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25 Gbps Mobile Visible light Communication System Employing Fast Adaptation Techniques

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ABSTRACT
Visible light communication (VLC) systems have typically operated at data rates below 20 Gbps and operation at this data rate was shown to be feasible by using laser diodes (LDs), beam steering, imaging receivers and delay adaptation techniques. However, an increase in the computational cost is incurred. In this paper, we introduce fast computer generated holograms (FCGHs) to speed up the adaptation process. The new, fast and efficient fully adaptive VLC system can improve the receiver signal to noise ratio (SNR) and reduce the required time to estimate the position of the VLC receiver. In addition, an imaging receiver and a delay adaptation technique are used to reduce the effect of inter symbol interference (ISI) and multipath dispersion. Significant enhancements in the SNR, with VLC channel bandwidths of more than 36 GHz are obtained resulting in a compact impulse response and a VLC system that is able to achieve higher data rates (25 Gbps) with full mobility in the considered indoor environment.

Keywords: Beam steering, imaging receiver, fast computer generated hologram, delay adaptation technique, SNR.

1. INTRODUCTION

Traditional radio and microwave communication systems suffer from limited channel capacity due to the limited radio spectrum available, while the data rates requested by the users continue to increase exponentially. Achieving very high data rates (multi gigabits per second) using the relatively narrow bandwidth of microwave and millimetre wave systems is challenging [1]. According to a GreenTouch research study, mobile Internet traffic over this decade (2010-2020) is expected to increase by 150 times [2]. Given this expectation of dramatically growing demand for data rates, the quest is already underway for alternative spectrum bands beyond microwaves and millimetre waves. Different technology candidates have entered the race to provide ultra-fast wireless communication systems for users. Visible light communication (VLC) systems are among the promising solutions to the bandwidth limitation problem faced by microwave systems [1]. They are also considered among the potential candidates for 5G indoor systems [3].

Previous work has shown that significant enhancements in the VLC system data rates can be achieved by replacing LEDs with LDs coupled with the use of an imaging receiver instead of the conventional wide field of view (FOV) receiver [4], [5], [6]. A data rate of 10 Gbps in a realistic environment has been shown to be possible with a VLC system when a delay adaptation technique in conjunction with laser diodes and imaging receiver were used with a simple modulation format (on-off keying, OOK) and without the use of relatively complex wavelength division multiplexing approaches [4]. Significant improvements were shown to be possible when a VLC relay assisted system is combined with an imaging receiver and a delay adaptation technique [7]. However, given typical parameters, the latter system cannot provide a throughput beyond 10 Gbps due to its low signal to noise ratio (SNR). Recently, beam steering has been proposed in VLC systems to maximise the SNR at the receiver [8]. Simulation results have shown that a significant improvement in the data rate (20 Gbps for a stationary user and 14 Gbps for a mobile user) can be achieved in a mobile VLC system that employs beam steering. The improvements achieved are however at the cost of complex adaptation requirements. The complexity is associated with the computation time required to identify the optimum location to steer the beam to, as well as the time needed to generate the hologram that generates beams at the optimum angles.

The work presented in this paper aims to address the impairments of VLC systems and provide practical solutions, hence achieving data rates beyond those reported in [4]-[8]. In this paper, we report the use of holograms and beam steering in VLC systems with efficient adaptation. The data rates achieved by our proposed system, i.e. 25 Gbps for a stationary user and 22.2 Gbps for a mobile user, are the highest data rates to date for an indoor VLC system with simple modulation format (OOK) and without the use of relatively complex wavelength division multiplexing approaches, to the best of our knowledge. We introduce new fast computer generated holograms (FCGHs) for beam steering making use of simulated annealing optimisation. Recently, we proposed the use of an imaging receiver for a VLC system to provide a robust link and mitigate multipath dispersion, as well as to improve the overall system performance [4]. In this study we used an imaging receiver with selective combining (SC) to choose the best pixel. The reminder of this paper is divided into sections as follows: Section 2 introduces the VLC room setup. Section 3 presents the systems' configurations. Simulation results and discussions are presented in Section 4. Finally, conclusions are drawn in Section 5.

