Chapter 6

Collaborative VLC/IROW Systems

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Additional information is available at the end of the chapter

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Abstract

Dimming is an important feature of an indoor lighting system where the illumination level can be controlled by the user. Therefore, integrating a visible light communication (VLC) system with an illumination system poses some challenges. One of the main issues is that the light unit should be "ON" all the time to ensure continuous communication. To ensure acceptance and adoption of VLC systems, an important issue should be addressed: how to communicate when the lights are "OFF" or partially dimmed. In this chapter, we propose five new infrared optical wireless (IROW) systems to support VLC systems when the light is totally turned off or significantly dimmed. To take advantage of both VLC and IROW, we introduce and implement the concept of a collaborative VLC/IROW system. In addition, we investigate the impact of partial dimming on the VLC system's performance, and we propose an adaptive rate technique (ART) to mitigate the impact of light dimming. Moreover, in the case of no dimming, the VLC and IROW systems can collaborate to increase the data rate so it is higher than that in the pure VLC system. We have achieved 10 Gbps in an indoor environment, which is a 2× increase in the data rate compared with a pure VLC system.

Keywords: collaborative VLC/IROW, delay spread, SNR

1. Introduction

A visible light communication (VLC) system has the potential to become a complementary technology to its radio frequency (RF) counterpart, and this is due to the hundreds of THz of license free bandwidth, high security, energy efficiency and immunity to electromagnetic interference [1]. Despite the advantages presented by the VLC medium, there are several challenges facing VLC systems to achieve high data rates. These challenges include the low modulation bandwidth of the light-emitting diodes (LEDs) and inter-symbol interference (ISI) due to diffuse transmission where the optical signal reaches the receiver through a number of different paths that result in pulse spread, which in turn leads to ISI. Various techniques have been proposed to mitigate the limitations (low modulation bandwidth of LEDs and ISI) in VLC systems to achieve high data rates. On-going research activities intend to increase the data rates of indoor VLC systems by replacing LEDs with visible laser diodes (LDs) coupled with the use of an imaging receiver instead of the conventional wide field of view (FOV) receiver [2–5].

The concept of VLC systems is based on the use of light units (LEDs/LDs) for both lighting and communications. Therefore, using light units (i.e. LED or LD) for communications should not interfere with the light units' main function (i.e. illumination). A user may arbitrarily dim the light source in the VLC system to save power, so it is essential to maintain communication in this case. An infrared optical wireless (IROW) system can be used to collaborate with the VLC system under partial/full dimming. IROW systems can provide high transmission rates similar to VLC systems [6, 7]. This is due to the wider modulation bandwidth of the laser sources used in IROW systems instead of white LEDs. IROW systems can use simple signal processing functionality and simple modulation formats while having a much higher bandwidth available for future usage. IROW systems have some additional advantages compared to VLC. For example, light dimming is not an issue in IR systems, and the uplink implementation using IR is convenient as it avoids bright visible light next to the user's equipment, next to a laptop, for example. However, IROW systems have two major challenges: multipath dispersion due to reflections and sensitivity to additive shot noise coming from artificial background lighting or sunlight [6, 8].

The received power at the VLC receiver is reduced when the user dims the light to low levels, and this will lead to a degradation in the signal-to-noise ratio (SNR) and affect the data rate achievable. Recently, hybrid schemes were proposed to support VLC systems. RF-based systems are used to supplement the VLC system [9, 10]. However, achieving a high transmission rate (multi gigabits per second) and security is the most challenging parts. Therefore, the VLC link needs to collaborate with the IROW connection to provide continuous data transmission. When the VLC link has recovered (i.e. there is no dimming), the VLC and IROW systems can cooperate together to increase the data rate at the receiver side.

In this chapter, we addressed the weakness of VLC systems and provide practical solutions when the light is partially dimmed or totally switched off. Subsequently, we have achieved data rates more than those reported in Refs. [9, 10]. In this study, we report the use of infrared systems that utilise a LD source to support the VLC system when the light is totally switched off. IR optical communication has the same advantages as VLC systems. It can also provide high transmission data rates similar to VLC systems and potentially higher data rates (data rates up to 15 Gbps can be achieved) [11]. In addition, we investigate the performance of a VLC system under the impact of different levels of dimming, propose an adaptive rate technique (ART) and produce the concept of cooperation between VLC and IROW systems. The VLC system is able to achieve high data rates (5 Gbps) when the light units are "ON." However, the achieved data rate (i.e. 5 Gbps) will decrease as a result of light dimming. Therefore, IROW systems are proposed to ensure the continuity of the wireless communication and to maintain the target data rate (5 Gbps), as the IROW system can be used to compensate for the degradation of the data rate due to dimming in the VLC system. In addition, the IROW system can be used to increase the data rates so they are higher than the target (5 Gbps) when the lights are "ON," and the VLC system is operating normally.

Five IROW systems are proposed: hybrid diffuse IR (HDIR) with wide field of view receiver, HDIR with imaging receiver, beam steering IR (BSIR) with imaging receiver, cluster distributed IR (CDIR) with imaging receiver and a cluster distributed beam steering IR (CDBSIR) system, to collaborate with the VLC system. The data rates achieved by our proposed backup systems are 2.5 and 5 Gbps when using a very simple modulation format (on-off keying, OOK) and avoid the use of relatively complex wavelength division multiplexing approaches. In this study, we used two types of receivers: wide FOV receiver and an imaging receiver with selective combining (SC) to choose the best pixel.

