7} for typical in-vehicle distances and demonstrating suitability for multiple data streams using wavelength division multiplexing. As far as we know, the use of optical fiber distributed light in VLC applications has not been addressed before.

Keywords—light distribution, optical communication, optical fibers, visible light communications, WDM.

I. INTRODUCTION

Visible Light Communications (VLC) are a branch of Optical Wireless Communications (OWC) which take lighting technologies to their next level, by integrating a wireless data transmission function [1], [2]. Thus, the VLC technology assumes the dual use of low-commutation time Solid State Lighting (SSL) sources for energy-efficient illumination but also for high data rate wireless communications [3]-[6]. As VLC implies the integration of two simultaneous functions, it must be clearly stated that data transmission should be developed on top of the illumination function and it must not perturb it in any way. In the last decade, the high potential of the VLC technology has enabled this technology to be considered suitable in numerous applications, where high data rate indoor applications [3]-[6], communication-based road safety applications [7], [8] and indoor localization [9] can be seen as the most promising ones. In addition, significant progress has been achieved in terms of networking protocols resulting in systems that can successfully handle user mobility and multiple users [10]. Consequently, based on intensive research efforts, the high potential of the VLC technology has been confirmed both analytically and experimentally.

In addition to the traditional use case, new utilizations for the VLC technology are being identified, ranging from underwater communications to applications that imply simultaneous sensing and communications [11]. In this context, this paper introduces *a new paradigm in VLC utilization: the use of VLC with optical fiber distributed light*.

This research is motivated by the utilization of optical fibers for enhancing the aesthetics of vehicles, particularly in luxury automobile contexts, thereby creating potential for wireless data transmission. As far as we know, this concept is new in the VLC literature, being recently introduced by our team in [12]. To demonstrate the proposed concept, a new VLC prototype has been designed, implemented and experimentally evaluated. The VLC emitter prototype has been integrated into a vehicle's optical fiber ambient lighting system. The experimental results confirmed the functionality of the new VLC concept, opening the door for new applications. Additionally, different from [12], this work demonstrates the utilization of the concept in Wavelength Division Multiplexing (WDM) applications. Thus, the experimental results showed that multiple data streams can be simultaneously transmitted using different LED colors. Although this paper demonstrates this concept in an in-vehicle communication scenario, other uses are of course compatible with this concept, opening new possibilities in VLC utilization.

II. DISCUSSIONS ON THE PROPOSED CONCEPT: WHY VLC WITH OPTICAL FIBER DISTRIBUTED LIGHT?

The new concept introduced in this paper envisions combining two optical communications technologies with individual long-established performances. So, the optical fiber communications are a technology which has a few decades of utilization and confirmed single channel performance at data rates going up to 1 Tb/s and beyond [13], with systems succeeding aggregate data rates in the petabit domain, based on Dense Wavelength Division Multiplexing (DWDM) and Space-Division Multiplexing (SDM) techniques [14][14]. Thus, the technological era as we know it today is largely due to the performance of fiber optic communications. On the other hand, the VLC technology has been in use for about one decade, rising to data rates of up to few tens of Gb/s [3]-[6], while having the potential to reach hundreds of Gb/s data rates. On these grounds, this new concept envisions the combination of the two technologies into a new utilization domain. Traditionally, the VLC concept envisions a LED-based VLC emitter having illumination and data transmission purposes and a photoreceiver-based VLC receiver, separated by the wireless optical communication channel. This concept has rapidly developed based on the experience of optical fiber communications and also on the experience of RF communications. Nowadays, optical fiber can transport light

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at very low attenuation, enabling high data rate communications. In addition to the main application in data communications, optical fibers are used in multiple decorative applications that do not imply data transmission. Nevertheless, based on the experience of VLC, it is only straightforward to evaluate the optical fibers for ambient lighting for data transmission purposes as well. So, the concept introduced in this work aims to provide these optical fibers with wireless data transmission capabilities, similar to the way LEDs have been enhanced with wireless communications capabilities in the VLC technology.