2. VLC ROOM SETUP

In order to study the performance of our proposed system, under mobility and multipath dispersion, consideration was given to an unoccupied rectangular room that had no furnishings, with dimensions of 4 m× 8 m × 3 m (width × length × height), similar to those considered in the previous works [4]-[8]. Experimental measurements of plaster walls have shown that they are roughly a Lambertian reflector [9]. Therefore, all the walls (including ceiling) and the floor were modelled as Lambertian reflectors with high reflectivity (reflection coefficients of 0.3 for the floor and 0.8 for the walls and ceiling). These relatively high reflectivities (within the typical range) were selected as they result in the greatest multipath dispersion (worst case scenario), and consequently considerable pulse spread. Reflections from doors and windows are considered to be the same as reflections from walls resulting in maximum pulse spread and a worse case scenario. To model the reflections, the room was divided into a number of equally sized squares with an area of dA and reflection coefficient of ρ. Each reflection element was treated as a small transmitter that transmits an attenuated version of the received signals from its centre in the same form as a Lambertian pattern with n=1, where n is the Lambertian emission order as defined in [10].

Previous research considered only LOS and reflections up to a first order [11]-[13]. However, this may not provide a full description of the characteristics of the system. Therefore, in this study reflections up to the second order were considered, since the second order reflections can have a great impact on the system performance at multi gigabits per second data rates [13]. Reflections can continue beyond second-order, however it is noted that the power received from the third-order reflections for the VLC systems is extremely low compared to LOS, first-order, and second-order reflections [7]. Therefore, for convenience, computer analysis up to second-order reflections has been considered in this study. It should be noted that reducing dA leads to improved resolution in the impulse response evaluation together with an increase in the computation time exponentially. To keep computations within practical limits, surface elements with sizes of 5 cm × 5 cm for first-order reflections and 20 cm × 20 cm for second-order reflections were used.

The room's illumination was provided by eight RGB-LD light units that were used to ensure that ISO and European standards are satisfied [14]. Each LD light unit had nine (3×3) RGB-LD. The LD lights were installed at a height of 3 m above the floor. The specifications of the RGB-LD used in this study were adapted from practical results reported in [15]. The VLC room with the coordinates of the RGB-LD light units and the physical structure of the imaging receiver are shown in Fig. 1. The height of the work desks where the transmitters and receivers associated with the user equipment were placed was 1 m. This horizontal plane was referred to as the "Communication Floor" (CF). The transmitted power from each RGB-LDs was 2 W.

The simulations and calculations reported in this paper were carried out using the MATLAB program. Our simulation tool is similar to one developed by Barry et al. [16]. In our evaluation channel characteristics, optical power received, delay spread, 3 dB channel bandwidth and SNR calculations were determined in similar ways to those used in [4]-[8], [10], [17], [18].

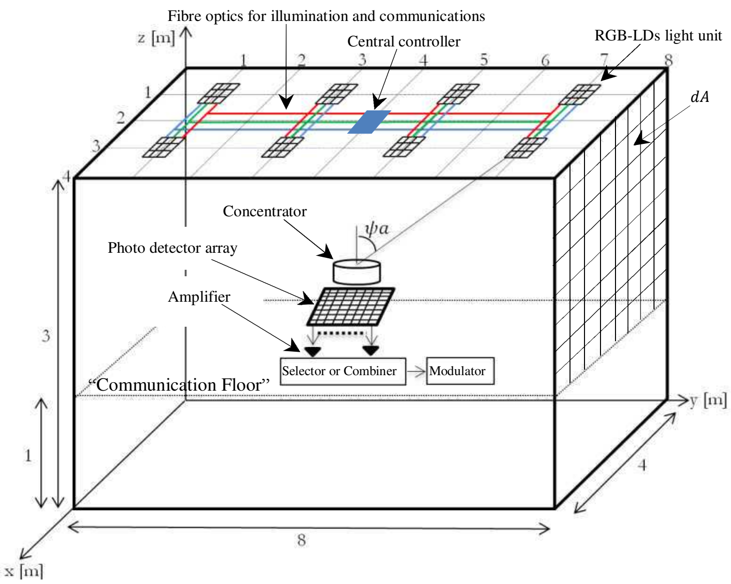


Figure 1. VLC system room and the physical structure of an imaging receiver.