The remainder of this chapter is organised into the following sections: Section 2 presents the simulation environment and VLC/IROW channel model. Section 3 presents the proposed systems' configurations. Section 4 introduces the ART and the impact of dimming on the VLC system performance. Section 5 introduces the simulation results and discussion of the IROW systems. Section 6 provides the simulation results and discussion of the collaborative VLC/IROW system in an empty room. Finally, conclusions are drawn in Section 7.

2. Simulation environment and VLC/IROW channel model

To study the benefits of our proposed systems in an indoor environment, a simulation based on a ray tracing algorithm was performed in an unoccupied room (empty) with 8 m × 4 m (length × width) floor dimensions and a height of 3 m to the ceiling. The walls and ceiling were segmented into small reflective elements (dA). The reflective elements were treated as small secondary emitters that diffuse the received signal in the shape of a Lambertian pattern with $n = 1$, where n is the Lambertian emission order, having a reflectivity of 0.8 for the walls and ceiling and 0.3 for the floor [12–15]. Element sizes of $5\ cm \times 5\ cm$ for the first order reflections and $20\ cm \times 20\ cm$ for the second order reflections are employed for all arrangements. Previous work has studied the received optical power within an indoor environment. They found that most of the received optical power is located within the two first-order reflections (1st and 2nd). Third order and higher reflections are highly attenuated [16]. Hence, two bounces are considered in our calculations.

In indoor OW communication systems, intensity modulation with direct detection (IM/DD) is the preferred choice as a result of its reduced cost and complexity [17]. The receiver makes use of a detector that produces a photocurrent $I(t)$ that is proportional to the received instantaneous optical power. The indoor optical wireless IM/DD channel can be given by [18]:

$$I(t, Az, El) = \sum_{m=1}^{M_t} Rx(t) \otimes h_m(t, Az, El) + \sum_{m=1}^{M_t} Rn_m(t, Az, El) \tag{1}$$

where t is the absolute time and El and Az represent the direction of the arrival in the elevation and azimuth angles, respectively. M_t is the total number of reflecting elements, $x(t)$ is the transmitted instantaneous optical power, $\otimes$ denotes convolution, R is the detector responsivity and $I(t, Az, El)$ is the received photocurrent at a certain location resulting from M_t reflecting surfaces. Lastly, $n_m(t, Az, El)$ represents the background light noise due to m^{th} reflecting elements at the receiver. Many parameters can be obtained from the simulated impulse response, for example, 3 dB channel bandwidth, the delay spread and SNR. The delay spread of an impulse response is given by [6]:

$$D = \sqrt{\frac{\sum (t_i - \mu)^2 P_{ri}^2}{\sum P_{ri}^2}} \tag{2}$$

where t_i is the delay time associated with the received optical power P_{ri}, and μ is the mean delay given by:

$$\mu = \frac{\sum t_i P_{ri}^2}{\sum P_{ri}^2} \tag{3}$$

1. The 3 dB channel bandwidth is equal to the frequency when the magnitude response falls by 3 dB.
2. The SNR of the received signal can be calculated by taking into account the powers associated with logic 0 and logic 1 (P_{S0} and P_{S1}), respectively. The SNR is given by [18]:

$$SNR = \left(\frac{R(P_{s1} - P_{s0})}{\sigma t}\right)^2 \tag{4}$$

where R is the receiver responsivity and σ_t is the standard deviation of the total noise that is the sum of the shot noise, thermal noise and signal dependent noise. σ_t can be calculated as follows:

$$\sigma t = \sqrt{\sigma_{shot}^2 + \sigma_{preamplifier}^2 + \sigma_{signal}^2} \tag{5}$$

where σ_{shot}^2 represents the background shot noise component, $\sigma_{preamplifier}^2$ represents the preamplifier noise component, and σ_{signal}^2 represents the shot noise associated with the received signal [19]. Bit rates of 2.5 and 5 Gbps are evaluated in our proposed systems. We used the preamplifier design proposed in Ref. [20]. In this study, we considered the SC method of processing the electrical signal from different pixels in an imaging receiver. In the SC, the receiver simply selects the pixel with the largest SNR among all the pixels. The SNR_{SC} is given by Ref. [18]:

$$SNR_{SC} = Max_i \left(\frac{R(P_{s1} - P_{s0})_i}{\sigma t_i}\right)^2 \; 1 \le i \le j \tag{6}$$

where j represents the number of pixels ($j = 50$ in our imaging receiver).

3. Proposed systems' configurations

In this section, proposed OW systems are presented, analysed and compared to identify a reliable and high data rate wireless communication system for an indoor user.

3.1. Imaging LD-VLC System

The imaging LD-VLC system used eight lighting fixtures (i.e. RGB-LDs) on the ceiling connected by fibre optic cable and controlled by a central controller. The imaging LD-VLC system was introduced in Ref. [2], and it is considered here to investigate its performance under the impact of different levels of dimming. In addition, it will be integrated with an IROW system to provide reliable and high data rate services for an indoor user. **Figure 1** shows the architecture of the imaging LD-VLC system.