III. HARDWARE IMPLEMENTATION AND EXPERIMENTAL EVALUATION OF THE IN-VEHICLE VLC SYSTEM BASED ON OPTICAL FIBERS DISTRIBUTED LIGHT

A. Hardware Implementation of the Proposed Prototype With Optical Fiber Distributed Light

In order to demonstrate the viability of the concept, a demonstrative architecture consisting of an in-vehicle VLC emitter and a VLC receiver, separated by the OWC channel has been implemented and experimentally tested. The purpose of the prototype is mainly to demonstrate a new use case for the VLC technology in which the light is carried by optical fibers before entering the free space optical channel. Figure 1 illustrates the schematic of the proposed system. Different from the traditional VLC notion, this newly developed concept envisions applications that use optical fibers for ambient illumination purposes. To accommodate such applications, the proposed VLC emitter uses a high power 3W RGB LED whose emitted light is focused with the help of an optical connector into 500 optical fibers. As learned from optical fiber communication, the connection between LEDs and optical fibers generates relatively high connection losses. In optical fiber communications, this issue imposed the transition toward laser diodes, especially in long range applications (i.e. above 2 km), generating in turn extended communication ranges. On the other hand, considering the decorative purposes and the relative low energy consumption associated with LEDs, these connection losses are not a major drawback in this case, as the envisioned purpose is to provide ambient lighting and short range communication. Next, the 500 optical fibers distribute the light onto the vehicle rooftop

on a 1 meter \times 2 meter surface, as shown in Fig. 2. To ensure the data transmission function, the VLC emitter uses a 600 MHz ARM Cortex M7 microcontroller board. In accordance with the IEEE 802.15.7 standard, the prototype uses On-Off Keying (OOK) modulation and Manchester coding. In terms of data rate, the current configuration is able to provide data rates up to 250 kb/s. Although this data rate is rather low, higher data rates could be enabled as demonstrated by both VLC and optical fiber communications technologies. Additionally, to accommodate more than one user or an aggregate transmission, WDM can be used as well. In this case, the in-vehicle transmitter uses three emitters, one for each of the three RGB colors.

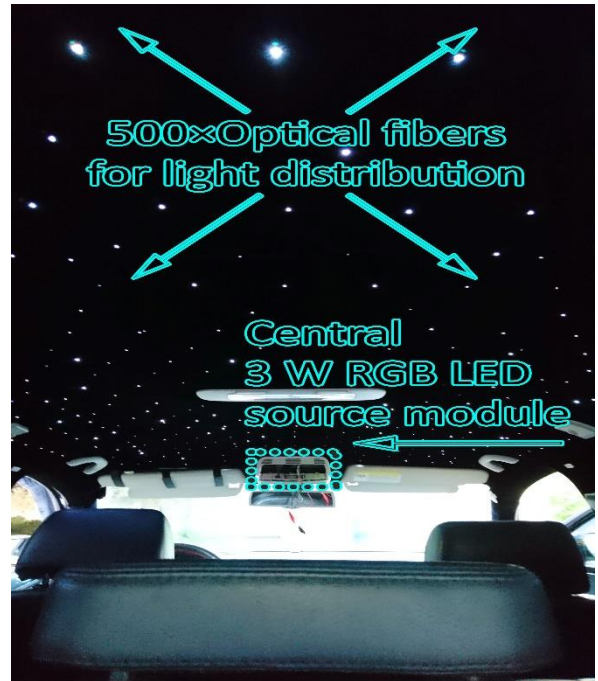


Fig. 2. Hardware implementation of the in-vehicle VLC emitter system integrating 500 optical fibers for light distribution.

