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Radiocommunication Sector of ITU

Report ITU-R SM.2422-2

(07/2022)

Visible light for broadband communications

SM Series

Spectrum management

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Foreword

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REPORT ITU-R SM.2422-2

Visible light for broadband communications

(Question ITU-R 238/1)

(2018-2019-2022)

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1 Scope

This Report considers how, in which way, and to what extent the use of (near) visible light communication (VLC) (or perhaps a better term might be: Optical Wireless Communication) can help to ease the congestion in the radio spectrum.

The following topics are addressed:

- distinctive characteristics (technical and operational) of the use of (near) VLC for broadband communications in terms of its use of the spectrum;
- advantages and disadvantages of the use of (near) VLC (these might include: efficiency, interference, health risks, cybersecurity);
- new applications associated with visible light used for broadband communications;
- barriers for the development of broadband communications in order to move to worldwide implementation of (near) VLC (e.g. regulatory, cultural, and/or economical);
- way in which (near) VLC connects to current telecom systems (fixed and mobile).

It should be noted that VLC is a technology and not a radiocommunication service.

2 History of VLC

From ancient times to the 19th century, all VLC communication systems relied on the human eye as the receiver. The invention of the Photophone by Alexander Graham Bell and Charles Sumner Tainter changed the nature of VLCs. They used the fact that selenium resistance varies with respect to light intensity and used this property by connecting it to a phone receiver in order to send audio signals. Many improvements were achieved on these systems until the 1950s, however most of the materials used for detection have higher sensitivity to infra-red radiations, hence precluding visible light to be used as a transmission medium.

The introduction of light-emitting diodes (LED) created new interest for the use of VLC. More specifically, the introduction of Gallium Arsenide (GaN) LEDs [1] and white light-emitting phosphors [2] provided visible light sources, which can be modulated at higher speeds, without sacrificing their main illuminating role. In 2004, the first high-speed communication demonstrations with LEDs were performed in Japan, using photodiodes. The proliferation of cellular phones with cameras, enabled them to be used as VLC receivers. Researchers started using LCD screens and other display elements as transmitters.

One of the first standardization bodies to work on a VLC standard was the Visible Light Communications Consortium (VLCC) of Japan. They expanded the infrared Dara Association (irDA) standard for infrared communications with the visible light spectrum in 2008.

3 Visible light and broadband

3.1 Possibilities of broadband use via visible light

Visible light optical wireless access data rates ranging from a few b/s to excess of 10 Gbit/s are possible at standard indoor illumination levels. VLC has the potential capability to ease congestion with low radio frequency (RF) spectrum bands since light spectrum can be used as an additional spectrum resource for broadband communications.

3.2 Efficiency gains of the use of visible light for broadband communications

VLC establish a directional optical wireless link. For instance, a single optical link can originate from a lamp on the ceiling pointing directly to the floor. It allows more than one user to share the same link. A number of VLC devices are available to be accommodated without interference through spatial reusability.

3.3 Use of the spectrum

VLC uses the visible spectrum (wavelengths between 390 and 750 nm) and can provide wireless communications using illumination and display elements.

Optical Wireless Communications (OWC) has the potential to ease congestion in the lower radio frequency (RF) spectrum bands since light can be used as an additional spectrum resource for broadband communications.

3.4 Possible applications/services benefiting from VLC

Possible visible light communication can be classified into three groups:

- Image sensor communications (ISC).
- Low rate photodiode receiver communications (LR-PC).
- High rate photodiode receiver communications (HR-PC).

With regards to the definition of low rate and high rate, the throughput threshold data rate is 1 Mbit/s as measured at the physical layer output of the receiver. Throughputs less than 1 Mbit/s rate are considered low rate, and higher than 1 Mbit/s are considered high rate.

Image sensor communications

ISC enable OWCs using lighting sources as a transmitter and image sensors as a receiver. Possible applications include:

- Location-based services/Indoor positioning and navigation
- Indoor office/home applications (conference rooms, shopping centres, museums, exhibition halls, etc.)
- Vehicular communications
- LED based tag applications
- Point-to-(multi)point/relay/communications
- Healthcare
- Digital signage and location-based content delivery
- In-Vehicle data services (flight, train, ship, bus, etc.)
- Connected-cars and Autonomous Vehicles
- Underwater/Seaside Communications
- Internet of Things (IoT).

The requirements to be observed by the ISC are: dimming control, power consumption control, coexistence with ambient light, coexistence with other lighting systems, simultaneous communication with multiple transmitters and multiple receivers (MIMO), nearly point image data source, identification of modulated light sources, low overhead repetitive transmission, image sensor compatibility, and localization.

For MIMO communications, a MIMO MAC protocol may be incorporated, so that the camera enabled receiving device knows how to process the received data. ISC should support communication when the light source appears as nearly a point source; i.e. the light source illuminates only a small number of image pixels.

ISC is capable of supporting several channels of communication between multiple coordinated/uncoordinated transmitters and multiple coordinated/uncoordinated receivers.

ISC should support compatible communication with a variety of cameras with different image sensing sampling rates (read-out time), resolutions and frame rates. Specifically, either constant frame rate or varying frame rate will be supported. Either constant resolution or varying resolution will be supported.

Low-rate photodiode communications

Low-rate photodiode communications require light sources as a transmitter and low speed photodiodes as receivers. The main applications are similar to those for image sensor applications.

LR-PC is mainly for the light tag sources (such as LED Tags and the smart phone flash lights, etc.) as transmitters. It may provide mechanisms to support handover between light sources, allowing the users to maintain a continuous network connection.

LR-PC may provide mechanisms that can be used to develop and deliver interference coordination techniques by higher layers and may support link recovery mechanisms to maintain connection in unreliable channels and reduce connectivity delays.

High-rate photodiode communications

The use of high-rate photodiode receivers will enable high-speed, bidirectional, networked and mobile wireless communications. The main applications of this mode are:

– Indoor office/home applications (conference rooms, shopping centres, museums, exhibition halls, etc.)
– Data centres/industrial establishments, secure wireless (manufacturing cells, factories, etc.)
– Vehicular communications.
– Wireless backhaul (small cell backhaul, surveillance backhaul, LAN bridging).
– Healthcare
– In-Vehicle data services (flight, train, ship, bus, etc.)
– Connected-cars and Autonomous Vehicles
– Underwater/Seaside Communications.
– Internet of Things (IoT)

In HR-PC, continuous data streaming for all applications should be supported with bidirectional functionality as well as short packet transmissions where low latency is required. Mechanisms to support adaptive transmission as well as multiple users communicating with different data streams from the same light source (multiple access) should be included.

4 Spectrum management aspects relevant to visible light

VLC are subject to substantially different propagation characteristics relative to frequencies in the radio frequency spectrum. As a result, the probability of interference is small, and light communications does not need to be managed by spectrum regulators.

IEEE 802 believes that light communications operations should be classified as license-exempt and not subject to exclusive licensing. This point of view was confirmed by a study commissioned by the Radio communications Agency Netherlands [18]. One of the conclusions from this study was: “There are still challenges to overcome before being deployed commercially. We recommend to focus more on standardisation efforts by ITU or IEEE rather than governmental rules and limit governmental regulation primarily to limits with regard to health hazards, carbon footprint, and commercial competition. Standardisation will increase not only compatibility among industrial products but also compatibility with already deployed technologies”. Adherence to the relevant local health and safety regulations regarding human eye safety and sensitivity is essential. Devices using VLC or OWC should adhere to any local regulations regarding spurious RF emissions and should avoid causing interference in RF spectrum bands.

Frequencies for optical communications are usually expressed in their wavelength. While 1550 nm is the most widely used wavelength for fibre optical communications due to the absorption and scattering characteristics of glass, this limitation does not apply to VLC in normal air. The usable frequency range is therefore 1.4-2.5 THz or 400-700 nm.

4.1 Issue 1: Spectrum opportunities and spectrum allocation

Increasing spectrum opportunities by combining radio, such as 2.4/5/60 GHz, with optical wireless, both indoors and outdoors: exploit possible synergies between Wi-Fi and Li-Fi, take care for fog and sunlight mitigation in outdoor scenarios, see [9] and [10]. It can be read in [18] that “The deployment of Optical Wireless Communication may be particularly interesting in environments where many high bandwidth demanding users access the network within a confined space, or where conventional radio technologies cannot be used, or cannot provide the necessary service level. Bringing together representatives from potential user groups, construction industry, communication industry, device manufacturers and solution providers may help to further advance use cases and requirements for standards and further developments and to identify niche markets where the introduction of OWC will be most beneficial”.

4.2 Issue 2: Spectrum planning principles

VLC systems are typically deployed using the (existing) LED illumination system, wherein the LEDs’ visible light is modulated in intensity in order to convey wirelessly data information to devices. Such illumination systems are usually designed to cover a large area, and thus typically provide data connections to multiple devices within that area. Hence these devices need a protocol according to which they share the capacity of the LED system, i.e. a medium-access-control protocol. Such a MAC protocol typically partitions the total communication capacity of the LED system in smaller parts, where each active device gets a part in competition with the other ones, thus implying that when one device wants more capacity, another device will get less. Working with a MAC protocol and thus sharing resources implies that it is difficult to provide a guaranteed amount of capacity to a device. Establishing a link to a device via a MAC protocol means that a connection has to be established in a negotiation process with the other devices. This process takes time, and the outcome is not guaranteed. This negotiation time reduces the net available time for data transmission, and thus reduces the network data throughput. Moreover, the LED illumination system needs to be switched on, in order to support the data transfer. This illumination-on state may not always be desired, e.g. when the room is already filled with bright daylight, or when the user prefers no or only dimmed light. Hence a VLC system may introduce undesired extra energy consumption when just communication is needed and no illumination.

Alternatively, one may use multiple confined beams of light to convey the data information (e.g. [4]). Each beam serves a single device and needs to be steered with sufficient accuracy towards it. The full capacity of that beam is thus dedicated to only one device. Hence no MAC protocol is needed, and there is no sharing of capacity with other devices. Thus, a guaranteed capacity can be offered to a device, no time is lost in a MAC process, and the net throughput of the network is improved. Moreover, the light beam is only offered to those devices which need it, and is confined to those places; therefore, the beam’s energy is optimally spent, and thus the energy consumption for the data communication is minimized. The light beams are preferably using light with a wavelength larger than 1.4 μm, as this allows beam powers up to 10 mW to be used without eye safety risks. The IR beam steering needs control processes which register first whether the device requests service, subsequently localizes the device, and with that localization information steers the beam into the right direction and thus establishes the communication link. The IR beam-steered system thus provides communication capacity on those places where and when needed, and therefore operates in the most energy-conscious way.

Channel models are a common method to perform “in system” management of the available light spectrum, this can be managed by the respective technical standards for the particular applications. Some information can be found in [17].

4.3 Issue 3: International and regional harmonization

Visible light spectrum preferably fit or comply with international standards (i.e. for Europe ETSI) and as any system and device, should comply with countries’ law and regulations. However, it is important the visible light communication devices do not impose any health hazards. They should be correctly and safely installed so that they do not produce any harmful Electromagnetic interference (EMI).

5 Technical and operational characteristics of short distance broadband communication via visible light

This section also includes text about products and prototypes taken from [16]. These are not necessarily broadband applications but included to demonstrate available technology.

5.1 Visible light communication transmitter

Carrier frequency: The carrier frequency will be limited in visible light frequency band.

Transfer mode: The ITU-R may provide multiple physical visible light device operating modes for low and high data rate communications that allow the optimal use of the available optical bandwidth on a given luminaire to support Image sensor communications, Low rate photodiode communications and High rate photodiode communications.

Eye safety and flicker: The modulated light will be safe for human eye in the aspects of frequency and intensity of light. In addition, the modulated light will not stimulate sickness such as photosensitive epilepsy.

Dimming control: The standard will support dimming control for all of applications.

Communication range: The communication range depends on multiple external factors (signal magnification, signal collimation, source power, etc.). These are implementation aspects and are provided as guidelines only. The committee will agree to use the same channel model to assess the performance capabilities of the proposed schemes.

Coexistence with ambient light: The standard will co-exist with ambient light that may be reflected on a surface of a transmitter and with three classified visible light communication service groups.

Coexistence with other lighting systems: The standard will co-exist with other lighting systems.

Identification of transmitter: The standard will support a scheme to identify transmitters when a receiver or a transmitter is moved to another location. A receiver can trace a transmitter identification of transmitting device.

5.2 Visible light communication receiver

VLC receiver measures the intensity of visible light and decode the transmitted information, as application usage need.

Being part of the user's device, an OWC receiver should be compact and low-cost, should not require tedious alignment and should capture enough optical power to enable a high down-stream data capacity. Hence it should have a large angle-of-view and a large aperture. However, increasing the active area of a photodetector typically is accompanied by a reduction of its bandwidth, and the "etendue" principle, which characterizes how "spread out" the light is in terms of angle and area, implies that the aperture times solid angle cannot decrease. Fish-eye lenses may be used to enlarge the receiver's aperture, or non-imaging optics such as a compound parabolic concentrator mirror, typically used for solar energy concentration. A 2D array of fast photodetectors, co-integrated with individual electrical pre-amplifiers and a summation stage can preserve a large bandwidth [11]. Alternatively, the light collection function may be separated from the light detection function, optimizing these functions separately.

A wide surface grating coupler (SGC), which collects incident light integrated with a waveguide to a fast photodiode, can support multi-Gbit/s OOK reception [12]. With an array of SGCs plus an on-chip combiner, the aperture can be extended further without compromising the bandwidth. The "etendue constraint" may be removed by λ-converting the received light and confining it in a fluorophore-doped slab waveguide [13].

In particular for beam steered OWC, localization and tracking of the user devices is needed. For example, Wi-Fi techniques can be used, 60 GHz antenna pattern nulling [14], or IR LED tags on the user's device monitored by a cheap camera [15], etc.

Optical wireless communication is especially fit for environments where radio is (or will be) less feasible because of a combination of factors:

– Spectrum scarcity

– Need for very high capacity

– Reluctance to use radio technology

– Legislation

– Need for wireless transmission that can be contained within the building.

Optical communication is applicable to various systems. How it is implemented within these systems depends on the required transmission range. Based on these ranges OWC applications can be divided into five classifications, namely:

– Ultra-short range wireless communication is a range that is applied to chip-to-chip communications where OWC can be applied through a means called Free-Space-Optical Interconnect (FSOI). It allows direct interconnection between chips through a beam of light. This application could solve some issues current copper-based electrical interconnections have like, data rates, electromagnetic interference, and power consumption.