3.2. IROW Systems

In this section, five IROW systems are presented, analysed and compared to identify the most appropriate system for use to collaborate with the VLC system (imaging LD-VLC).

3.2.1. Hybrid diffuse IR (HDIR) system employing wide FOV receiver

The HDIR employed one IR transmitter located at the centre of the ceiling, which can provide a direct LOS link at the receiver on the communication plane (CP). **Figure 2** shows the HDIR communication architecture. In this case, most of the power is gathered from the LOS link, and the rest of power is collected through reflections. The proposed system (HDIR) uses a

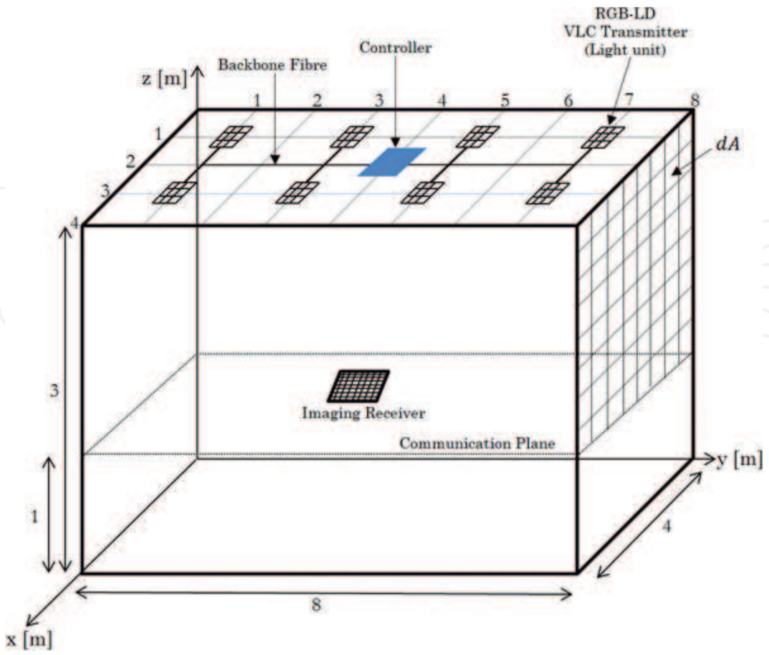

Figure 1. Architecture of imaging LD-VLC system with imaging receiver on communication plane.

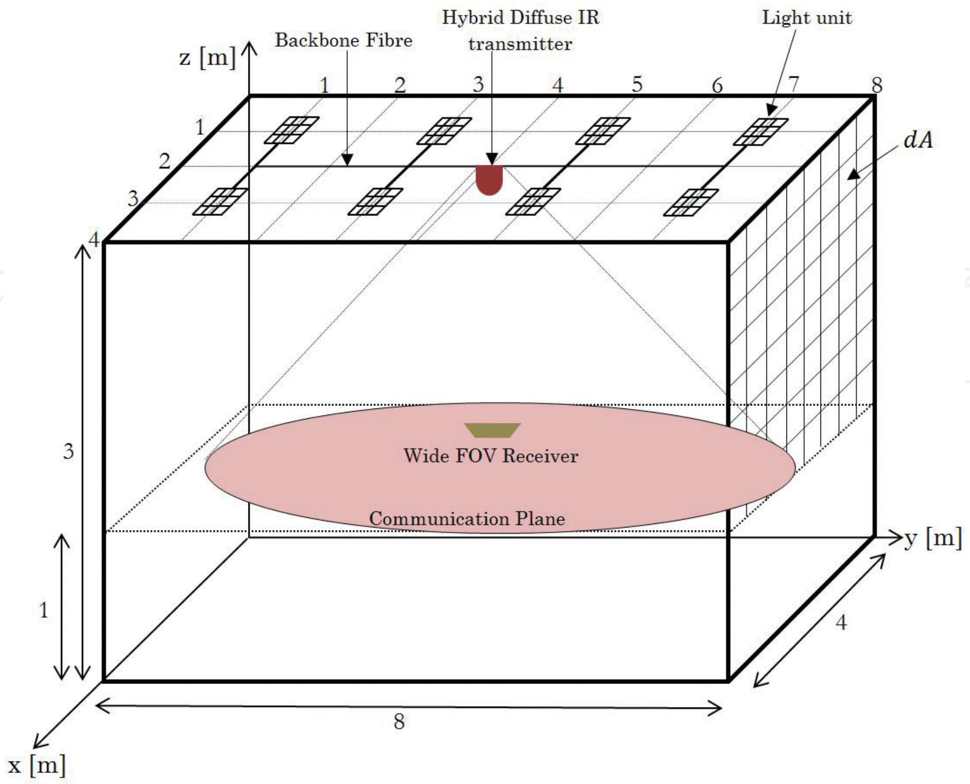

Figure 2. Architecture of HDIR with wide FOV receiver on communication plane.