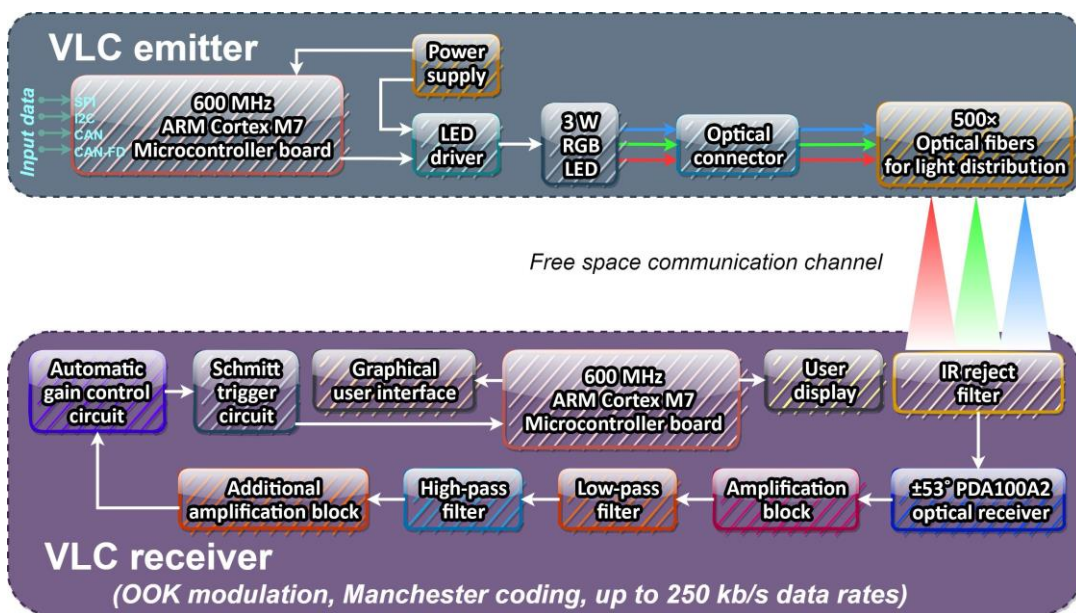


Fig. 1. Schematic of the in-vehicle VLC system and optical fiber integration.

The mobile VLC receiver follows the typical structure of a VLC receiver. To reduce the impact of parasitic light sources and to improve the SNR, a IR-reject optical filter is integrated within the optical collecting component. Alternatively, when the system is working in the WDM mode, RGB optical filters are used instead. Next, a PIN-photodiode connected in a transimpedance circuit transforms the incident light containing the data signal into an electrical signal. The following blocks are used to ensure signal amplification, signal band-pass filtering, complementary and adaptive amplification and signal regeneration. Once the signal has reached proper characteristics, a 600 MHz microcontroller is responsible to extract the binary data and to process it accordingly. Fig. 3 shows the hardware implementation of the VLC receiver. Table I summarizes the prototype's parameters, whereas additional details are available in [12].

TABLE I. SUMMARY OF THE SYSTEM'S PARAMETERS

Parameter of the VLC System	Value
Modulation	OOK
Coding	Manchester
Data rate	<ul style="list-style-type: none"> • 250 kb/s for a single optical link • 750 kb/s for three simultaneous data streams accommodated using WDM
Optical filters used for the VLC receiver	<ul style="list-style-type: none"> • IR-reject 380-680 nm <ul style="list-style-type: none"> • R 450±20 nm • G 520±20 nm • B 630±20 nm

B. Experimental Results and Discussion on the Results

This section aims to provide the experimental evaluation of the proposed prototype and also aims to deliver experimental evidence concerning the feasibility of the newly introduced concept. In order to provide sufficient evidence, several aspects have been investigated. One of the first experiments intended to evaluate the coupling efficiency by comparing the irradiance of the 3W RGB LED with the output measured at the 500 optical fibers. The result of this experiment has shown a 12% coupling efficiency. Although this coupling efficiency is rather low, this aspect is not a major impediment neither from the decorative point of view, nor from the overall lost energy.