3. SYSTEMS' CONFIGURATIONS

In this section, two VLC systems are presented, analysed and compared to identify the most appropriate system for use in high-speed VLC systems (25 Gbps and beyond).

3.1 Imaging LDs-VLC System

The imaging LDs-VLC system employed eight RGB-LDs transmitters (lighting fixtures) on the ceiling connected by fibre interconnect and controlled by a central controller and an imaging receiver with 50 pixels. The imaging LDs-VLC system was previously proposed in [4] and it is considered here to compare it with our new proposed VLC system.

3.2 Fully Adaptive Imaging LDs-VLC System

The recently proposed beam steering LDs-VLC system has achieved 20 Gbps for stationary user and 14 Gbps for mobile user (the time required for adaptation algorithms during mobility was 296 ms) [8]. However, high complexity is associated with the computation required to identify the optimum beam steering location. In order to solve this problem, we introduce a new FCGHs using simulated annealing to speed up the beam steering process. The holograms are pre-calculated and stored in the proposed system (each hologram is suited for a given (range of) transmitter and receiver locations) and eliminate the need to calculate a real-time hologram at each transmitter and receiver location. In this work the RGB-LDs light unit has the ability to direct part of the white light towards the receiver location to enhance the SNR when operating at high data rates. The adaptation algorithms are implemented in a certain RGB-LDs light unit for a single receiver at a given set of positions. When the receiver starts moving, they are applied in another RGB-LDs light unit according to the new receiver location (coordinates). The reduction in complexity and SNR improvement at high data rates (i.e. 25 Gbps) can be achieved according to the following algorithms:-

A. Select the best (STB)

STB algorithm is proposed to locate the closest transmitter (RGB-LDs) to the receiver to implement the fully adaptive imaging VLC system. The STB algorithm identifies the closest transmitter to the receiver according to the following steps:

1- A pilot signal is sent from one of the VLC transmitters.
2- The SNR is estimated at the receiver by pixel 1 of the imaging receiver.
3- Repeat step 2 for the other pixels in the imaging receiver.
4- Repeat steps 2 and 3 for the other VLC transmitter units.
5- The receiver sends (using an infrared beam) a low data rate control feedback signal to inform the controller of the SNRs associated with each transmitter.
6- The transmitter that yields the best SNR is chosen by the controller (typically the closest transmitter to the receiver in our simulations).

Once the receiver receives the coded signal from the RGB-LDs light unit, the SNR is computed and a feedback signal is sent. If the time taken to calculate the value of each SNR with each RGB-LDs unit is equal to 1 ms (based on typical processor speeds) then the STB algorithm training time is 8 ms (8 RGB-LDs units × 1 ms).

B. Fast computer generated holograms (FCGHs)

For a large room of 8m × 4m, the communication floor is divided into eight regions (2m × 2m per region). The floor (2m × 2m) under the visible light sources is subdivided into small areas, for example we divided it to 256 subdivisions. In the case of classic beam steering [8] the transmitter first sequentially tries all m holograms (256 holograms in this case) and the receiver computes the SNR associated with each hologram at the receiver and relays this information to the transmitter for the transmitter to identify the best hologram to use (update the holograms). This is an exhaustive search mechanism among the stored holograms. If each SNR computation is carried out in 1 ms (based on typical processor) then the total adaptation time when the receiver moves is 256 ms. A further improvement in SNR can be achieved by increasing the number of regions on the floor which leads to smaller regions and improved SNR, but a larger number of holograms to choose from leading to an increase in the time required to identify the best holograms. For instance, increasing the number of regions from 256 to 512 will lead to an increase in the total number of holograms to 512. Hence the computation time required to identify the optimum holograms is increased to 512 ms. In order to overcome this problem, a FCGHs algorithm is introduced to effectively improve the SNR (through the use of more holograms) while reducing the computation time required to identify the optimum hologram.