single-wide beam source, typically with a Lambertian pattern where the transmitted optical signal fully diffuses over the environment. The IR transmitter is connected to all the visible light sources via fibre links (to link to main network in the building) and simple control circuits (located at the centre of the room). When the light is dimmed or the received optical power falls below a certain threshold, a feedback IR signal at a low rate is sent by the receiver to the controller to switch the link into the backup system (i.e. HDIR). The receiver consists of the VLC and IR detectors connected through an electronic switch to control their functions. In this system, we used a conventional single-element wide FOV (90°) photodetector with photo sensitive area of 1 mm^2. The HDIR transmitter is positioned at the centre of the room at (2, 4, and 3 m), is pointed downwards, and emits 1 W with an ideal diffuse pattern. Exposure to optical radiation at such power levels can be hazardous to the skin and eyes. Nevertheless, different techniques can be used to reduce the impact of the high laser power, such as extending the source size, destroying its spatial coherence using holograms mounted on the transmitter or the use of arrays of transmitters. Pohl et al. have shown that such a source may use an integrating sphere as a diffuser to emit optical power in the range from 100 mW to 1 W [21]. Therefore, a transmitter power of 1 W will be assumed in this system.

3.2.2. Hybrid diffuse IR (HDIR) system employing imaging receiver

The HDIR system with imaging receiver has a comparable room configuration and uses the same IR transmitter as the former system. However, a 50 pixels imaging receiver is used here. The imaging receiver shows two main pros over the traditional non imaging receivers. Firstly, all detectors share a common concentrator (e.g. a lens). Hence, it can be fabricated with a smaller size and lower cost. Secondly, all photodetectors can be placed on a single plane. Therefore, the designer can opt to use a larger number of detectors with small detector areas and narrow FOV. This will improve the receiver bandwidth (the input capacitance can be reduced by reduce photodetector area) and mitigate the effect of multipath dispersion. In this chapter, we employed the imaging receiver design proposed in Ref. [2].

3.2.3. Beam steering IR (BSIR) system employing imaging receiver

In contrast to the HDIR, in the BSIR system, the IR transmitter uses beam steering to direct the IR beam toward the receiver position. The IR transmitter faces downward at the centre of the ceiling as shown in **Figure 3**.

It has been proved that beam steering is an effective approach that can help to maximise the receiver's SNR, regardless of the receiver's FOV, the receiver's orientation and the transmitter's position [5]. However, this technique requires intensive time and calculations on the processor to generate a hologram at each step. In our new BSIR system, we propose an efficient stored vocabulary hologram method for beam steering in our backup system. For a large room of 4 m × 8 m, the floor (i.e. CP) is divided into 512 regions (0.25 m × 0.25 m per region). The total number of holograms to be stored in our design is *N*, where *N* represents the number of regions into which the CP is divided. This large number of regions has been chosen to accurately identify the receiver location during its motion (user mobility). Since the

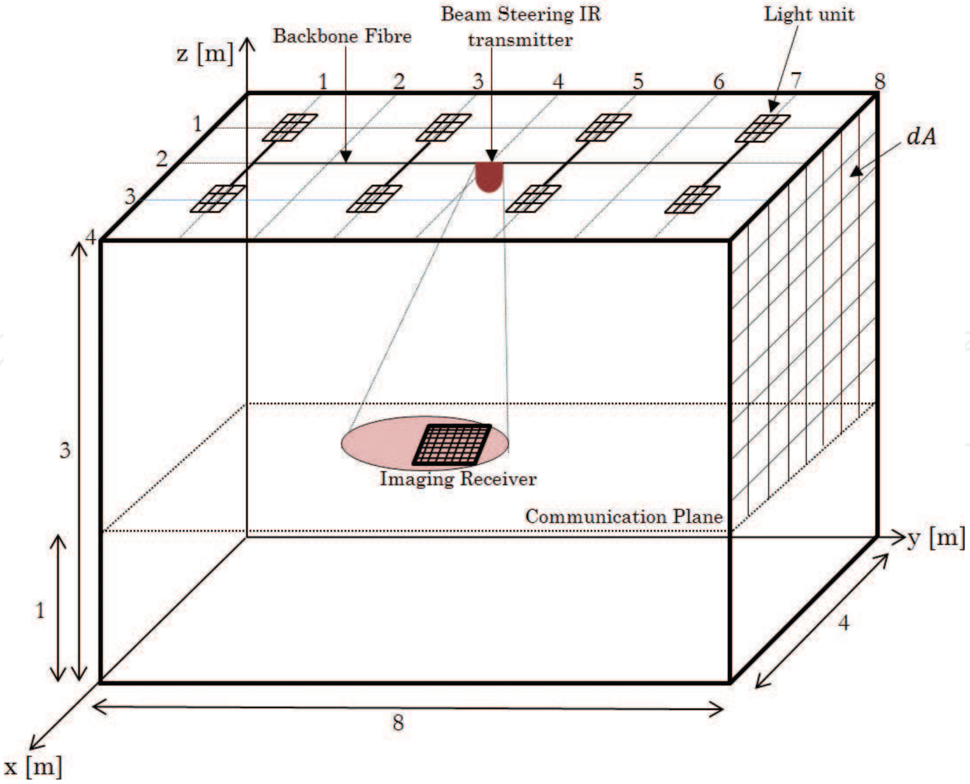

Figure 3. Architecture of BSIR with imaging receiver on communication plane.

transmitter is fixed at the centre of the room (close to the controller), the transmitter uses a hologram that steers the beam (narrow direct LOS link) to the optimum location if the receiver exists in any one of the regions. The idea of finite vocabulary stored holograms has been recently proposed in VLC systems [5], and it is developed here for the first time in the BSIR system to improve the performance of the HDIR system.