In the following experiment, the BER performance has been evaluated for the data transmission case with white light

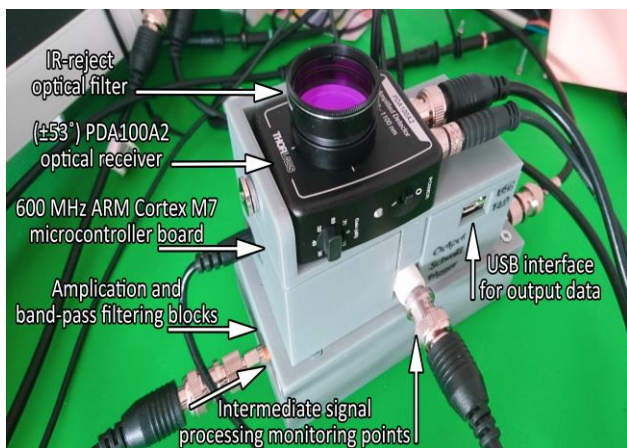


Fig. 3. Hardware implementation of VLC receiver prototype.

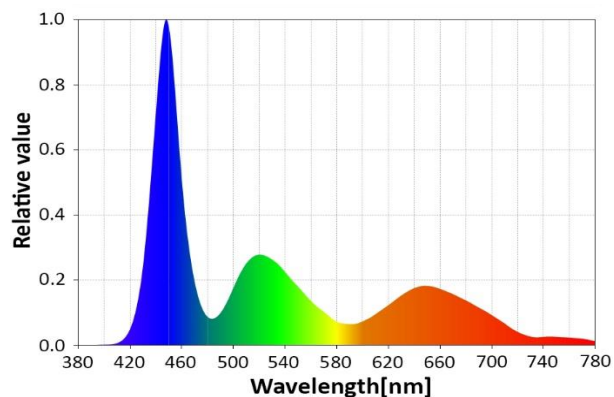


Fig. 4. Spectral analysis of the RGB LED used for data transmission.

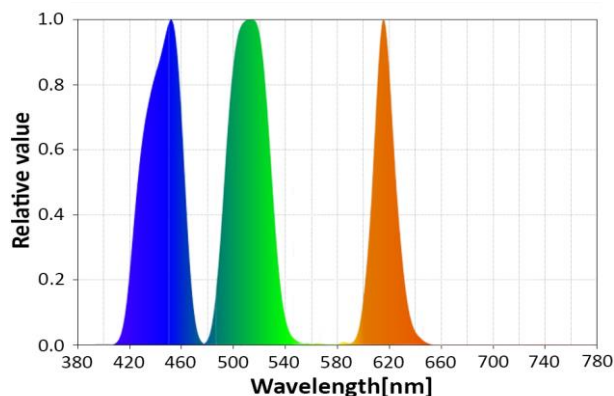


Fig. 5. Spectral response of the optical filters used at the VLC receiver level.

obtained from the RGB LED. Fig. 4 illustrates the results of the spectral analysis of the RGB LED used for the data transmission. For this case, the experimental results showed that in the absence of direct exposure to parasitic light, a BER lower than 10^{-7} can be achieved. As the optical fiber is uniformly distributed on the vehicle rooftop, the low BER can be maintained within the vehicle. Additionally, the BER was maintained within the 10^{-7} limit for distances between 10 and 80 cm from the rooftop.

The third experiment had the purpose of evaluating the ability of the system to accommodate multiple users and/or to provide improved data rates. For this purpose, WDM with three different data streams are being transmitted by the RGB LED. At the receiver side, three optical filters are used to separate the three data streams. Fig. 5 shows the experimental determination of the spectral response of the three optical filters, whereas Fig. 6 provides the oscilloscope screen with signals received by the VLC receiver englobing the sum of the three data streams. Additionally, Fig. 6 is also showing the signal reconstruction process at the VLC receiver level. As one can see, the narrowband optical filters significantly reduce the optical irradiance reaching the PIN photodiode, imposing a higher signal amplification at the VLC receiver level. On the other hand, the narrow band optical filters also limit the optical noise reaching the PIN photodiode enhancing the SNR level. So, the VLC receiver is able to effectively process and extract data from input signals whose amplitude is as low as 2 mV. The results of this experiment has shown that by using matched optical filters, WDM can be adequately applied