The FCGHs algorithm determines the optimum hologram that yields the best receiver SNR based on a divide and conquer (D&C) algorithm. The transmitter divides the stored holograms into four quadrants with a boundary based on the hologram transmission angles ($-\delta_{min}$ to 0) and (0 to δ_{max}) in both $x,\ y$ axes. The transmitter first tries the middle hologram at each quadrant (four holograms will be first tried) to identify the sub-optimal quadrant; hence reducing the number of holograms that need to be tried by a factor of 4 in the first step. The receiver sends a feedback signal at a low rate, which informs the transmitter about the SNR associated with each hologram. The hologram that results in the best receiver SNR is identified as a sub-optimum hologram, and the quadrant that includes this sub-optimum hologram will be divided in the next step into four sub-quadrants. The transmitter again scans the middle hologram at four new sub-quadrants and identifies the second sub-optimal hologram; hence identifying the second sub-optimal quadrant. The transmitter again divides the new second sub-optimal quadrant into four quadrants in a similar manner to the first and second sub-optimal quadrants to identify the third sub-optimal quadrant. The quadrant that is represented by the third sub-optimal hologram will be scanned. This technique helps to reduce the computation time required to identify the optimum hologram when a very large number of holograms is used. The proposed FCGHs algorithm can be described for a single transmitter and receiver as follows:

1- The RGB-LDs light unit that has been chosen in the STB algorithm first divides the stored holograms into four main groups associated with quadrants based on the hologram transmission angles. The boundary angles associated with the first quadrant are δ_{max-x} to 0 in the x-axis and δ_{max-y} to 0 in y-axis.
2- The RGB-LDs transmits a pilot signal using the middle hologram in each quadrant in order to determine the first sub-optimum hologram.
3- The SNR is computed at each step (each hologram) and the receiver sends a control feedback signal at a low rate to inform the controller of the SNR associated with each scan. This feedback channel can be implemented using an infrared beam.
4- The hologram that yields the best SNR is chosen by the controller (identifies sub-optimal quadrant for next iteration).
5- The new scanning area is divided into four quadrants and repeats steps 2 to 4 to identify the second sub-optimal quadrant.
6- Repeat steps 2 to 5 to identify the best location that gives the highest SNR (the divide and conquer process continues and the transmitter determines the optimal hologram transmission angles that maximise the receiver's SNR).

The proposed FCGHs reduce the computation time from 296 ms taken by the classic beam steering LDs-VLC system to 32 ms (32 possible locations should be scanned in all iterations × 1 ms).

C. Delay adaptation technique (DAT)

A delay adaptation technique (DAT) for a VLC system was proposed in [4] and it is used here as it is shown to offer channel bandwidths of more than 36 GHz (in a worst case scenario), which enables the VLC system to operate at data rates of more than 25 Gbps.

If the time taken to determine the value of each SNR and delay associated with each transmitter (relative to the start of the frame) is equal to 1 ms (based on typical processor speeds), then the STB algorithm, FCGHs and DAT training time will be 112 ms (8 RGB-LDs units × 1 ms + 32 possible locations should be scanned in all iterations × 1 ms + 9 RGB-LDs in each transmitter unit × 8 transmitter units × 1 ms). This time (112 ms, once every one second frame) is sufficient given that adaptation algorithms have to be carried out at the rate at which the environment changes (pedestrian movement). Therefore, the fully adaptive imaging VLC system can achieve 100% of the specified data rate when it is stationary, and 88.9% in the case of user movement, (user or object movement in the room).

4. SIMULATION RESULTS

In this section, we evaluate the performance of the proposed fully adaptive imaging VLC system in an empty room in the presence of multipath dispersion and mobility. The results are presented in terms of impulse response, delay spread, 3 dB channel bandwidth and SNR.