In the BSIR system, the transmitter emitted 100 mW, where the hologram used $n = 45$ to focus the beams within a 0.25 m × 0.25 m area. A small transmitted power (100 mW) is used in our proposed system to satisfy the eye safety regulations in the indoor OW environment.

3.2.4. Cluster distributed IR (CDIR) system employing imaging receiver

In the CDIR system, IR transmitters are used that utilise LD sources to support the VLC systems when the light is partially dimmed or totally switched off. The CDIR system employs more than one IR source and distributes them on the ceiling, that is, each IR source is attached to a VLC transmitter (i.e. light unit). All IR sources are connected via fibre and a control unit to perform cluster mechanisms. The new concept of using IR clusters is employed to design a new geometry that can achieve a good performance in mobile IR communications.

A custom design for the imaging receiver (similar to the one in the previous systems) is used to reduce the impact of multipath dispersion and ISI. **Figure 4** shows the architecture of our CDIR system. The proposed system consists of eight IR sources, and each is attached to a visible light source located on the ceiling, which can provide a direct LOS link to the receiver on the CP. The IR transmitters are connected to all visible light sources through fibre links (to link to the main network in the building) and simple control circuits. As shown in **Figure 4**,

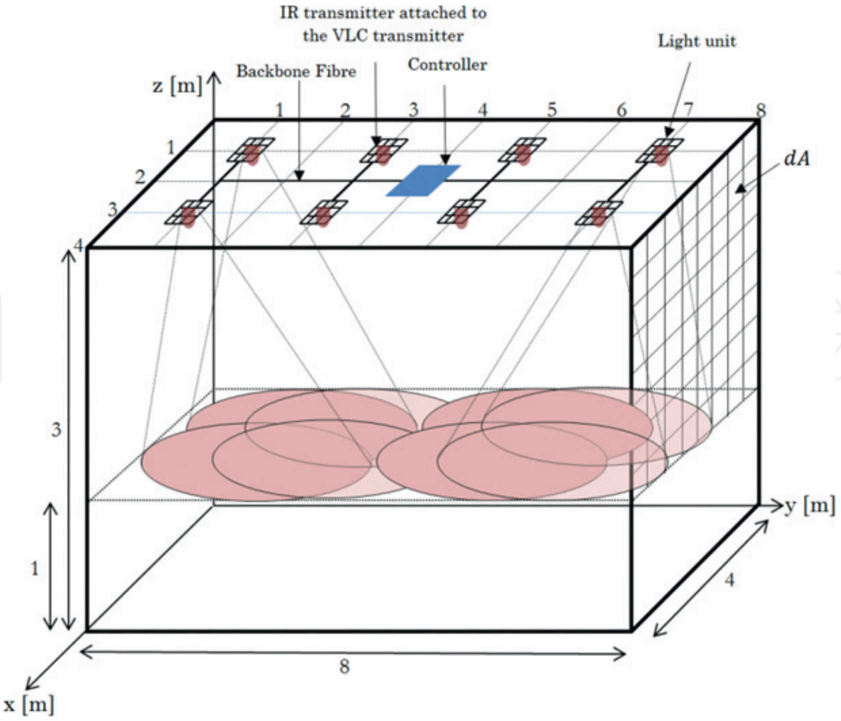

Figure 4. Architecture of CDIR when all IR transmitters are "ON".

each IR source forms part of a cluster that can cover over 2 m × 2 m. When the light is dimmed or the received optical power falls below a certain threshold, the receiver sends a feedback signal at a low rate to the VLC transmitter to switch the link into the supporting CDIR system. A select the best (STB) algorithm is used (similar to the ones used in Ref. [22]) to select the optimum link between the IR transmitter and receiver (under mobility, this algorithm can be called periodically). The first step is to switch ON each IR source individually. Each source uses a single-wide beam, typically with a Lambertian pattern with $n = 1$, where n is the Lambertian emission order (the transmitted optical signal fully diffuses over the environment). The receiver then computes the received power and the SNR associated with each source. The receiver sends a signal, at a low rate, back to the control unit conveying the information about the SNR weight associated with each source to identify the receiver location (the receiver is located near to the source that has the highest SNR). The transmitter switches ON only the optimal IR source (source that is nearest to the receiver location) and other sources remain off to reduce the impact of multipath dispersion.

3.2.5. Cluster distributed beam steering IR (CDBSIR) system

In contrast to the CDIR, in the CDBSIR system, the IR transmitter uses the beam steering technique to steer the IR beam towards the receiver location. Like CDIR, the CDBSIR system employs a STB algorithm to select the closest IR transmitter to the receiver. The selected IR transmitter in the STB algorithm will then apply a finite stored hologram in the system, instead of a diffuse source (as in the CDIR system). The stored hologram in the proposed system produces an IR beam to scan an area of 2 m × 2 m and steer the IR beam towards the receiver location. The floor (2 m × 2 m) under the IR source is subdivided into small areas; for example, we divided it to 256 subdivisions (0.125 m × 0.125 m) as shown in **Figure 5**. The IR 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 and y axes. The transmitter first tests the middle hologram at each quadrant (four holograms will be initially tested) to identify the sub-optimal quadrant; hence, this will reduce the number of holograms that need to be tested by a factor of four in the first step. The receiver sends a feedback signal at a low rate that 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. A number of iterations are carried out until the final optimum location is identified. The concept of beam steering has been recently proposed in a VLC system [5], and it is developed here to improve the performance of the CDIR system.