– Short range wireless communication is commonly applied to wireless body area network (WBAN) and wireless area network (WPAN) applications. It is meant to collect and transmit data in the vicinity of an individual. New systems are being developed using OWC in Healthcare known as optical WBAN (OWBAN), since it may provide a safe and interference free alternative to RF based WBANs.

Medium range wireless communication is a range applied to wireless local area networks (WLANs). Current OWC systems within this range classification can be distinguished into VLC and beam-steered infrared light communication. VLC typically builds on the existing LED ambient illumination system, and re-uses the LEDs for data modulation. The VLC system thus covers a wide area, in which multiple user terminals have to share its capacity by a suitable MAC protocol. Beam-steered IR light communication only provides a direct connection between devices. Multiple beams may independently serve user terminals within the room, hence each terminal can get a guaranteed capacity without conflict with other terminals. These systems can replace or offload current systems (e.g. Wi-Fi) since it works in a higher spectrum range contrast to RF based WLANs. Other applications for a medium range wireless communication are inter-vehicular and vehicle-to-infrastructure communications.

Long range wireless communication is capable of reaching distances from 300 metres to circa 10 kilometres. It is, for instance, applied to building-to-building connections and wireless metropolitan area networks by enterprises and urban markets. OWC applies a system called Free-Space-Optical Communication (FSO), which is a direct beam connection between a transmitter and a receiver.

Ultra-long range wireless communication can reach a distance of circa 84 000 kilometres, which makes it ideal for aeronautical and space communication. For this, a system similar to FSO is applied; only, it uses a very narrow light beam and a vacuum channel to transmit and receive the information. This system is called an Optical Wireless Satellite Network FSO (OWSN FSO).

Many efforts have been done to predict specific applications for access technologies. But in reality, what will be the most important applications and devices in more than a few years is very difficult to predict. Think about ‘internet’, ‘smart phones’, ‘tablets’ and ‘navigation systems’, the success of which is only predicted at the moment the success already started.

Success of applications is driven by worldwide success of combination of devices/operating systems/fixed and mobile infrastructures/existing application ecosystems.

5.3 Current standardization activities

The IEEE 802.15 Working Group completed, in 2011, IEEE Std 802.15.7-2011 on “Short-Range Wireless Optical Communication Using Visible Light” [3] A project to revise IEEE Std 802.15.7-2011 was authorized in December 2014 with the name of Optical Wireless Communications (OWC) which includes LED-ID, Optical Camera Communication (OCC) and LiFi, and is currently active [6]. It intends to develop a standard for optically transparent media using light wavelengths from 10,000 nm to 190 nm. In March 2017, the group is divided. 802.15.7m will continue work on Optical Camera Communications, whereas the IEEE 802.15.13 Task Group established for “Multi-Gigabit per Second Optical Wireless Communications (OWC)” project which employs high-speed photodiodes [7]. In addition, IEEE 802.15 Vehicular Assistant Technology (VAT) Interest Group is considering VLC as a communication option.

The IEEE 802.11 Working Group initiated, in late 2016, a Topic Interest Group (TIG) on Light Communication [8], aiming to determine the technical and economic opportunity presented by using the light medium for wireless communications. In 2018, the project authorization request of the group is approved. 802.11 Task Group bb is responsible for the development of the standard document.

ITU-T Study Group 15 is responsible in ITU-T for the development of standards for the optical transport network, access network, home network and power utility network infrastructures, systems, equipment, optical fibres and cables. This includes related installation, maintenance, management, test, instrumentation and measurement techniques, and control plane technologies to enable the evolution toward intelligent transport networks, including the support of smart-grid applications. The group is responsible of G.vlc standard which is entitled “High speed indoor visible light communication transceiver – System architecture, physical layer and data link layer specification”.

5.4 Collected VLC related activities in the countries

5.4.1 VLC research in China

Huawei, China Telecom, Sanan Optoelectronics, Shenzhen Absen, Unilumin, Cnlight and Tsinghua University are the VLC based research and product development focused institution/companies in China.

5.4.2 VLC research in Japan

Nakagawa Laboratory in Keio University, Panasonic Corporation, CASIO, NEC, and FUJI Electric are the VLC research and product development institution/company in Japan.

5.4.3 VLC research in Korea

Seoul National University of Science and Technology, Kookmin University, Kongju University, Namseoul University, Samsung, LG, and ETRI are the VLC research and product development institution/company in South Korea.

5.4.4 VLC research in The Netherlands

Eindhoven University of Technology, department Telecommunication Technology and Electromagnetics, Group electro-optical communication. Signify (recently known as Philips Lighting), KPN and KIEN are also partner in VLC related projects.

5.4.5 VLC research in Turkey

Main research institutions working on VLC are Tubitak Bilgem, Okatem, Ozyegin University and Istanbul Medipol University. Ford Otosan, Farba, Aselsan and Turk Telekom are partners in VLC related projects.

5.4.6 EU-China collaboration

Internet of Radio Light (IoRL) EU-China collaborative research project is being managed by Eurescom GmbH and collaboratively performed by Brunel University, Viavi Solutios, University of Leicester, Institut supérieur d'électronique de Paris, Mostlytek, Issy Media, Building Research Establishment, Fraunhofer Institute for Integrated Circuits IIS, National Centre for Scientific Research Demokritos, Joada, Warsaw University of Technology, Arcelik, RunEL, Holon Institute of Technology, Ferrovial, Oledcom, Fundación Centro de Innovación de Infraestructuras Inteligentes, Tsinghua University, Leadpcom and Shanghai-Feilo/Yaming. It develops a 5G Network Function Virtualisation/Software Defined Network for buildings whose hybrid VLC and mmWave radio access network points are integrated within pervasively located light systems access points.

5.5 Collected VLC related activities in the Academia, Industry and Research Institutes

5.5.1 Basic6

Basic6 is a start-up company founded in the United States of America developing an indoor positioning system GeoLiFi, which uses a store’s lighting infrastructure to anonymously deliver proximity messaging, information about products, related promotions, and visual shopping lists to customers and employees. At the same time, the solution provides the retailer with detailed analytics of such metrics as customer and employee engagement rates as well as store and department dwell times. The company works on software and actively partners with other lighting companies that provide hardware for LiFi (such as OLEDCOMM [28] a French start-up company of the University of Versailles Saint-Quentin-en-Yvelines).

5.5.2 Fraunhofer Heinrich Hertz Institute (HHI)’s LiFi Hotspot

The LiFi Hotspot developed at Fraunhofer HHI allows for the installation of a private, high-speed network without imposing cables. The system offers high data rates of up to 1 Gbps, over a distance of up to 30 m and its small size is easily aligned and inexpensive to install. A prototype has been installed in a conference room on Mainau Island, Germany (Constance Lake). HHI also provides components for Visible Light Communication with off-the-self white light LEDs using three light colours (RGB), capable of speeds of up to 3 Gbits/s.

In addition to LiFi broadcasting modules sending data in one direction, technology developed at Fraunhofer IPMS offers the possibility of a real-time capable and bidirectional, ‘full duplex’ communication.

5.5.3 Hyperion technologies

Hyperion technologies, a Turkish start-up company, develops cutting-edge optical wireless communication-based solutions to empower next generation wireless networks both at access and backhaul levels. The company contributed 802.15.7r1 standardization project and continues to attend 802.11 light communications and 802.15.13 optical wireless communication standardization groups.

5.5.4 Lucibel

Lucibel, a French company that specializes in the design of new-generation lighting solutions based on the LED technology, have developed and are in the process of marketing Europe’s first, fully industrialized LiFi luminaire: Ores LiFi [5]. The Lucibel LiFi solution enables the deployment of a full wireless network through a bidirectional line rate up to 42 Mbit/s. The Lucibel LiFi system offers high-speed mobile connectivity within a network while supporting multiple access and the “handover.” Each LiFi luminaire can simultaneously serve multiple (up to eight) LiFi stations. The implemented handover functionality allows users to keep automatically a stable connection from one luminaire to another. Sogeprom, major property developer subsidiary of Société Générale Group, was the first user to test the LiFi high bandwidth in its Parisian premises by installing the first Lucibel prototype. Microsoft is also implementing the LiFi solution at its innovation centre in Issy-les-Moulineaux in order to provide the next generation of wireless connectivity for its customers.

5.5.5 Luciom

LUCIOM is a French start-up company created in October 2012. The company has several products in their portfolio such as:

- Geo VLC: low bandwidth transmitter/receiver kits for indoor location with different functionality.
- High data rate solutions with LED LiFi internet transmitters and USB LiFi/infrared dongles providing data rates of 20 Mbit/s (downlink) and 5 Mbit/s (uplink).

5.5.6 LVX system

LVX System is a US company based in Kennedy Space Center with a patented technology offering high quality LED light systems that also securely stream high-speed data. They have recently signed a Space Act Agreement with NASA.

5.5.7 pureLiFi

pureLiFi is a start-up company founded in 2012 by Prof. Haas of the University of Edinburgh to market visible light communication technology after four years of extensive research. The company first developed a ceiling unit called Li-Flame capable of 10 Mbit/s downlink and 10 Mbit/s uplink communication with a range of up to 3 m using standard LED light fixtures. pureLiFi has now evolved the Li-Flame into the LiFi-X, a new generation of drivers and receivers that were introduced at the 2016 Mobile World Congress. LiFi-X provides an access point that connects to any LiFi enabled LED light. It offers full duplex communication with a 40 Mbit/s downlink and 40 Mbit/s uplink as well as full mobility and multiple users per LiFi Access Point.

5.5.8 Velmenni

Velmenni is an Estonian start-up company that had successful trials of the LiFi technology in various offices and industrial environment in Tallinn, Estonia and are presently doing numerous pilot projects to utilize Visible Light Communication in diverse industrial contexts (in collaboration with Airbus to test the technology on the airplanes). The prototype consists of a LED transceiver and an external photodetector receiver that is connected to a laptop via USB. The system works in duplex regime (uplink and downlink) and the reported data rates go as fast as 1 Gbit/s. The demonstrated distances between Tx-Rx are several tens of cm. However, it will take some years before the prototype becomes a commercial product.

5.5.9 Tsinghua advanced integrated visible light and power line communication system

Tsinghua University is a national university in China. Tsinghua University focus on the key technical R&D and industrialization of PLC and VLC. After several years R&D, an advanced Integrated Visible Light and Power Line Communication[1] System was proposed. The system provides a unified framework for signal processing in both electrical and optical domains. It supports information services without an RF signal or at high RF sensitivity environments such as deep mining and power tunnels, power stations, aircrafts, factories, and hospitals.

The system takes advantage of the natural connections between power network and illumination network, with powerline communication (PLC) as a backbone and LED-based visible light communication (VLC) as an access point, to support mobile services as well. It utilizes the single-frequency network to effectively increase the system coverage, and significantly reduce the communication interruption caused by user movement and object blocking. The system adopts amplify-and-forward method in transmission to lower the implementation cost, power consumption, and space requirement inside the luminaire.

This system is already used in an underground tunnel of power supply cable by State grid of China.

Some lab measurement results are shown in Annex 1.

5.5.10 EU-China Research Project – Internet of Radio Light

IoRL is a joint EU-China Horizon 2020 5G research project, which develops broadband communication solutions for buildings by exploiting the pervasiveness and accessibility of the existing electric light access points, the broadband capacities of both mmWave and VLC technologies and the flexibility of SDN/NFV. It industrially designs a radio-light solution with a sufficiently small electronic footprint so that it can be integrated into the myriad of form factors of existing electric light systems and consumer products.

6 Other relevant aspects (user needs, socio-economic aspects) for decisions on visible light

Regarding eye safety, the modulated light that can be seen by the human eye shall be safe with respect to the frequency and intensity of light (e.g. IEC 60825-1:2014), and the modulated light should not stimulate sickness, such as photosensitive epilepsy.

Eye safety aspects plus references

The most vulnerable part of the human eye is the retina, located in the back of the eye, which performs the actual vision process. Visible light (obviously) reaches the retina, and the power exposure should stay limited in order not to cause any (permanent) harm to the retina. In VLC, the LED systems have been designed for illumination purposes and typically send out diverging cones of light and will, in practical circumstances, not harm the retina. In optical beam-steered communication, visible light beams (such as may come from laser pointers) clearly can be harmful; their power should stay below a fraction of a mW. However, when infrared beams are used, the physiology of the human eye implies that the beam’s intensity is heavily attenuated (by the cornea, the lens, the vitreous body) before it can

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[1] Other terminology used for Power Line Communication is Power Line Telecommunication (PLT).

reach the retina. Thus, much higher powers are allowed before the eye safety limit is exceeded; at wavelengths beyond 1400 nm, CW powers up to 10mW are acceptable.

The eye safety standards are specified in the regulatory documents IEC 60825 and ANSI Z136. The study in [18] recommends "For optical wireless, eye- and skin-safety are the most critical issues. Although the use of optical wireless by the general public can be made safe for almost all conditions, it is recommended to take a closer look to safety issues for people who are working in a close proximity of intense light sources for installation and maintenance".

Acceptance and deployment

As with all communication systems both functionality and protection of user data is required. See [18], where it is stated: "Acceptance and deployment of OWC will benefit from a clear vision on interworking with existing or emerging popular wireless standards, such as Wifi, for instance in the area of authentication, encryption and seamless roaming between Access Points. It is recommended to promote reuse of existing solutions where possible, for instance with regard to authentication and signal encryption. Such reuse may ease the development of interworking mechanisms (for instance handovers) between OWC and radio communication technologies. Also, this way of new developments with a still relatively small user base may benefit from improvements of solutions with a large user base".