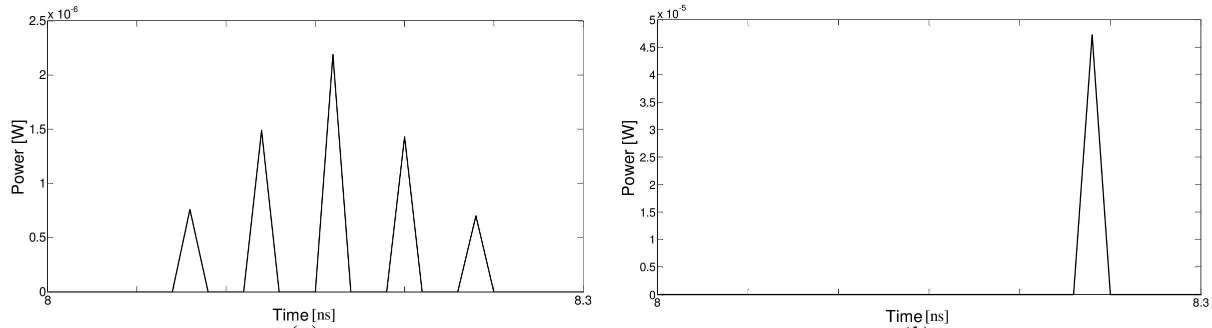
4.1 Impulse Response

The impulse responses of the two systems (imaging LDs-VLC and fully adaptive imaging LDs-VLC) at the room centre are depicted in Fig. 2. The LOS components have a great impact on the system performance; therefore, we magnified the impulse responses for these systems to show the LOS contributions clearly. First and second order reflection components exist in the original impulse response, but they do not appear in this figure due to magnification of the LOS components. It can be seen that the fully adaptive imaging LDs-VLC system impulse response is better than that of the imaging LDs-VLC in terms of received optical power. A significant increase in the received optical power can be achieved when the fully adaptive imaging LDs-VLC replaces the imaging LDs-VLC system, by a factor of 7, from 6.68 μW to 47.46 μW. This significant improvement in the received power is due to steering a beam of white light towards the receiver location.

4.2 Delay Spread and 3 dB Channel Bandwidth Analysis

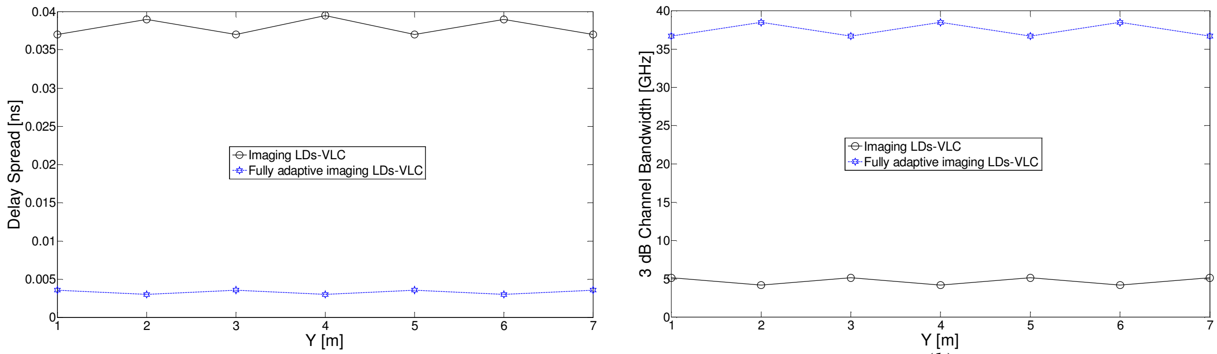
Fig. 3a evaluates the delay spread of the two systems under the worst case scenario (when the receiver moves along *x*=2m). The middle of the room (*x*=2m) is considered to be the worst communication link in the communication floor area due to its associated high ISI and multipath propagation level; therefore, we only consider the *x*=2m line. The delay spread for the imaging LDs-VLC system is relatively low (0.04 ns in the worst case) and this is due to the narrow FOVs associated with each pixel in the imaging receiver, and this limitation in the FOV minimises the number of rays accepted. However, to operate at high data rates (25 Gbps and beyond) the delay spread should be further reduced (i.e. less than 0.04 ns). The results show that the fully adaptive system reduces the delay spread by a factor of 11.4 compared with the imaging LDs-VLC system (from 0.04 ns to 0.0035 ns) at the room centre.

Although, the transmitter modulation bandwidth problem in the VLC system can be solved by replacing LEDs with LDs, the channel bandwidth remains an issue that needs to be solved to achieve multi-gigabit per second data rates. Previous work [4] has shown that the imaging LDs-VLC system can provide a 3 dB channel bandwidth of more than 4 GHz under the worst case scenario. However, the main problem with such a system is the low SNR at high data rates (10 Gbps and beyond). Therefore, to enable it to operate at 25 Gbps we proposed the beam steering technique to enhance the SNR at high data rates and to utilize the significant increase in the channel bandwidth that will enable our proposed system (fully adaptive imaging VLC system) to operate at 25 Gbps. The 3 dB channel bandwidth at *x*=2m in our two systems is given in Fig. 3b. The results show that the fully adaptive imaging VLC system has the ability to offer a communication channel with 3 dB bandwidth greater than 36 GHz.