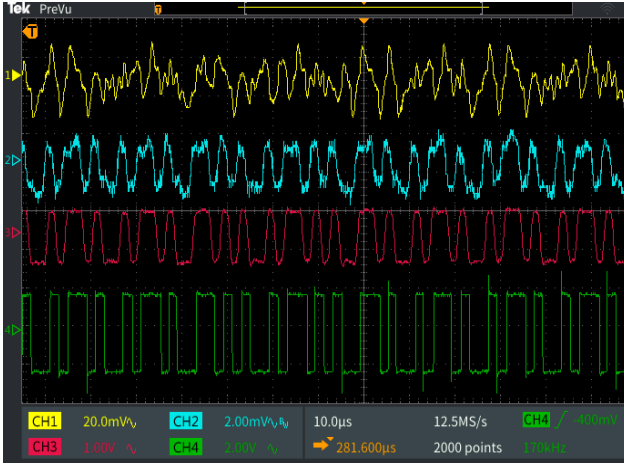


Fig. 6. Oscilloscope screen showing the signal processing steps at the VLC receiver level: channel 1 (yellow) shows the sum of three data signals before wavelength division demultiplexing; channel 2 (cyan) shows the output of the optical detector for one data signal; channel 3 (red) shows the data signal after amplification and band-pass filtering; channel 4 (green) shows the final signal used for data extraction.

within the proposed concept. Table II provides the summary of the experimental results.

TABLE II. SUMMARY OF THE EXPERIMENTAL SETUP AND EXPERIMENTAL RESULTS

Parameter of the VLC System	Value
LEDs irradiance at 5 cm distance	20,100 $\mu\text{W}/\text{cm}^2$
Irradiance at 5 cm distance from the output of one optical fiber	4.8 $\mu\text{W}/\text{cm}^2$
Distributed irradiance for 500 optical fibers	2400 $\mu\text{W}/\text{cm}^2$
Coupling and transmitted efficiency	12%
VLC distance	10–80 cm
BER for white light generated by RGB LED (250 kb/s)	$<10^{-7}$
BER for R / G / B light with WDM (750 kb/s)	$<10^{-6}$

C. Debate on the Experimental Results, Benefits of the Proposed Concept, Potential and Future Developments

The experimental results showed that the proposed concept is viable and highly promising as BER lower than 10^{-7} has been achieved. Although the experimental 250 kb/s data rate is relatively low, it is obvious that higher data rates can be achieved as both fiber optics and VLC enable tens of gigabits per second data rates. Nevertheless, as the purpose of this work was to demonstrate the viability of the concept, higher data rates have not been envisioned for these initial tests. Additionally, experimental results also showed that the proposed concept is compatible with the WDM concept, enabling improved data rates and paving the way to the multiple-input multiple-output (MIMO) concept.

On the down side, rather high optical losses have been measured. These losses are caused by the high attenuation of visible light spectral components in optical fibers and also by the connection losses between LEDs and optical fibers. Nevertheless, the importance of this work comes from the fact that this is one of the first works that combines the utilization of optical fiber communications and of VLC.

IV. CONCLUSIONS

As wireless communications are being used in more and more applications, this paper proposes a new optical wireless communication concept which combines fiber optical communications and VLC technology. In this new concept, the light carrying the data travels through optical fibers before entering the free space optical communication channel and continuing its traveling to the VLC receiver. To demonstrate the viability of this concept, a VLC prototype has been implemented and experimentally evaluated. The experimental results showed a 250 kb/s data rate for single channel communications and 750 kb/s for three parallel links. Future work on this project should be focused on demonstrating the functionality of this concept at higher data rates and on identifying new utilizations for this novel concept. Also, we will consider interference problems in the evaluation of the VLC system.

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