Industrial and manufacturing

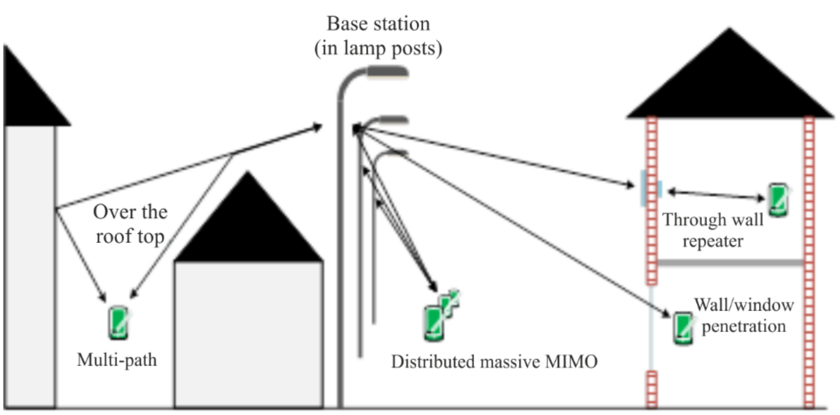
In industrial and manufacturing scenarios, nowadays wired solutions are mainly used because of high requirements with respect to robustness, security and low latency. Industrial protocols (i.e. ProfiNet) assign regular network access to the clients and ensure the transmission of data within a specific period and low latency. Industrial wireless is also attractive due to easy deployment and flexibility. VLC based solutions may provide benefits over RF based solutions with respect to:

i) Suitability for dense deployment: Manufacturing belongs to the so-called dense wireless scenarios with multiple links maintained, simultaneously all offering the above-mentioned high service quality. VLC can deliver safe wireless communications with low latency because it has well-confined propagation conditions in very small cells. Moreover, VLC can be used complementary to RF systems for data off-loading.

ii) Coexistence with other RF services: One big issue for industrial wireless networks is coexistence with other services. Using other RF links in the same spectrum requires protocols, such as "listen before talk", which implies unpredictable delays and contradicts low latency requirements. Getting dedicated spectrum for industrial wireless is one way. VLC could be another way to alleviate the current situation. Note that ambient light imposes little interference on VLC as discussed below in "VLC Technical Feasibility".

iii) Robustness against jamming: it is possible for attackers to easily jam the used RF spectrum from great distances outside the plant with simple RF devices. The use of RF-based wireless links instead of cables obviously has a potentially harmful impact on the safe operation of the connected manufacturing facilities in general. In addition, the presence of strong electromagnetic interference may not be suitable for RF communication, such as in a steel mill, in nuclear power plants, or in a power station. On the other hand, VLC is inert against RF jamming and EMI, the propagation is confined inside the plant.

FIGURE 1



Report SM.2422-01

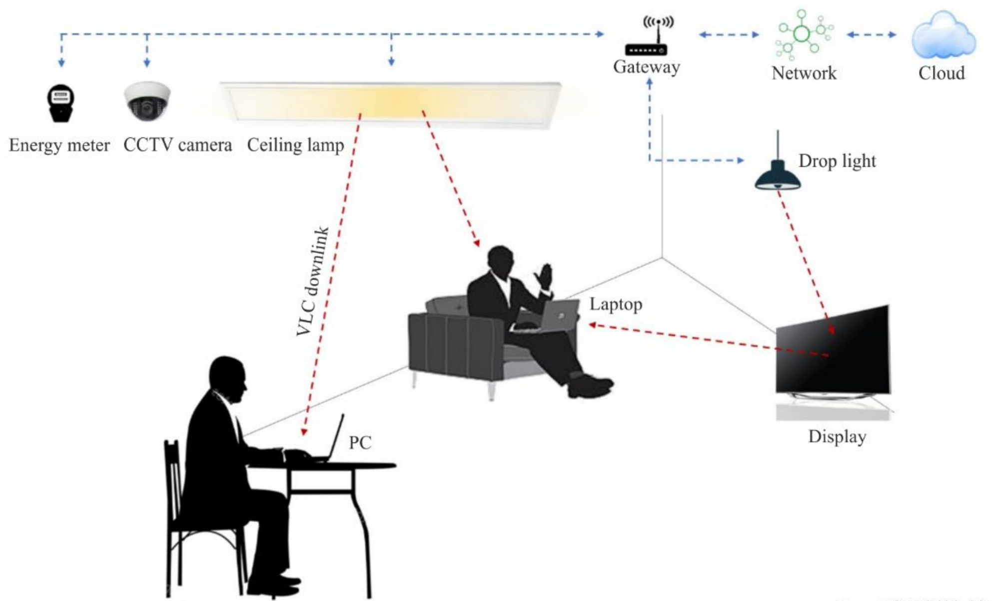
Smart home

Presently, smart home includes many kinds of home appliances, an energy management system, a healthcare system, advanced multimedia services, and a surveillance and security system, through complex wired and wireless connectivity. The connected devices for smart home can be operated in interactive and independent way, and these capabilities improve the quality of life within the household in various respects, such as automation of routine tasks, provision of health services, rationalization of energy consumption, improved individual efficiency, and enhanced home security, as well as entertainment, etc.

The smart home uses the local wireless networking approach and is based on standards such as Local Area Network (LAN), Body Area Network (BAN) or Personal Area Network (PAN), which are used to describe a network of a smaller scale ranging from 12 to 100 metres such as Bluetooth, ZigBee, WiFi, Z-Wave and others.

VLC can be used to connecting devices that convey sensitive information like CCTV cameras, baby monitors and others, and can be a more private and secure network [19].

FIGURE 2



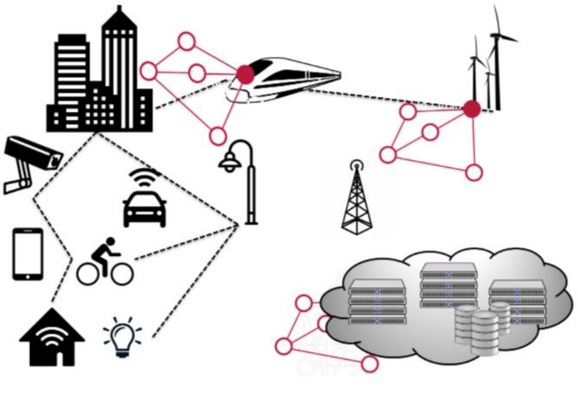
Report SM.2422-02

Smart city mapping (city genome)

Cities can be considered as evolving living complex organisms. This is not just because of the people who live in the city and who are complex 'systems' in themselves. Life itself, seems to become increasingly complex through disruptive and exponential developments. Technological developments, especially in the realm of ICT, are playing a crucial part. However, it is not a given that quality of live, a major goal, will benefit. There exist enormous opportunities, but equally ominous threats may emerge. To make true qualitative progress, an integral systemic approach is a necessity. Incremental, linear thinking and design will not suffice. A first step is to understand the distinction between the 'hardware' and the 'software' of the city, like respectively 'body' and 'mind' in a human being or living entity, or 'genotype' and 'phenotype', 'house' and 'home'. The first parts are palpable, the latter not. Generically, the first is denoted as 'infrastructure' and the second as 'suprastructure'. Obviously, infrastructure and suprastructure are interdependent and cannot be dealt with on their own. This is a challenge, because the infrastructures are the domain of the technical sciences and the expertise for the suprastructures dominantly resides in the alpha sciences.

Looking at the infrastructures, the ICT-networks have become more and more important. It is here that the centres for wireless and photonics can contribute. All optical, photonic networks are foreseen in which a new generation of fibres and Photonic Integrated Circuits (PICs) will be the main components. This certainly is the case in the core and metropolitan networks. Nearing the access points, wireless technologies will have a place. As a future development, it can be seen that at the edges of the network, a transition from fixed to wireless is realized. Such a place could be very well a piece of street furniture, more specifically a 'streetlight'. Note that in the Netherlands alone there are close to 4 million streetlights. The latter can be configured in an optical mesh network. From the streetlights bandwidth can be transferred towards or from the home, using repeaters in a next generation of multi-functional windows of all 7,5 million houses and 300 000 buildings. Inside the houses and buildings, VLC will be the future technology.

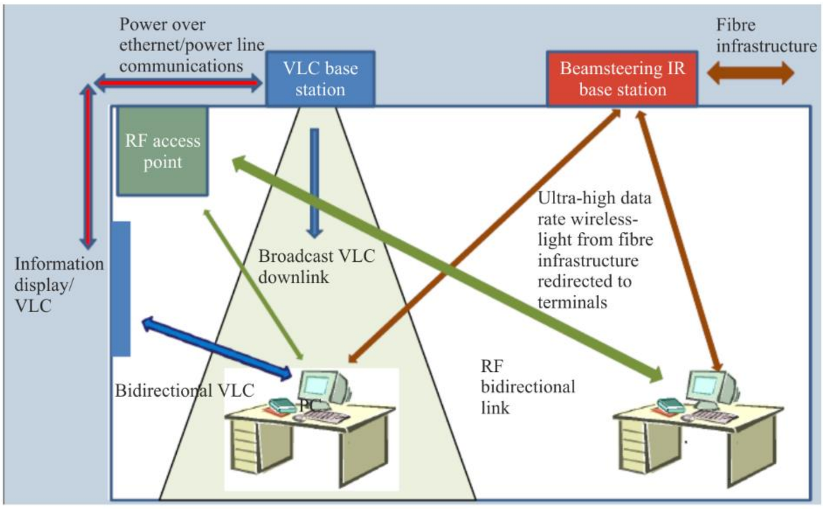
FIGURE 3



Report SM.2422-03

Looking at the houses and buildings themselves and how they are connected by more physical infrastructures in the public space, it is obvious that the faculty of the Built Environment can contribute with its expertise. As a near maverick development, the gain in looking at the build-up of houses, buildings and public infrastructures and suprastructures can be seen as living things with their body and mind, their genotype and phenotype are studied. Indeed, if today a human genome can be determined within one hour for less than a hundred euros, why would that not be possible for these far simpler physical constructions? And what enormous options could then be realized! Macro-parameters such as energy, safety and sustainability labels can then be accurately calculated. Scenarios for improvement can be designed and valued.

FIGURE 4



Report SM.2422-04

Looking at the data that can be tapped or fed to the houses, buildings and public infrastructures, it is clear that the data science centre is the centre that can play a crucial role. The journey from pure data towards information, knowledge and new wisdom will generate countless applications for both infrastructures and suprastructures, networks and services, houses and homes. They inherently will need to be designed in a secure and safe way. Likewise, investigations can be carried on the method by which the complex systems encountered can be modelled, using e.g. Complex Adaptive Systems Graph- and matrix theory.

The above brings modelling of overall realistic scenarios for smart cities substantially closer through an integral systemic approach.

In relation to the user needs and socio economical aspects more study is required since the fields of application are very diverse and not fully explored. As stated in [18], “It is also recommended to stimulate close contacts between (national) industrial R&D and academic research, as there is (still) much diversity in the OWC technologies being explored. Early identification of which are potential winning technologies among them and facilitating and promoting convergence and interworking will support the industrial development and speed up market introduction”.

There is also work and research to be done on the actual placement of VLC equipment in buildings and offices as stated in [18]: “OWC is not replacing, but is complementing the use of other transmission as e.g. Wifi for in-building communication infrastructures in which OWC can off-load the bandwidth-hungry applications from Wifi. Due to this co-existence with the current Wifi technology, we recommend designing and building offices, public spaces and houses such that the potential of OWC is taken into account especially for creating the fixed (wired) infrastructure accommodating sufficient OWC access points and backhaul. Combining transporting data with powering optical wireless Access Points using Ethernet cables (Power over Ethernet) becomes increasingly interesting, and therefore it is recommended to pay attention to it for construction purposes”.

Connected-cars and autonomous vehicles

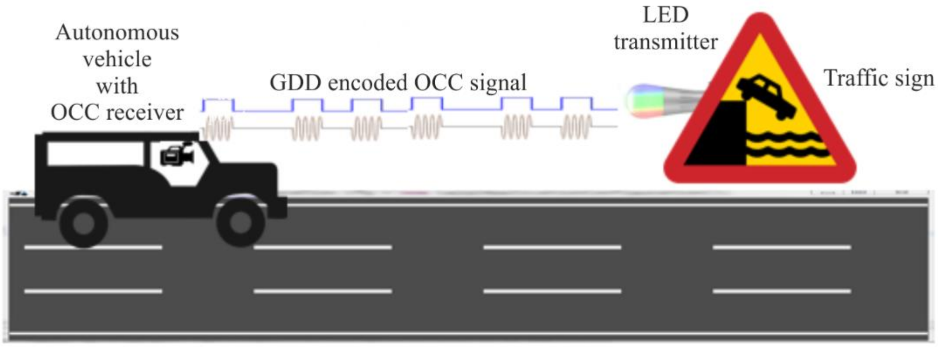
VLC can be applied for the Connected-cars and Autonomous Vehicles. Usually drivers should watch the traffic signs while driving. Autonomous Vehicles should recognize the traffic signs as image recognition technology, but sometimes it can be misread. One example of Connected-cars and Autonomous Vehicles is traffic sign recognition using VLC and Graphic Data Dictionary (GDD). GDD has been developed by ISO TC204with the intent of creating a common basis for transmitting encoded information for existing road traffic signs and pictograms. The coding system of it has been developed as language independent, such that data that can be interpreted, irrespective of language or regional differences. This is intended to support Intelligent Transport System messaging. An approach was required to characterize the large set of existing road traffic signs and pictograms into functional groups – this is done by means of Information Elements.

In the transmitter part, a suggested GDD data encoder (generator) is designed. The encoded data can be transmitted using two types of transmitters, one is simply to install a LED signal transmitter together with existing traffic sign, and the LED transmit the encoded data fit for a specific traffic sign. The advantage of this simple type of transmitter is that it can be applied to every existing traffic sign. The only difference between each sign is that uniquely encoded data is transmitted from it.

In the receiver part, the GDD receiver is composed of a camera with image sensor and data decoding unit. The images could be sensed on the image sensor behind the optical camera lens, and it receives data transmitted by optical camera communication [20].