3.3. Collaborative VLC/IROW System

It is desirable to continue to provide a high data rate service, while a user dims the light source to any level. However, the received power at the VLC receiver is reduced when the user dims the light to low levels, and this leads to a degradation in the SNR and affects the achievable data rate. Therefore, a collaborative VLC/IROW system is introduced to address this issue, and when the VLC has partial dimming, such as 75 or 50%, both the IROW and VLC systems can collaborate to maintain the target data rate (5 Gbps). The IROW system can be used to

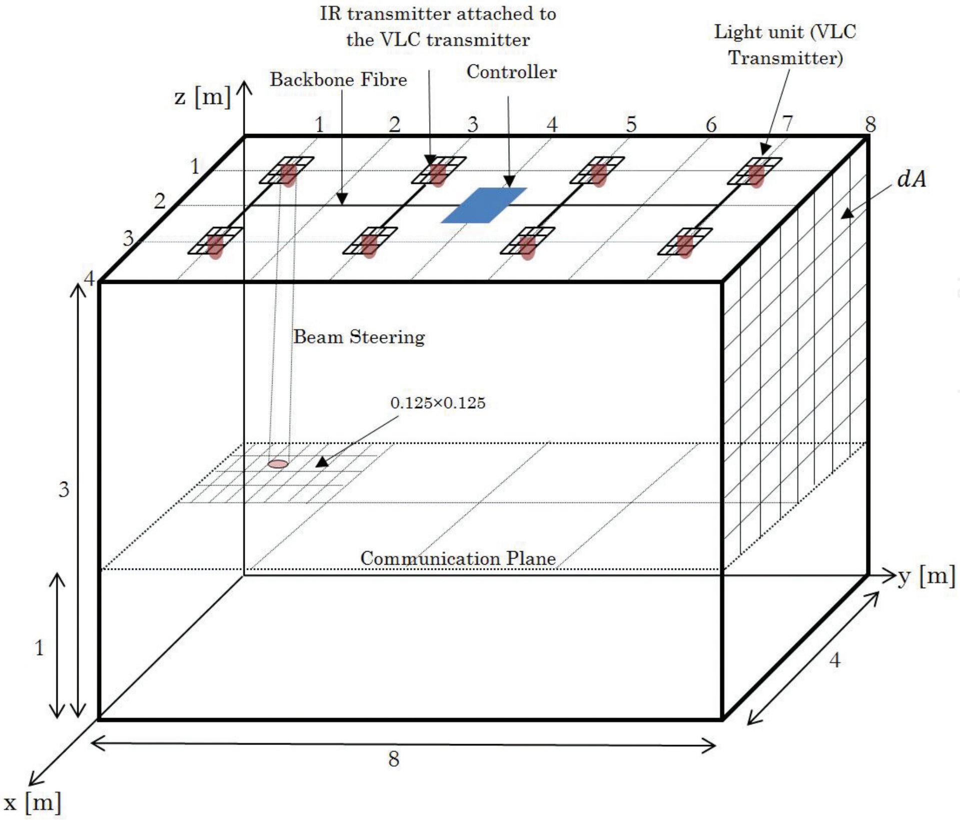

Figure 5. Architecture of CDBSIR system.

compensate for the degradation of the data rate due to dimming in the VLC system. It should be noted that the IROW system sends information at a fixed rate of 5 Gbps. In the case of no dimming, the VLC and IROW can be used to increase the data rate higher than the maximum VLC data rate (i.e. higher than 5 Gbps); hence, the achieved data rate will be 10 Gbps instead of 5 Gbps. **Figure 6** shows the architecture of the VLC/IROW system. The proposed system consists of eight IR sources (similar to those used in the CDBSIR system) and eight VLC transmitters (similar to those used in the imaging LD-VLC system) and employs an imaging receiver with 50 pixels. In order to eliminate interference between uplink and downlink channels, the downlink IR channel is used 850 nm and the IR uplink is used 1550 nm.

4. Adaptive rate technique

In this section, we introduce the ART and evaluate the performance of the imaging LD-VLC system under the impact of multiple levels of light dimming (25, 50 and 75%). The results are presented in terms of the SNR at different operating data rates (5, 2.5 and 1.25 Gbps).

It should be noted that an SNR equal to 13.54 dB is needed for a 10^{-6} probability of error (BER). Therefore, we have chosen BER = 10^{-6} as the threshold in the imaging LD-VLC, and we employ an ART to ensure that we have an acceptable quality communication link under different levels of dimming.