(*a*) (*b*)

Figure 2. Impulse responses of the two systems, (a) imaging LDs-VLC (b) fully adaptive imaging LDs-VLC at room centre (x=2m, y=4m, z =1m).



(*a*) (*b*)

Figure 3. Delay spread and 3 dB channel bandwidth, (a) delay spread of the two systems at x=2m and along y-axis (b) the 3 dB channel bandwidth of the two systems at x=2m and along y-axis.

4.3 SNR Analysis

In this study, the PIN-HMET optical receiver proposed by Klepser [19] was used for the fully adaptive 25 Gbps VLC system. The noise current spectral density for this preamplifier is 12 pA/√Hz and the preamplifier has a bandwidth of 18 GHz. We considered SC method of processing the electrical signal from different pixels in an imaging receiver. In SC, the receiver simply selects the pixel with the largest SNR among all the pixels. To achieve a BER of 10^{-9} in OOK, a SNR of 15.6 dB is required [18], [20]. It can be noted that the fully adaptive VLC system has the ability to provide SNR values higher than this required value in all the receiver locations. The fully adaptive VLC system outperforms imaging LDs-VLC system in terms of SNR (see Fig. 4). It achieves about a 25 dB SNR gain over the imaging LDs-VLC system at the worst case scenario. This significant improvement in the SNR level is attributed to the ability of the beam steering technique to steer a part of the light towards the receiver location and thus increase the power received by the pixels. The imaging LDs-VLC system does not have the ability to operate at 25 Gbps due to the impact of ISI and multipath propagation. However, these effects can be mitigated by employing fully adaptive imaging LDs-VLC system. The highest value of BER in the fully adaptive VLC system is equal to 4×10^{-12}, and this value can provide a very good communication link. Forward error correction coding (FEC) can be used to further reduce the BER.

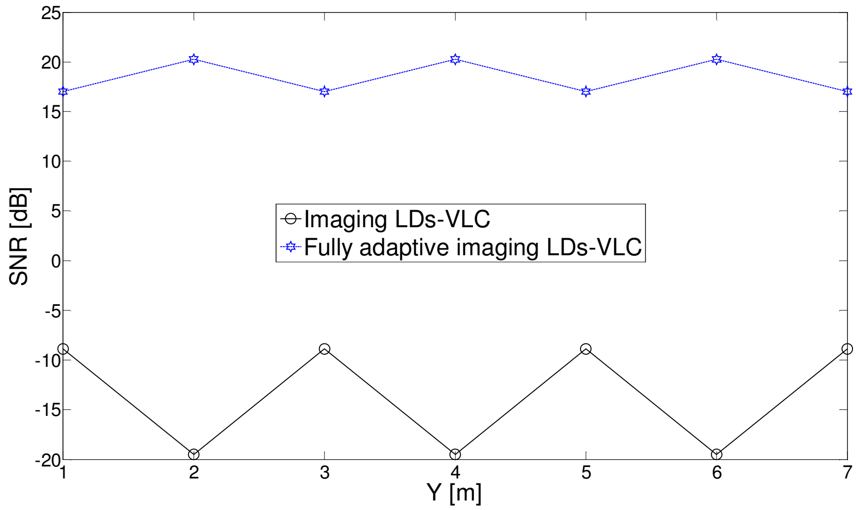


Figure 4. SNR of the two systems when operating at 25 Gbps at x=2m and along the y-axis.

5. CONCLUSIONS

In this paper, we introduced a FCGHs VLC system and introduced a new fully adaptive VLC system that has ability to achieve 25 Gbps. The proposed FCGHs can effectively steer the VLC beam nearer to the receiver location at each given receiver location. It should be noted that the FCGHs are pre-calculated and stored in our proposed system without adding any complexity at the transmitter to reproduce (compute) the holograms. Thus the time required to find the optimum location to steer the beam to, was reduced from 224 ms to 112 ms. Therefore, the fully adaptive imaging LDs-VLC system can achieve 100% (25 Gbps) of the specified data rate when it is stationary, and 88.9% (22.2 Gbps) in the case of user movement, (user or object movement in the room).

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