FIGURE 5

Autonomous vehicle receiving OCC signal from traffic sign



Report SM.2422-05

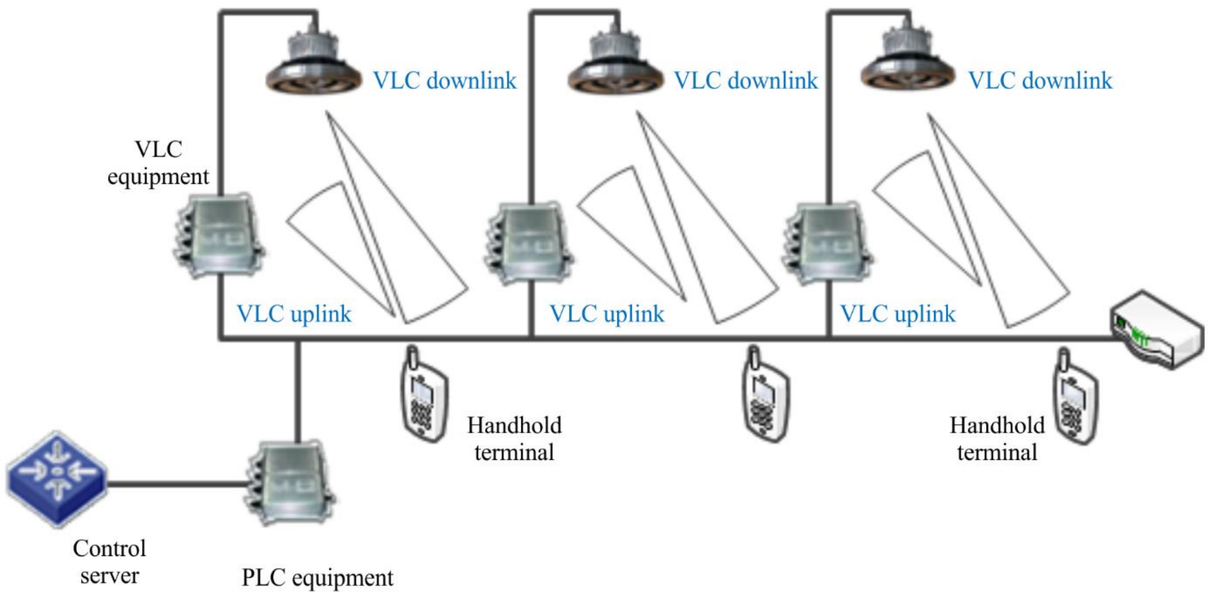
Information communication for intelligent mining and tunnel monitoring

Visible light communication technology, capable to support communication, data exchanges, and positioning functionalities, has found broad applications in the intelligent mining and tunnel monitoring.

The communication function requirement comes from the fact that mines or tunnels located at a depth of tens to several hundred metres underground or with a length of more than a kilometre. Due to the structurer of mines or tunnels and the physical characteristics of cable, the attenuation on wireless signals is very large, and the wiring of the wired systems is very difficult. For the maintenance, inspectors need to regularly communicate with the people at the control centre. At the same time, during the event of the connection failures or accidents, it is absolutely necessary to contact the control centre for faults elimination and rescue. Visible light communication is not affected by the structure of mines or tunnels as it uses the lighting equipment for the information acquisition or exchanges (more specifically, combining the powerline communication and visible light communication) to transmit voice and video information, and maintains the real-time communication with the control centre.

FIGURE 6

VLC-PLC system and control server



Report SM.2422-06

The requirements of information exchanges include the data transmission for the fixed sensors and the data transmission for the mobile applications. This system can integrate online monitoring, video surveillance, infrared temperature sensor integrated equipment at cable joints, temperature, fan, water pump, ground current, fire, gas combined with inductive devices such as intrusion alarms and tube defences for the online real-time transmission of the monitoring data. The regular transmission of monitoring data will identify and help eliminate faults more accurately and timely. It can also shorten emergency repairing time and reduce corresponding losses. During this process, the inspection personnel can use this system to maintain data exchanges and service interaction with the control centre, thereby it will greatly facilitate the automation-level of the online monitoring and improve the efficiency of inspection.

Internet of radio-light for media and entertainment in buildings

Wireless networks in buildings suffer from congestion, interference, security and safety concerns, restricted propagation and poor in-door location accuracy. The Internet of Radio-Light (IoRL) project develops a safer, more secure, customizable and intelligent building network that reliably delivers increased throughput (> 10 G bps within a building) from access points pervasively located within buildings with latencies of < 1 ms, whilst minimizing interference and harmful EM exposure and providing location accuracy of < 10 cm. It thereby solves problem of broadband wireless access in buildings and promotes establishment of a global standard in ITU. Building landlords will be incentivized to find funding to realize this solution for their properties to increase their value resulting in a stimulated market for broadband networking products in buildings, benefiting society and stimulating the world Gross Domestic Product. The IoRL project is developing a proof of concept portable demonstrator, which acts as the basis for standardization of a global solution exploiting the broadband capacities of VLC, mmWave, the flexibility of NFV/SDN technologies, and the accessibility of the existing electric light access points. It shows how an industrial redesigned VLC and mmWave radio-light solution can be integrated into existing electric light consumer products to become a universal electromagnetic access point in rooms within buildings, and in the final year of the project it aims to demonstrate it operation in homes, museums, train stations, and supermarkets.

7 Conclusions

Recent developments in OWC, standardization activities and existing lighting products show that VLC is a mature technology with many benefits for offloading the radio spectrum.

It may be concluded that the management of VLC devices and the VLC spectrum is not a regulatory task but something that should be organized in technical standards. A close cooperation of the standardization bodies involved in VLC and those in the traditional radio applications could be beneficiary.

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Annex 1

Tsinghua University lab results of an indoor broadband broadcasting system based on power line communication and visible light communication

Visible light communication (VLC) using the light-emitting diode (LED) has become an appealing alternative to the radio-frequency communication technology for indoor wireless broadband broadcasting. However, the LED lamps should have access to the backbone information network, and this requirement is not easily satisfied. Power line communication (PLC) systems utilise the ubiquitous power line network to power the LED lamps while serving as the backbone network for the indoor VLC systems naturally. China is considering an indoor broadband broadcasting system based on the deep integration of PLC and VLC. The proposed scheme significantly reduces the complexity of the VLC network protocol, and requires much less modification to the current infrastructure, while providing better signal coverage. Lab test result of this system with orthogonal frequency-division multiplexing (OFDM) modulation is introduced in this Annex.

1 Brief introduction

A deeply integrated PLC and VLC system for efficient indoor broadcasting is shown in Fig. 7. In this scheme, the data is first modulated by the PLC modulator and becomes analogue signals. Then the signals are coupled to the power line through the coupler. The system uses a 'PLC to VLC' module in the LED illumination fixture to receive the coupled signal from the power line, as shown in Fig. 8. After signal amplification, this module adds the data signal to the direct current (DC) bias of LED by driving the LED lamps, and acts as an optical transmitter to cover the indoor area. All the LED lamps connected to the same power adapter transmit the same data. In this way, the broadcasting network could be homogeneous and simplified as an SFN, which could well solve the problem above. For the LED lamps connected to different power adapters, the transmitted signal could be different for various services and better signal coverage.

FIGURE 7

System models of proposed schemes based on PLC and VLC

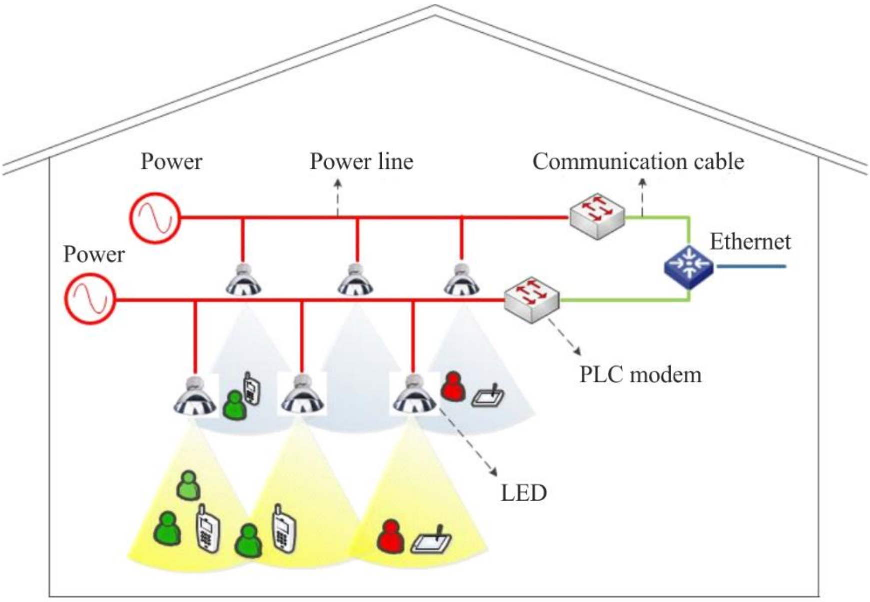

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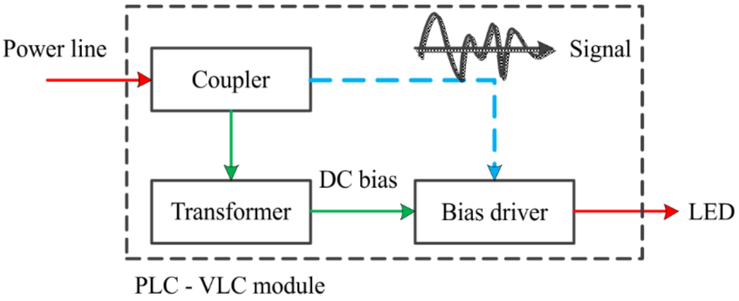
FIGURE 8

Block diagram of 'PLC to VLC' module



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2 Demonstration implementation and evaluation

2.1 Demonstration setup

In the laboratory environment, a demonstration is built and its feasibility is shown through experiments, as shown in Fig. 9. The video data are encoded, modulated and coupled to the power line in the PLC modulator. In the 'PLC to VLC' module, the signal is added to the DC offset to drive the LED lamp, which is the key component of the integrated system. The signal is detected in the avalanche photo diode (APD), then demodulated and decoded at the receiver. To evaluate the interference of the LED lamps, two LED lamps were used to construct a simplest SFN, as described in Fig. 10.

This composition of whole system is quite simple and does not require new installation of communication wiring. After the basic communication modules of the system, such as PLC modulator, 'PLC to VLC' module and the receiver being plugged in, the system will start to work without too much modification of the existing infrastructures. In fact, such modules can be small enough to be easily installed for commercializing. From implementing the system in real-life, some key parameters, such as the system operating point, the modulation depth and the sensitivity of the optical detector, should be rationally chosen. The key parameters are listed in Table 1 for illustration. All the hardware except the optical detector is designed as shown in Figs 11 to 13.

FIGURE 9

Demonstration setup of the broadcasting system in the laboratory environment

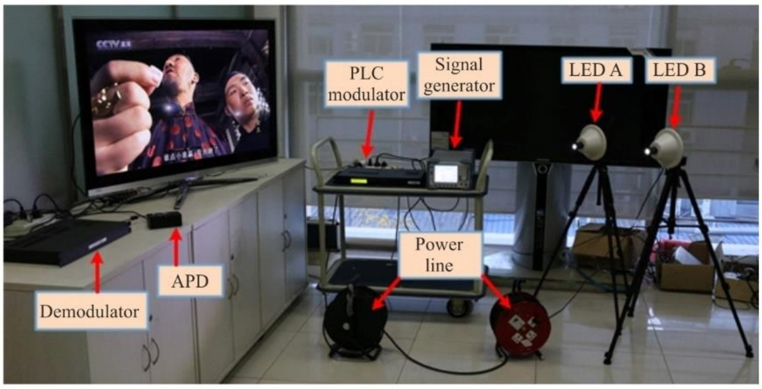

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FIGURE 10

Block diagram of the demonstration

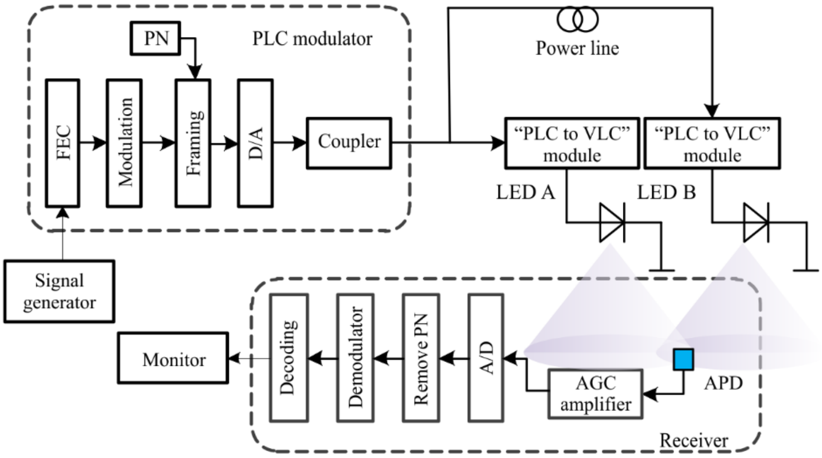

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FIGURE 11

LED lamp and ‘PLC to VLC’ module

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FIGURE 12

PLC modulator

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FIGURE 13

Demodulator in the receiver

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TABLE 1

Demonstration configurations

Index	**Value**
Input voltage (V)	3.8
Operating current (A)	0.26
Illuminance at the APD (lx)	300
Half-intensity beam angle (degrees)	30
Modulation depth (percentage)	15
Photo sensitivity (A/W)	0.42
Distance between the LED lamp and receiver (m)	3

2.2 Performance evaluation

A high-definition TV programme is modulated by the time domain OFDM (TDS-OFDM), and then transmitted in the hybrid system to evaluate its performance. The mode (16QAM, Multi-carrier, PN420, FEC 0.6, TI720) was used for the test.

The system bandwidth is 8 MHz. The point-to-point system (with one LED lamp on) can still work well with the visible light path up to 8 metres when there is the interference from the normal indoor lighting devices and provide a raw date rate up to 48 Mbit/s within 8 MHz bandwidth when 64QAM is used.

For the two LED lamps, LED A is connected directly to the PLC modulator and LED B is connected to the modulator via a section of power line. The receiver which contains the APD is placed with an equal distance of 3 metres[2] away from the two LED lamps to imitate the case that the receiver is located in the overlapping area or roaming between different LED lamps. In order to evaluate the system performance under different multipath propagations, the length of power line connected to the LED B and the power of the transmitted signal from LED B are set to different values (the power of the transmitted signal from LED A is fixed) in our demonstration configurations. The evaluation configurations are provided in Table 2.