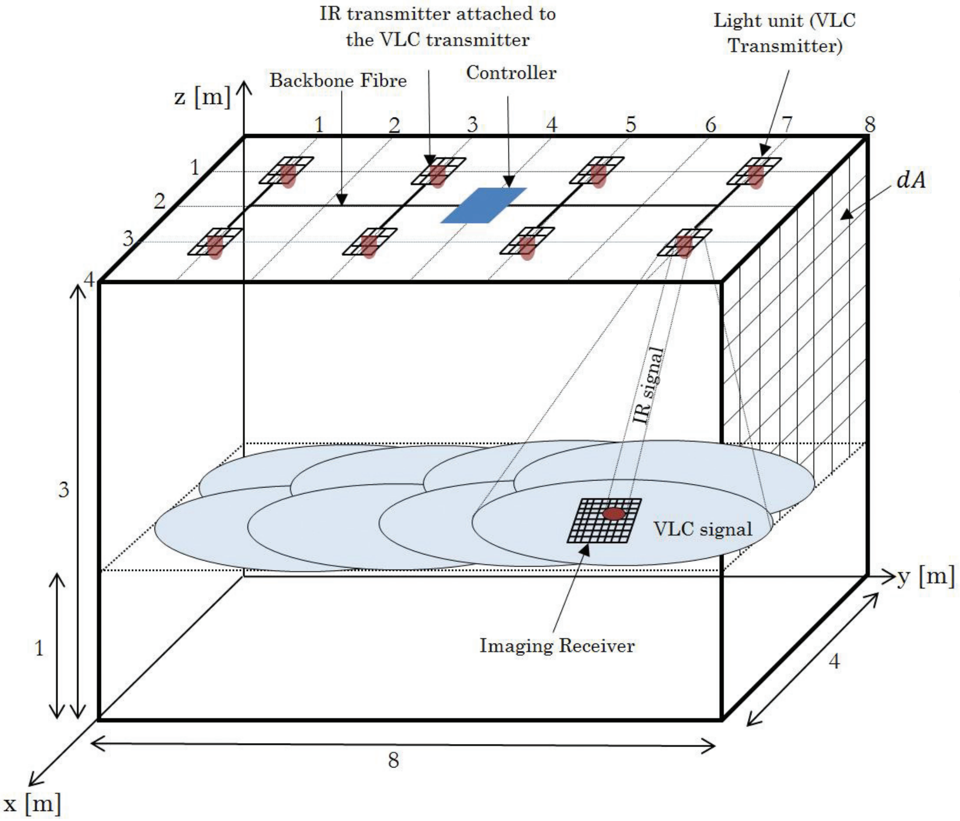

Figure 6. Architecture of VLC/IROW collaborative system.

ART is carried out at the receiver and the controller. First, the receiver monitors BER continuously, and when it becomes higher than 10^{-6}, the receiver sends a feedback signal called the channel quality indicator (CQI) to inform the controller to move to the next transmission rate (lower transmission rate when the BER becomes higher than 10^{-6}).

In our VLC system, we provide three data rates (5, 2.5 and 1.25 Gbps). For example, when the receiver is operating at 5 Gbps and the BER becomes higher than 10^{-6} (i.e. the SNR decrease below 13.54 dB), the receiver will send CQI_1 to inform the controller to reduce the transmission rate to 2.5 Gbps. Then, the receiver measures the SNR, and if the BER is still higher than 10^{-6}, then the receiver will send CQI_2 to inform the controller to further reduce the data rate (i.e. from 2.5 to 1.25 Gbps). Again, if the BER is still higher than 10^{-6}, then the receiver will send CQI_3 to inform the controller to stop transmission, and the communication link is disconnected. However, it is desirable to maintain communication, while a user arbitrarily dims the light source. Therefore, we have introduced a collaborative VLC/IROW system to address this issue (i.e. degradation in the SNR due to dimming will lead to disconnect in the communication link).

It should be noted that the ART has two procedures: down convert and up convert. Down convert is when the controller reduces the data rate due to degradation in the BER (when dimming occurs). Up convert is when the controller increases the data rate (e.g. from 1.25 to 2.5 Gbps) due to maintaining a very low BER at the receiver side (i.e. 10^{-9}). The CQI_4 and CQI_5 signals can be used to inform the controller to increase the data rate from 1.25 to 2.5 Gbps and from 2.5 to 5 Gbps, respectively.

ART is carried out at the start of a one second frame, and if the BER has changed compared to the previous frame's values, then the receiver uses the feedback channel to update the controller.

The ART (down convert) can be applied according to the following steps:

1. The receiver sends (using an infrared beam) a low data rate control feedback signal (CQI) to inform the controller that the BER has become lower than 10^{-6}.
2. The controller decreases the current data rate to the lower service (e.g. 5–2.5 Gbps).
3. The receiver estimates the BER, and if it is still below 10^{-6}, it will send another CQI to inform the controller.
4. The controller further decreases the data rates (e.g. from 2.5 to 1.25 Gbps), and if it receives another CQI from the receiver, the controller will stop the transmission.

A flow chart of the down convert ART is shown in **Figure 7**. To evaluate the performance of the imaging LD-VLC system at different levels of light dimming, the SNR was calculated at 5, 2.5, and 1.25 Gbps. **Figure 8** illustrates the SNR of the VLC system when it was operated at 5 Gbps; the imaging LD-VLC system achieved about a 15.66 dB SNR at the room centre (worst case scenario) when dimming did not exist. However, it can be clearly seen that when the user dims the light by more than 25%, the SNR is decreased, and the BER becomes higher than 10^{-6}. This means that the VLC system cannot operate at this data rate (5 Gbps) when the light is dimmed by more than 25%. **Figures 9** and **10** show the SNR of the imaging LD-VLC system when operating at 2.5 and 1.25 Gbps, respectively. When the imaging LD-VLC is operated at 2.5 Gbps, it is able to maintain a BER of 10^{-6} at a dimming level of up to 50%. On the other hand, the VLC system has the ability to achieve 1.25 Gbps with a BER lower than 10^{-6} at deferent levels of dimming (25, 50 and 75%), as shown in **Figure 10**.