TABLE 2

Evaluation configurations

Power line length	**0 dB**	**3 dB**	**6 dB**
100 m	Case 1	Case 2	Case 3
200 m	Case 4	Case 5	Case 6

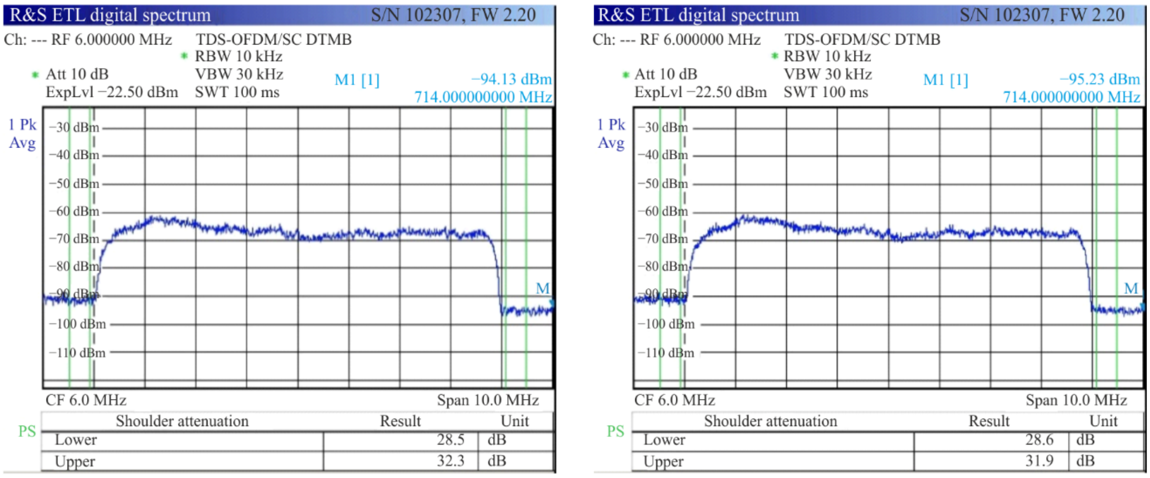
The spectrum of the received signal as well as the multipath channel of the whole system were also measured, as shown in Figs 14 to 17. It can be seen from Figs 16 and 17 in the proposed scheme that the multipath effect will cause channel frequency selectivity.

---

[2] Here, the communication distance of the VLC part is set to be 3 metres because 3 m is the typical height of the ceilings in many indoor scenarios.

FIGURE 14

Spectrum of the received signal only from LED A (Cases 1 to 6)



Ch: --- RF 6.000000 MHz TDS-OFDM/SC DTMB
RBW 10 kHz
Att 10 dB VBW 30 kHz
ExpLvl −22.50 dBm SWT 100 ms
M1 [1] −94.13 dBm 714.000000000 MHz
CF 6.0 MHz Span 10.0 MHz

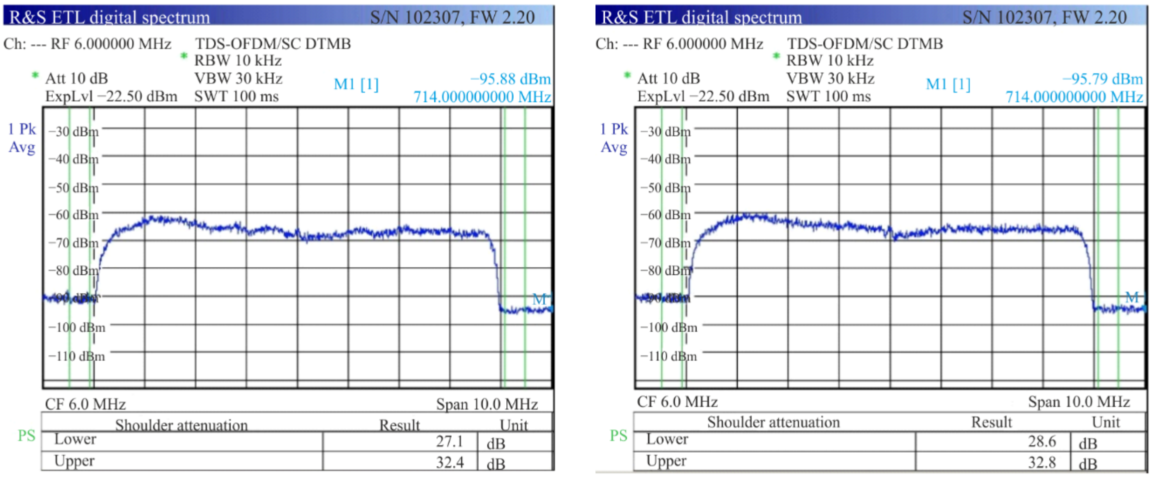
Shoulder attenuation	Result	Unit
Lower	28.5	dB
Upper	32.3	dB

Case 1

Ch: --- RF 6.000000 MHz TDS-OFDM/SC DTMB
RBW 10 kHz
Att 10 dB VBW 30 kHz
ExpLvl −22.50 dBm SWT 100 ms
M1 [1] −95.23 dBm 714.000000000 MHz
CF 6.0 MHz Span 10.0 MHz

Shoulder attenuation	Result	Unit
Lower	28.6	dB
Upper	31.9	dB

Case 2



Ch: --- RF 6.000000 MHz TDS-OFDM/SC DTMB
RBW 10 kHz
Att 10 dB VBW 30 kHz
ExpLvl −22.50 dBm SWT 100 ms
M1 [1] −95.88 dBm 714.000000000 MHz
CF 6.0 MHz Span 10.0 MHz

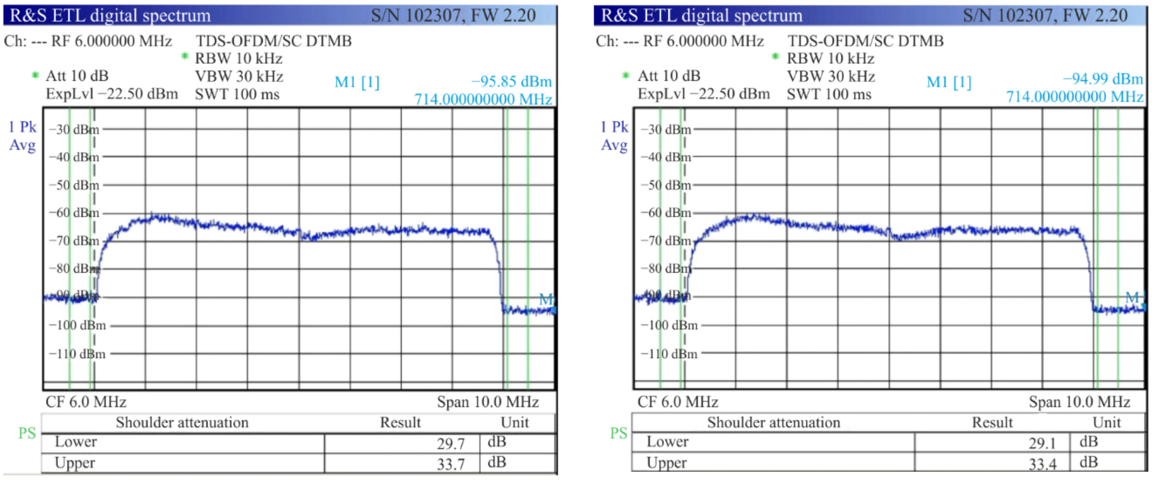
Shoulder attenuation	Result	Unit
Lower	27.1	dB
Upper	32.4	dB

Case 3

Ch: --- RF 6.000000 MHz TDS-OFDM/SC DTMB
RBW 10 kHz
Att 10 dB VBW 30 kHz
ExpLvl −22.50 dBm SWT 100 ms
M1 [1] −95.79 dBm 714.000000000 MHz
CF 6.0 MHz Span 10.0 MHz

Shoulder attenuation	Result	Unit
Lower	28.6	dB
Upper	32.8	dB

Case 4



Ch: --- RF 6.000000 MHz TDS-OFDM/SC DTMB
RBW 10 kHz
Att 10 dB VBW 30 kHz
ExpLvl −22.50 dBm SWT 100 ms
M1 [1] −95.85 dBm 714.000000000 MHz
CF 6.0 MHz Span 10.0 MHz

Shoulder attenuation	Result	Unit
Lower	29.7	dB
Upper	33.7	dB

Case 5

Ch: --- RF 6.000000 MHz TDS-OFDM/SC DTMB
RBW 10 kHz
Att 10 dB VBW 30 kHz
ExpLvl −22.50 dBm SWT 100 ms
M1 [1] −94.99 dBm 714.000000000 MHz
CF 6.0 MHz Span 10.0 MHz

Shoulder attenuation	Result	Unit
Lower	29.1	dB
Upper	33.4	dB

Case 6

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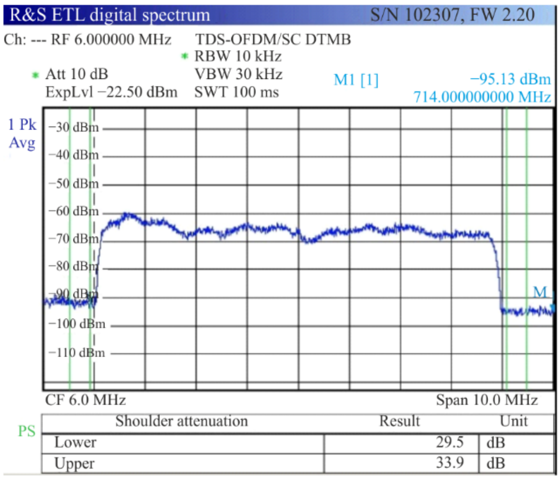
FIGURE 15

Spectrum of the received signal only from LED B (Cases 1 to 6)


R&S ETL digital spectrum S/N 102307, FW 2.20

Ch: --- RF 6.000000 MHz TDS-OFDM/SC DTMB

RBW 10 kHz

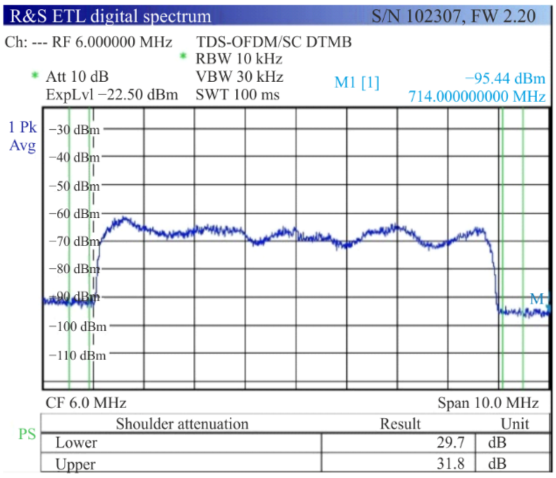
Att 10 dB VBW 30 kHz

ExpLvl −22.50 dBm SWT 100 ms

M1 [1] −95.13 dBm 714.000000000 MHz

Shoulder attenuation	Result	Unit
Lower	29.5	dB
Upper	33.9	dB

Case 1


R&S ETL digital spectrum S/N 102307, FW 2.20

Ch: --- RF 6.000000 MHz TDS-OFDM/SC DTMB

RBW 10 kHz

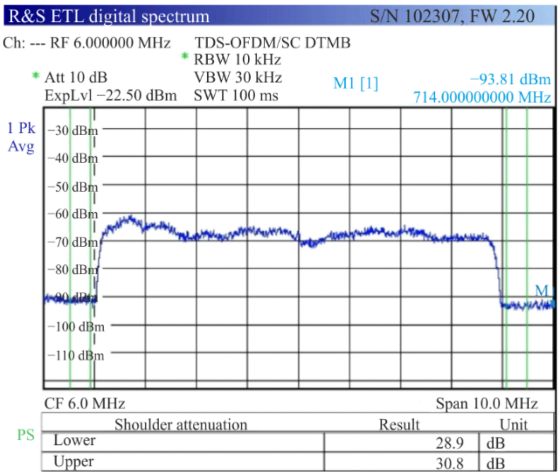
Att 10 dB VBW 30 kHz

ExpLvl −22.50 dBm SWT 100 ms

M1 [1] −95.44 dBm 714.000000000 MHz

Shoulder attenuation	Result	Unit
Lower	29.7	dB
Upper	31.8	dB

Case 2


R&S ETL digital spectrum S/N 102307, FW 2.20

Ch: --- RF 6.000000 MHz TDS-OFDM/SC DTMB

RBW 10 kHz

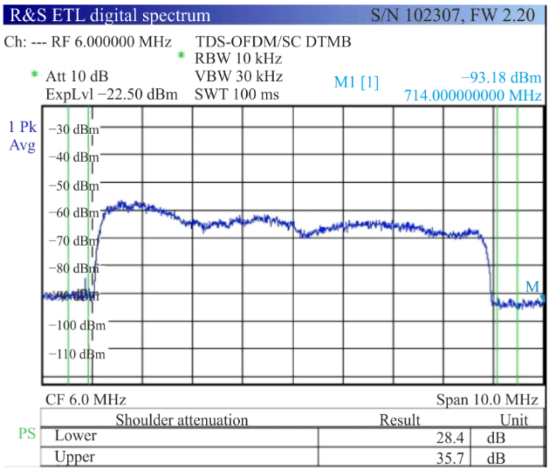
Att 10 dB VBW 30 kHz

ExpLvl −22.50 dBm SWT 100 ms

M1 [1] −93.81 dBm 714.000000000 MHz

Shoulder attenuation	Result	Unit
Lower	28.9	dB
Upper	30.8	dB

Case 3


R&S ETL digital spectrum S/N 102307, FW 2.20

Ch: --- RF 6.000000 MHz TDS-OFDM/SC DTMB

RBW 10 kHz

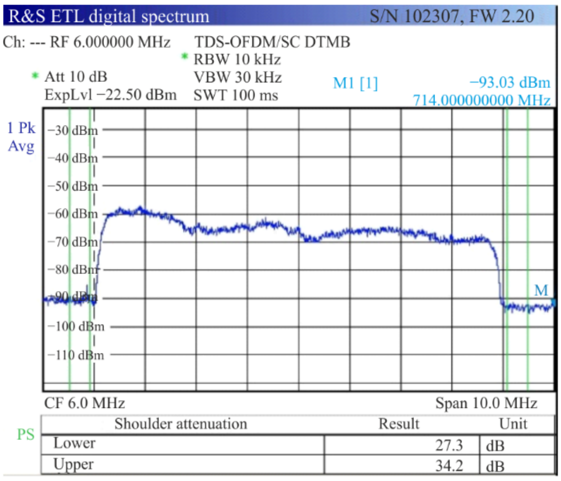
Att 10 dB VBW 30 kHz

ExpLvl −22.50 dBm SWT 100 ms

M1 [1] −93.18 dBm 714.000000000 MHz

Shoulder attenuation	Result	Unit
Lower	28.4	dB
Upper	35.7	dB

Case 4


R&S ETL digital spectrum S/N 102307, FW 2.20

Ch: --- RF 6.000000 MHz TDS-OFDM/SC DTMB

RBW 10 kHz

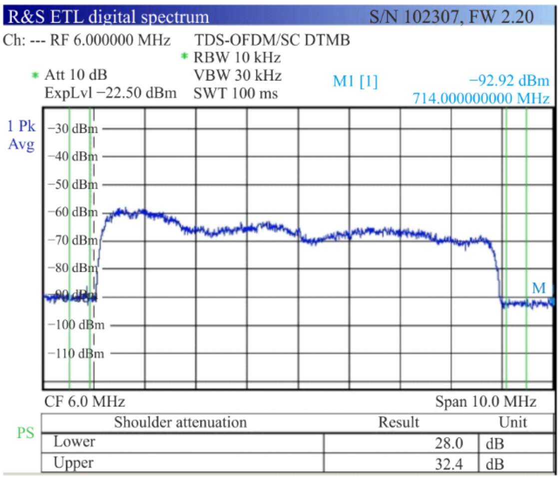
Att 10 dB VBW 30 kHz

ExpLvl −22.50 dBm SWT 100 ms

M1 [1] −93.03 dBm 714.000000000 MHz

Shoulder attenuation	Result	Unit
Lower	27.3	dB
Upper	34.2	dB

Case 5


R&S ETL digital spectrum S/N 102307, FW 2.20

Ch: --- RF 6.000000 MHz TDS-OFDM/SC DTMB

RBW 10 kHz

Att 10 dB VBW 30 kHz

ExpLvl −22.50 dBm SWT 100 ms

M1 [1] −92.92 dBm 714.000000000 MHz

Shoulder attenuation	Result	Unit
Lower	28.0	dB
Upper	32.4	dB

Case 6

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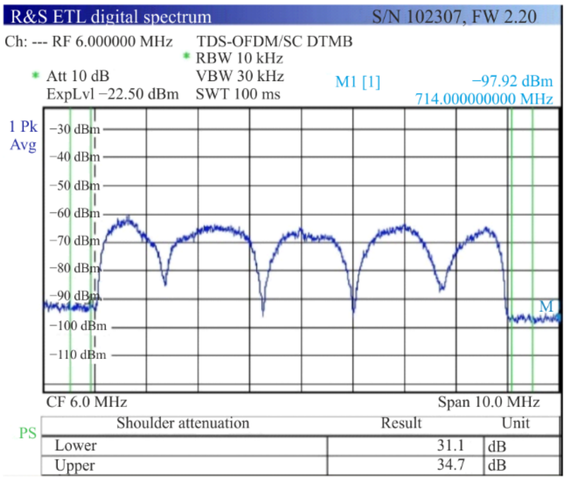
FIGURE 16

Spectrum of the received signal when the power of the transmitted signal from LED B is equal to that from LED A (Cases 1 to 6)

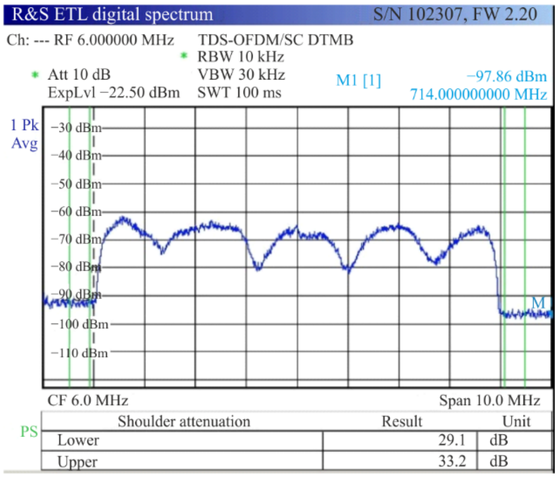

R&S ETL digital spectrum S/N 102307, FW 2.20

Ch: --- RF 6.000000 MHz TDS-OFDM/SC DTMB
* RBW 10 kHz
* Att 10 dB VBW 30 kHz M1 [1] −97.92 dBm
ExpLvl −22.50 dBm SWT 100 ms 714.000000000 MHz

CF 6.0 MHz Span 10.0 MHz

Shoulder attenuation	Result	Unit
Lower	31.1	dB
Upper	34.7	dB

Case 1

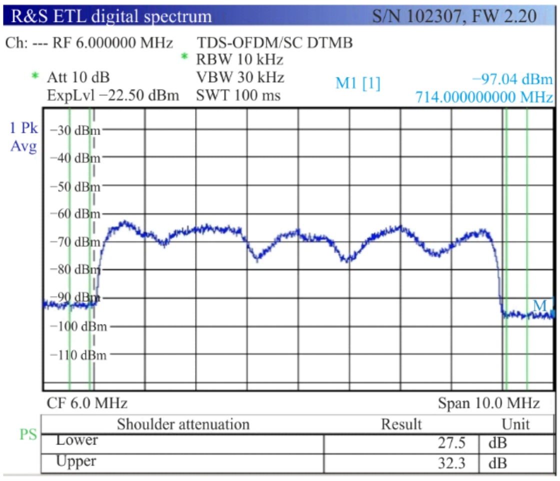

R&S ETL digital spectrum S/N 102307, FW 2.20

Ch: --- RF 6.000000 MHz TDS-OFDM/SC DTMB
* RBW 10 kHz
* Att 10 dB VBW 30 kHz M1 [1] −97.86 dBm
ExpLvl −22.50 dBm SWT 100 ms 714.000000000 MHz

CF 6.0 MHz Span 10.0 MHz

Shoulder attenuation	Result	Unit
Lower	29.1	dB
Upper	33.2	dB

Case 2

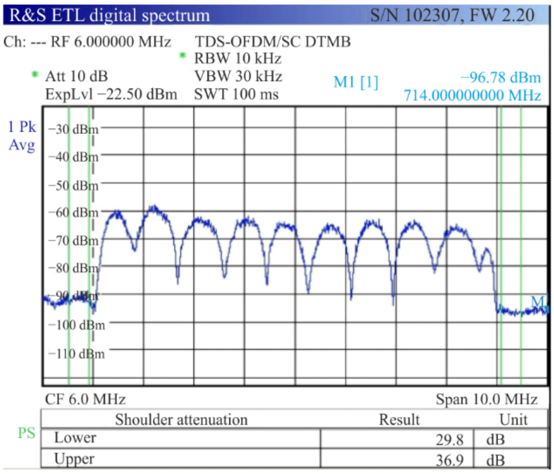

R&S ETL digital spectrum S/N 102307, FW 2.20

Ch: --- RF 6.000000 MHz TDS-OFDM/SC DTMB
* RBW 10 kHz
* Att 10 dB VBW 30 kHz M1 [1] −97.04 dBm
ExpLvl −22.50 dBm SWT 100 ms 714.000000000 MHz

CF 6.0 MHz Span 10.0 MHz

Shoulder attenuation	Result	Unit
Lower	27.5	dB
Upper	32.3	dB

Case 3

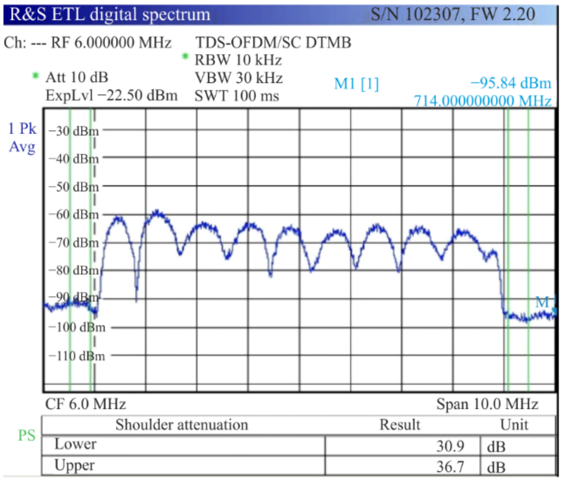

R&S ETL digital spectrum S/N 102307, FW 2.20

Ch: --- RF 6.000000 MHz TDS-OFDM/SC DTMB
* RBW 10 kHz
* Att 10 dB VBW 30 kHz M1 [1] −96.78 dBm
ExpLvl −22.50 dBm SWT 100 ms 714.000000000 MHz

CF 6.0 MHz Span 10.0 MHz

Shoulder attenuation	Result	Unit
Lower	29.8	dB
Upper	36.9	dB

Case 4

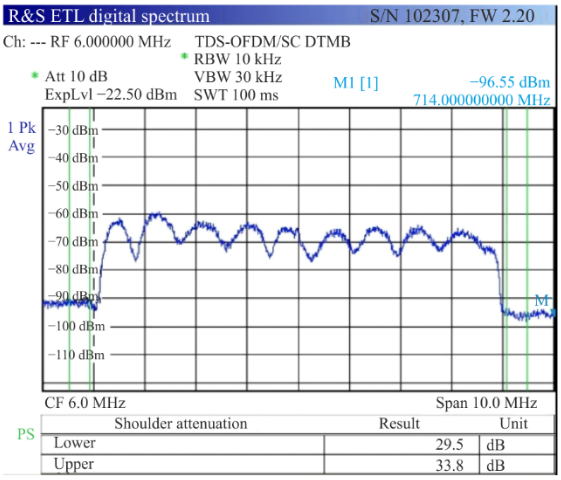

R&S ETL digital spectrum S/N 102307, FW 2.20

Ch: --- RF 6.000000 MHz TDS-OFDM/SC DTMB
* RBW 10 kHz
* Att 10 dB VBW 30 kHz M1 [1] −95.84 dBm
ExpLvl −22.50 dBm SWT 100 ms 714.000000000 MHz

CF 6.0 MHz Span 10.0 MHz

Shoulder attenuation	Result	Unit
Lower	30.9	dB
Upper	36.7	dB

Case 5


R&S ETL digital spectrum S/N 102307, FW 2.20

Ch: --- RF 6.000000 MHz TDS-OFDM/SC DTMB
* RBW 10 kHz
* Att 10 dB VBW 30 kHz M1 [1] −96.55 dBm
ExpLvl −22.50 dBm SWT 100 ms 714.000000000 MHz

CF 6.0 MHz Span 10.0 MHz

Shoulder attenuation	Result	Unit
Lower	29.5	dB
Upper	33.8	dB

Case 6

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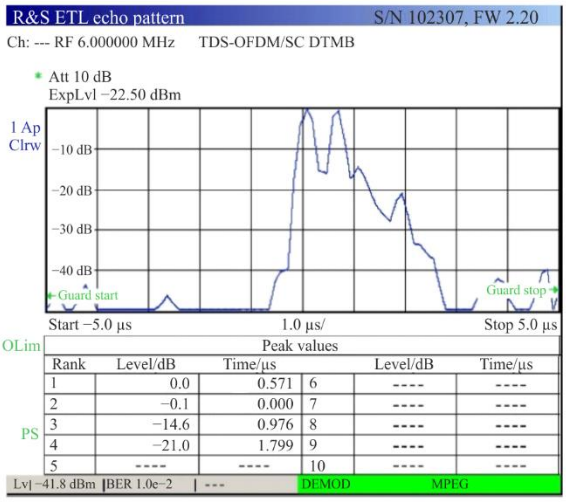
FIGURE 17

Measurement of the multipath channel of the whole system (Cases 1 to 6)



R&S ETL echo pattern S/N 102307, FW 2.20

Ch: --- RF 6.000000 MHz TDS-OFDM/SC DTMB

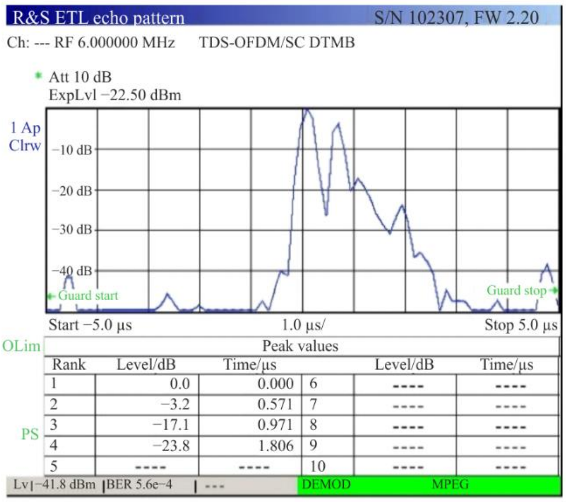
Att 10 dB
ExpLvl −22.50 dBm

Peak values

Rank	Level/dB	Time/µs		Level/dB	Time/µs
1	0.0	0.571	6	----	----
2	−0.1	0.000	7	----	----
3	−14.6	0.976	8	----	----
4	−21.0	1.799	9	----	----
5	----	----	10	----	----

Lv|−41.8 dBm |BER 1.0e−2 | --- DEMOD MPEG

Case 1



R&S ETL echo pattern S/N 102307, FW 2.20

Ch: --- RF 6.000000 MHz TDS-OFDM/SC DTMB

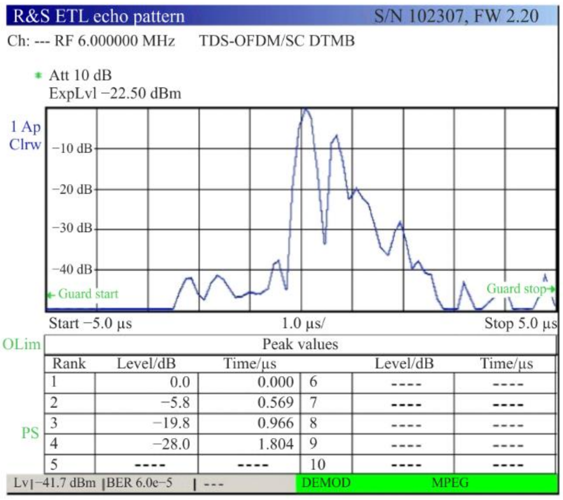
Att 10 dB
ExpLvl −22.50 dBm

Peak values

Rank	Level/dB	Time/µs		Level/dB	Time/µs
1	0.0	0.000	6	----	----
2	−3.2	0.571	7	----	----
3	−17.1	0.971	8	----	----
4	−23.8	1.806	9	----	----
5	----	----	10	----	----

Lv|−41.8 dBm |BER 5.6e−4 | --- DEMOD MPEG

Case 2



R&S ETL echo pattern S/N 102307, FW 2.20

Ch: --- RF 6.000000 MHz TDS-OFDM/SC DTMB

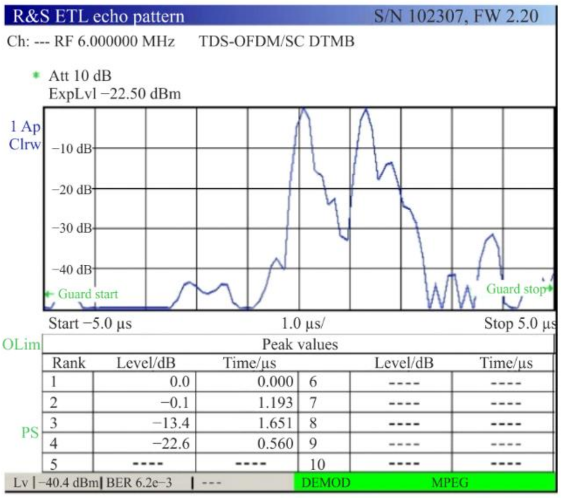
Att 10 dB
ExpLvl −22.50 dBm

Peak values

Rank	Level/dB	Time/µs		Level/dB	Time/µs
1	0.0	0.000	6	----	----
2	−5.8	0.569	7	----	----
3	−19.8	0.966	8	----	----
4	−28.0	1.804	9	----	----
5	----	----	10	----	----

Lv|−41.7 dBm |BER 6.0e−5 | --- DEMOD MPEG

Case 3



R&S ETL echo pattern S/N 102307, FW 2.20

Ch: --- RF 6.000000 MHz TDS-OFDM/SC DTMB

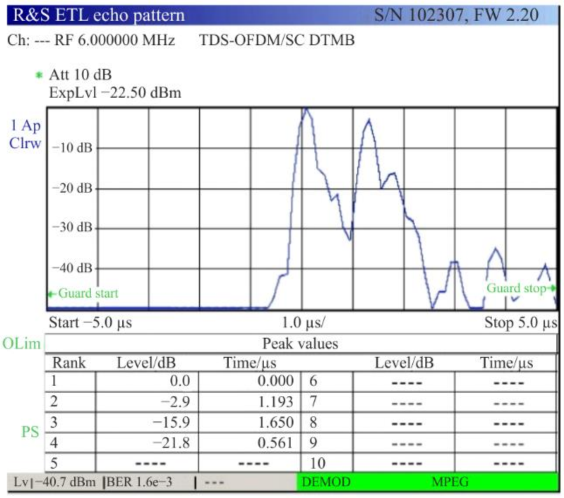
Att 10 dB
ExpLvl −22.50 dBm

Peak values

Rank	Level/dB	Time/µs		Level/dB	Time/µs
1	0.0	0.000	6	----	----
2	−0.1	1.193	7	----	----
3	−13.4	1.651	8	----	----
4	−22.6	0.560	9	----	----
5	----	----	10	----	----

Lv |−40.4 dBm| BER 6.2e−3 | --- DEMOD MPEG

Case 4



R&S ETL echo pattern S/N 102307, FW 2.20

Ch: --- RF 6.000000 MHz TDS-OFDM/SC DTMB

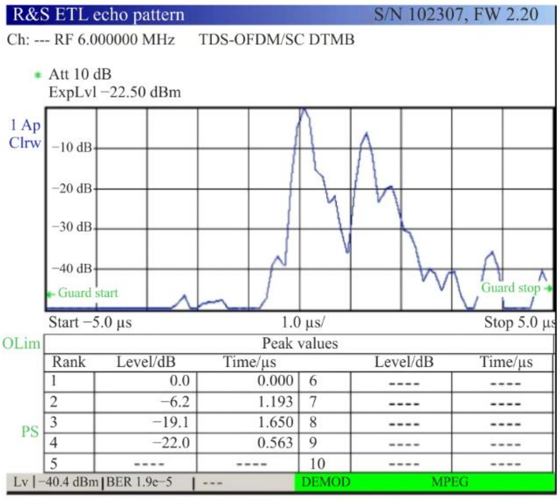
Att 10 dB
ExpLvl −22.50 dBm

Peak values

Rank	Level/dB	Time/µs		Level/dB	Time/µs
1	0.0	0.000	6	----	----
2	−2.9	1.193	7	----	----
3	−15.9	1.650	8	----	----
4	−21.8	0.561	9	----	----
5	----	----	10	----	----

Lv|−40.7 dBm |BER 1.6e−3 | --- DEMOD MPEG

Case 5



R&S ETL echo pattern S/N 102307, FW 2.20

Ch: --- RF 6.000000 MHz TDS-OFDM/SC DTMB

Att 10 dB
ExpLvl −22.50 dBm

Peak values

Rank	Level/dB	Time/µs		Level/dB	Time/µs
1	0.0	0.000	6	----	----
2	−6.2	1.193	7	----	----
3	−19.1	1.650	8	----	----
4	−22.0	0.563	9	----	----
5	----	----	10	----	----

Lv |−40.4 dBm|BER 1.9e−5 | --- DEMOD MPEG

Case 6

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Furthermore, the modulation error ratio (MER), a common parameter to quantify the communication link quality, is used to evaluate the demo, which is defined as below.

$$MER = 10\log_{10}\frac{\sum\left[(I_j-\hat{I}_j)^2+(Q_j-\hat{Q}_j)^2\right]}{\sum(\hat{I}_j^2+\hat{Q}_j^2)}$$

where:

I_j : real component of the ideal *j*-th symbol

Q_j : imaginary component of the ideal *j*-th symbol

$\hat{I}_j$: real component of the received *j*-th symbol

$\hat{Q}_j$: imaginary component of the received *j*-th symbol.

The MER represents the signal-to-ratio quality per symbol, and higher MER ensure the probability of successful demodulation for the system. As shown in Table 3, the MER is proportional to the power line length and inversely proportional to the power of the transmitted signal from LED B. It can be explained by that the interference will be less as the delay of the secondary path becomes larger or the power of it reduces. The constellation diagrams of the received signals are measured for the 16QAM mode, diagram of LEDA, LEDB and LEDA+LEDB for cases 1 to 6 as shown in Figs 18 to 22.

TABLE 3

Measured MERs

Case 1	**Case 2**	**Case 3**	**Case 4**	**Case 5**	**Case 6**
20.0 dB	22.8 dB	24.4 dB	20.8 dB	22.4 dB	24.4 dB

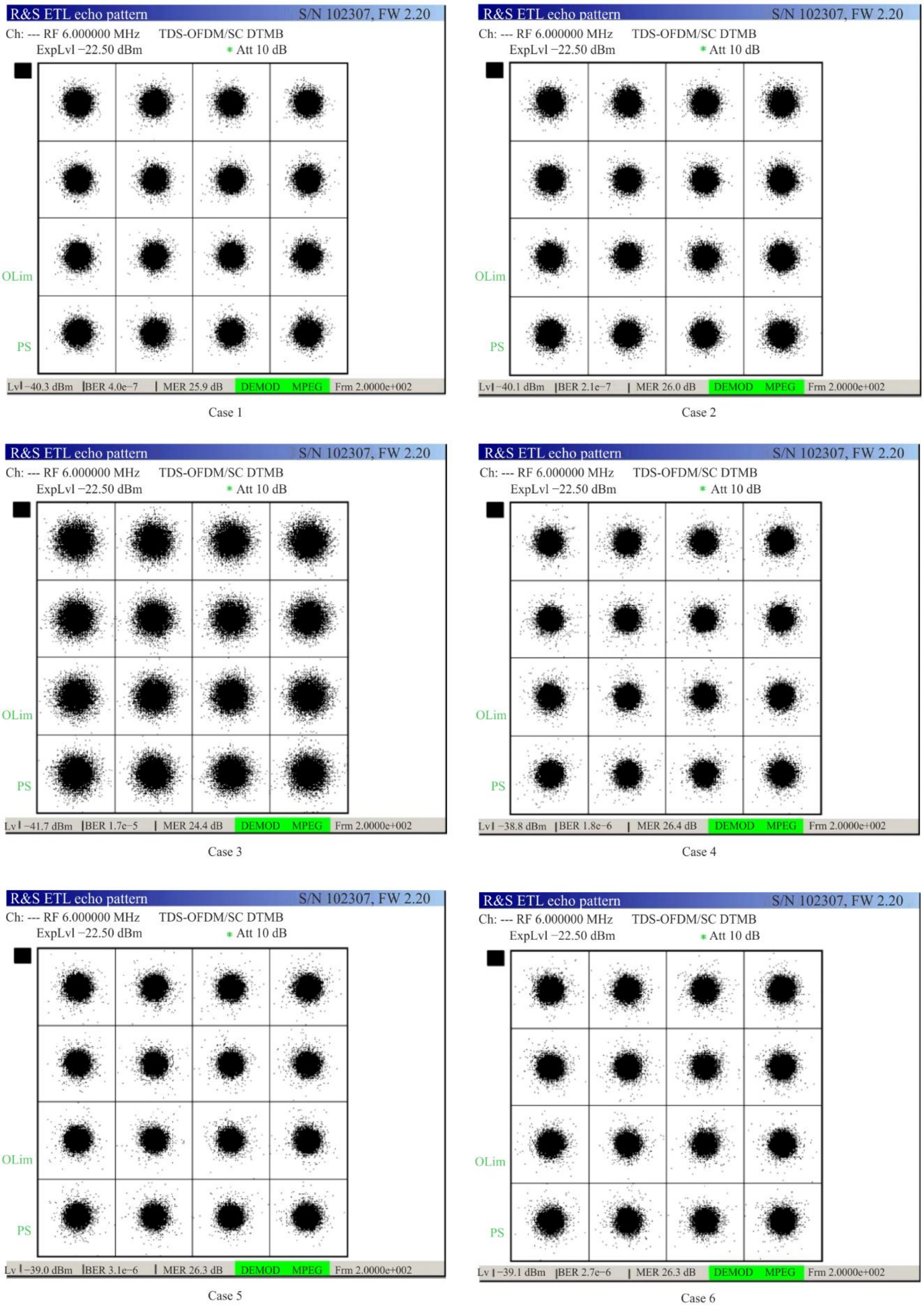
3 Future work

The next step for the demonstration is to try higher order constellation mapping and wider band occupation to fully utilize the system potential. The integrated system was implemented with the raw data rate of 192 Mbit/s in a 24 MHz bandwidth when 256APSK is used. At the same time, some efficient techniques such as the Gray amplitude phase shift keying (APSK) constellation, the appropriate channel coding, MIMO and the relays, will be adopted as the system options to enhance the robustness and throughputs of the system and satisfy different quality of services. Moreover, the handover or switching protocols for the other schemes will be investigated.

The implementation has also started on a low data rate integrated VLC and PLC communication by utilizing the commercial camera of the mobile phones.

FIGURE 18

Measured constellation diagram of the received signals for LEDA (Cases 1 to 6)



R&S ETL echo pattern S/N 102307, FW 2.20
Ch: --- RF 6.000000 MHz TDS-OFDM/SC DTMB
ExpLvl −22.50 dBm Att 10 dB
Lvl −40.3 dBm BER 4.0e−7 MER 25.9 dB DEMOD MPEG Frm 2.0000e+002

Case 1

R&S ETL echo pattern S/N 102307, FW 2.20
Ch: --- RF 6.000000 MHz TDS-OFDM/SC DTMB
ExpLvl −22.50 dBm Att 10 dB
Lvl −40.1 dBm BER 2.1e−7 MER 26.0 dB DEMOD MPEG Frm 2.0000e+002

Case 2

R&S ETL echo pattern S/N 102307, FW 2.20
Ch: --- RF 6.000000 MHz TDS-OFDM/SC DTMB
ExpLvl −22.50 dBm Att 10 dB
Lvl −41.7 dBm BER 1.7e−5 MER 24.4 dB DEMOD MPEG Frm 2.0000e+002

Case 3

R&S ETL echo pattern S/N 102307, FW 2.20
Ch: --- RF 6.000000 MHz TDS-OFDM/SC DTMB
ExpLvl −22.50 dBm Att 10 dB
Lvl −38.8 dBm BER 1.8e−6 MER 26.4 dB DEMOD MPEG Frm 2.0000e+002

Case 4

R&S ETL echo pattern S/N 102307, FW 2.20
Ch: --- RF 6.000000 MHz TDS-OFDM/SC DTMB
ExpLvl −22.50 dBm Att 10 dB
Lvl −39.0 dBm BER 3.1e−6 MER 26.3 dB DEMOD MPEG Frm 2.0000e+002

Case 5

R&S ETL echo pattern S/N 102307, FW 2.20
Ch: --- RF 6.000000 MHz TDS-OFDM/SC DTMB
ExpLvl −22.50 dBm Att 10 dB
Lvl −39.1 dBm BER 2.7e−6 MER 26.3 dB DEMOD MPEG Frm 2.0000e+002

Case 6

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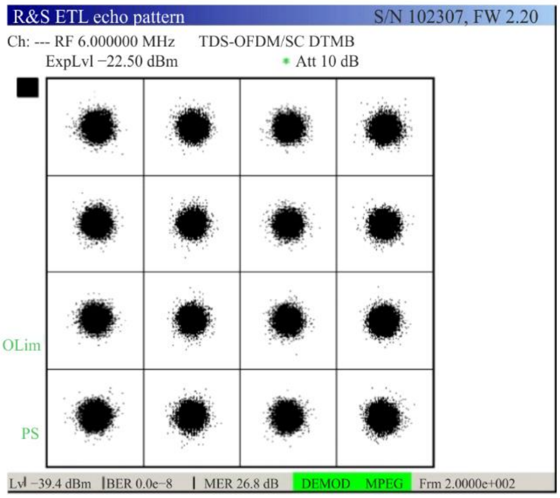
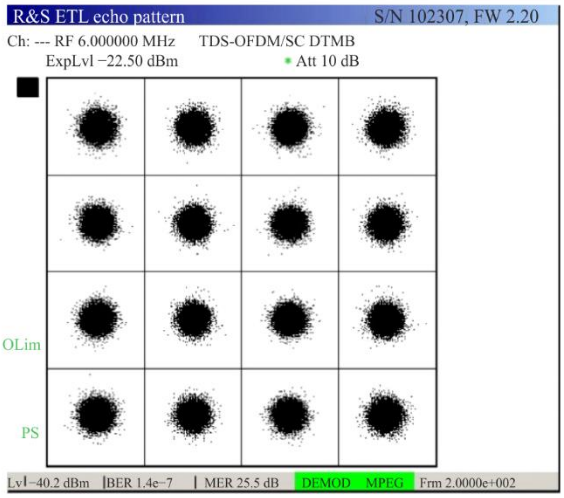
FIGURE 19

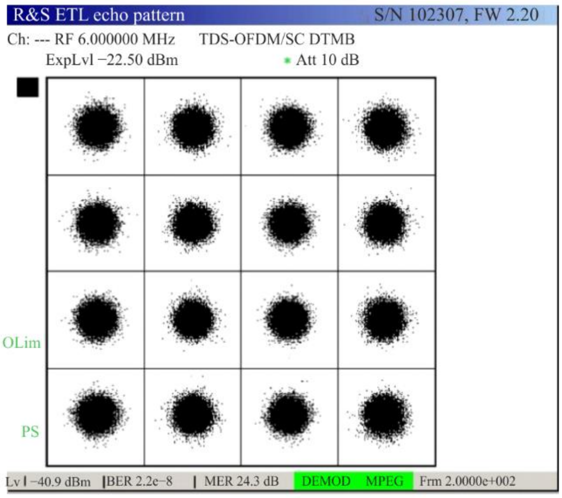
Measured constellation diagram of the received signals for LEDB (Cases 1 to 6)


R&S ETL echo pattern S/N 102307, FW 2.20
Ch: --- RF 6.000000 MHz TDS-OFDM/SC DTMB
ExpLvl −22.50 dBm Att 10 dB
Lvl −39.4 dBm | BER 0.0e−8 | MER 26.8 dB DEMOD MPEG Frm 2.0000e+002

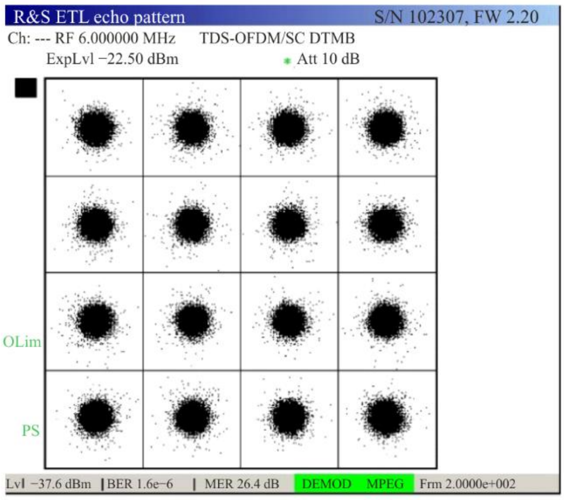
Case 1


R&S ETL echo pattern S/N 102307, FW 2.20
Ch: --- RF 6.000000 MHz TDS-OFDM/SC DTMB
ExpLvl −22.50 dBm Att 10 dB
Lvl −40.2 dBm | BER 1.4e−7 | MER 25.5 dB DEMOD MPEG Frm 2.0000e+002

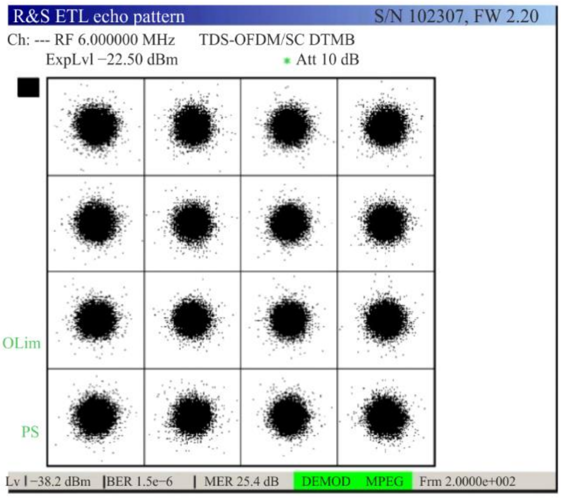
Case 2


R&S ETL echo pattern S/N 102307, FW 2.20
Ch: --- RF 6.000000 MHz TDS-OFDM/SC DTMB
ExpLvl −22.50 dBm Att 10 dB
Lvl −40.9 dBm | BER 2.2e−8 | MER 24.3 dB DEMOD MPEG Frm 2.0000e+002

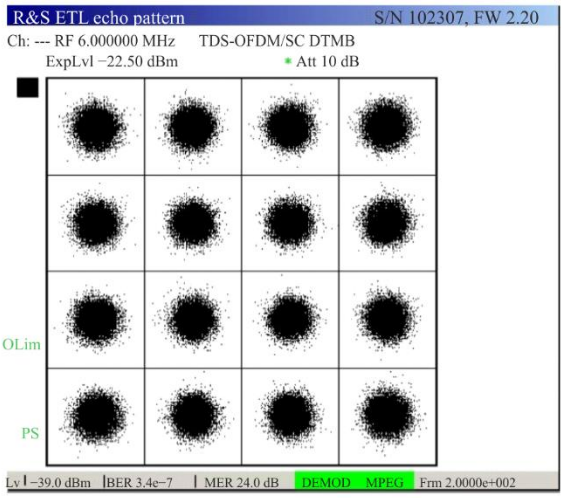
Case 3


R&S ETL echo pattern S/N 102307, FW 2.20
Ch: --- RF 6.000000 MHz TDS-OFDM/SC DTMB
ExpLvl −22.50 dBm Att 10 dB
Lvl −37.6 dBm | BER 1.6e−6 | MER 26.4 dB DEMOD MPEG Frm 2.0000e+002

Case 4


R&S ETL echo pattern S/N 102307, FW 2.20
Ch: --- RF 6.000000 MHz TDS-OFDM/SC DTMB
ExpLvl −22.50 dBm Att 10 dB
Lvl −38.2 dBm | BER 1.5e−6 | MER 25.4 dB DEMOD MPEG Frm 2.0000e+002

Case 5


R&S ETL echo pattern S/N 102307, FW 2.20
Ch: --- RF 6.000000 MHz TDS-OFDM/SC DTMB
ExpLvl −22.50 dBm Att 10 dB
Lvl −39.0 dBm | BER 3.4e−7 | MER 24.0 dB DEMOD MPEG Frm 2.0000e+002

Case 6

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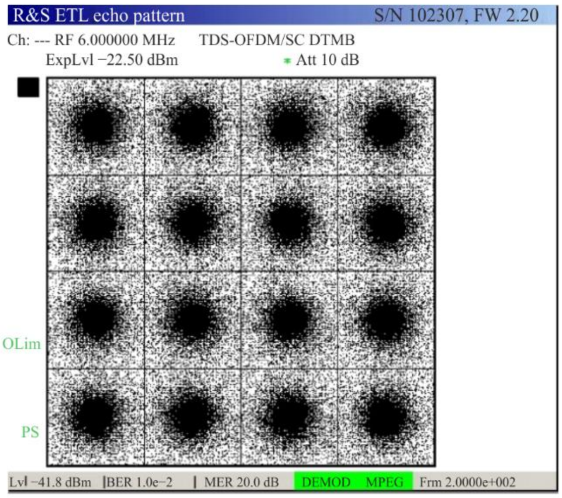
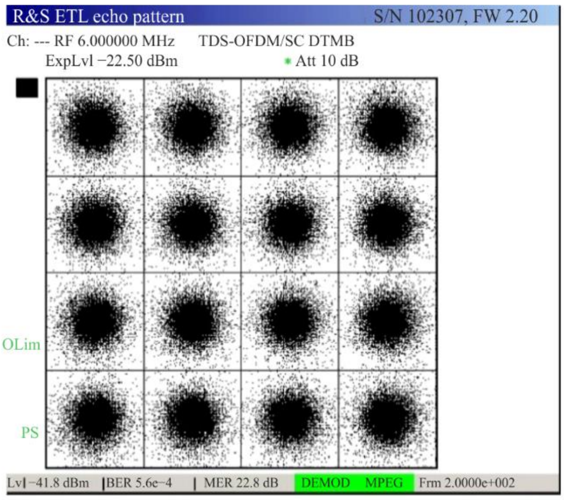
FIGURE 20

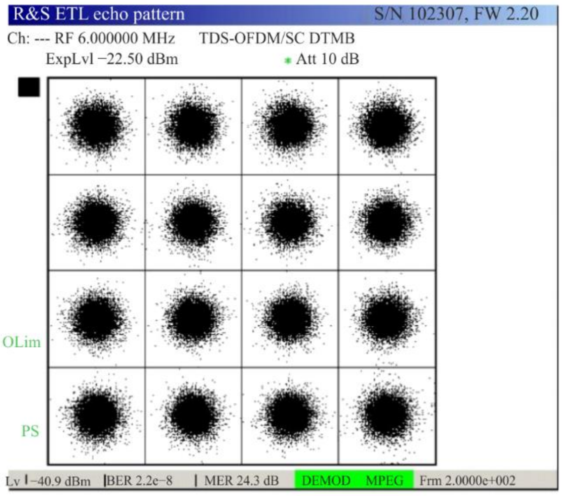
Measured constellation diagram of the received signals for the 64QAM mode (Cases 1 to 6)


R&S ETL echo pattern S/N 102307, FW 2.20
Ch: --- RF 6.000000 MHz TDS-OFDM/SC DTMB
ExpLvl −22.50 dBm Att 10 dB
Lvl −41.8 dBm BER 1.0e−2 MER 20.0 dB DEMOD MPEG Frm 2.0000e+002

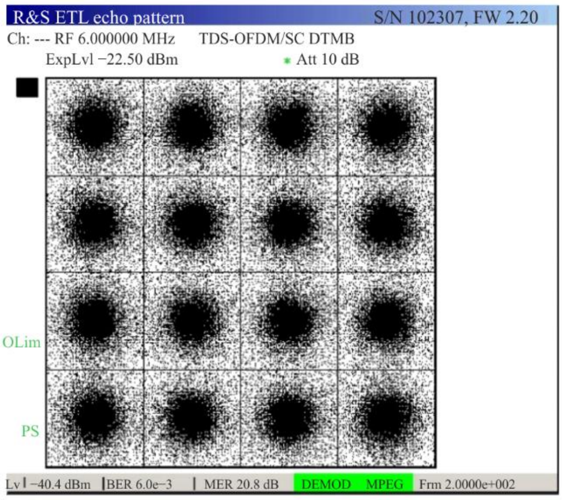
Case 1


R&S ETL echo pattern S/N 102307, FW 2.20
Ch: --- RF 6.000000 MHz TDS-OFDM/SC DTMB
ExpLvl −22.50 dBm Att 10 dB
Lvl −41.8 dBm BER 5.6e−4 MER 22.8 dB DEMOD MPEG Frm 2.0000e+002

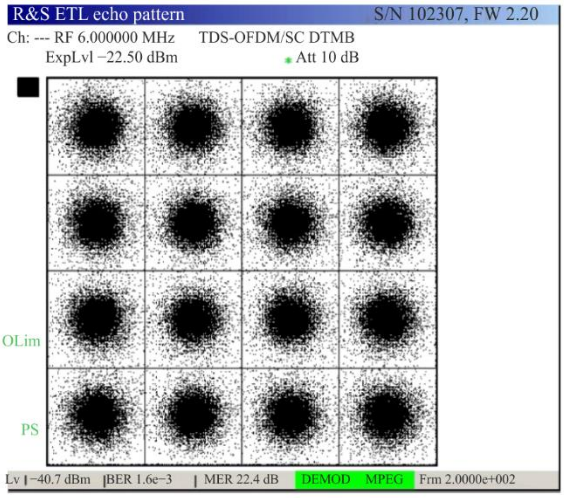
Case 2


R&S ETL echo pattern S/N 102307, FW 2.20
Ch: --- RF 6.000000 MHz TDS-OFDM/SC DTMB
ExpLvl −22.50 dBm Att 10 dB
Lvl −40.9 dBm BER 2.2e−8 MER 24.3 dB DEMOD MPEG Frm 2.0000e+002

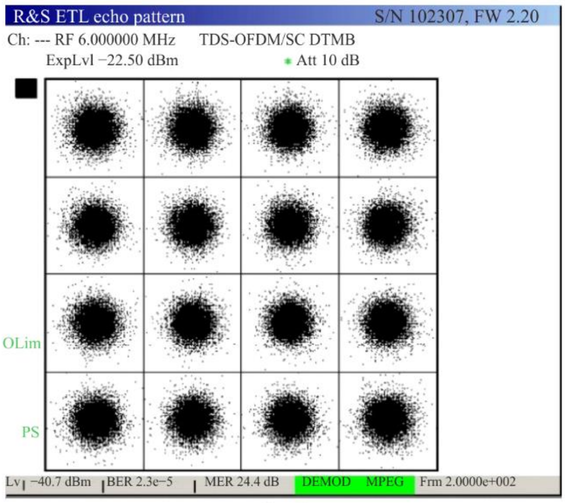
Case 3


R&S ETL echo pattern S/N 102307, FW 2.20
Ch: --- RF 6.000000 MHz TDS-OFDM/SC DTMB
ExpLvl −22.50 dBm Att 10 dB
Lvl −40.4 dBm BER 6.0e−3 MER 20.8 dB DEMOD MPEG Frm 2.0000e+002

Case 4


R&S ETL echo pattern S/N 102307, FW 2.20
Ch: --- RF 6.000000 MHz TDS-OFDM/SC DTMB
ExpLvl −22.50 dBm Att 10 dB
Lvl −40.7 dBm BER 1.6e−3 MER 22.4 dB DEMOD MPEG Frm 2.0000e+002

Case 5


R&S ETL echo pattern S/N 102307, FW 2.20
Ch: --- RF 6.000000 MHz TDS-OFDM/SC DTMB
ExpLvl −22.50 dBm Att 10 dB
Lvl −40.7 dBm BER 2.3e−5 MER 24.4 dB DEMOD MPEG Frm 2.0000e+002

Case 6

Report SM.2422-20