5. Simulation results and discussion of IROW systems

In this section, we evaluate the performance of the proposed support systems in an empty room in the presence of multipath dispersion, receiver noise, back ground noise (light units) and mobility. The results are presented in terms of delay spread and SNR.

5.1. Delay spread

A comparison of the channel delay spreads of our proposed systems is given in **Figure 11**. The receiver moves along the $x = 1$ m line in the HDIR (with wide FOV and imaging receiver) and BSIR systems, which is considered the worst communication path due to its associated high ISI and path loss. In the CDIR and CDBSIR systems, the receiver moves along $x = 2$ m, which is considered the worst communication link. The HDIR system with wide FOV receiver shows much more signal delay spread due to the wide receiver FOV (FOV = 90°), which accepts a

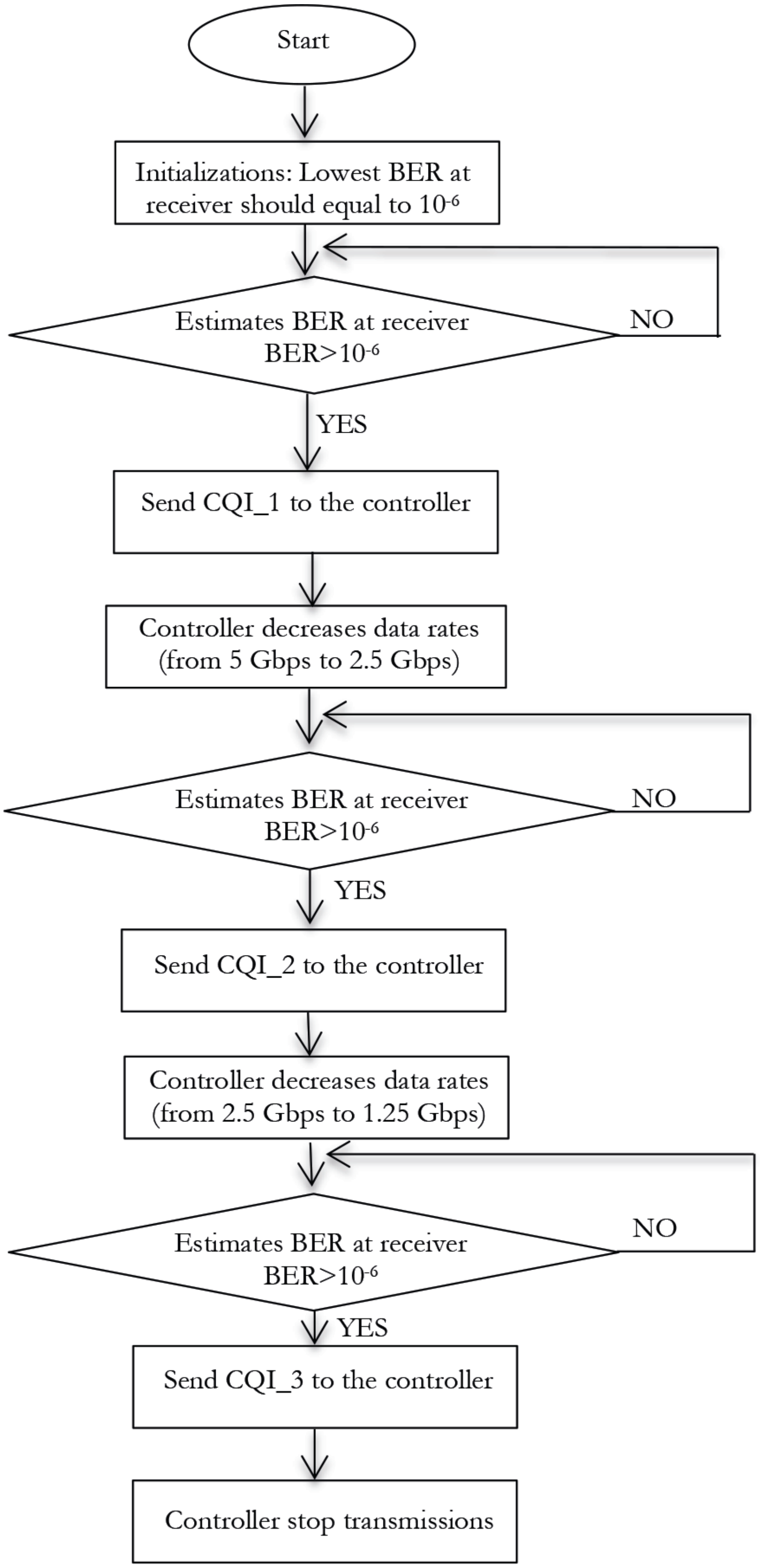

Figure 7. Flow chart of ART (down convert case).

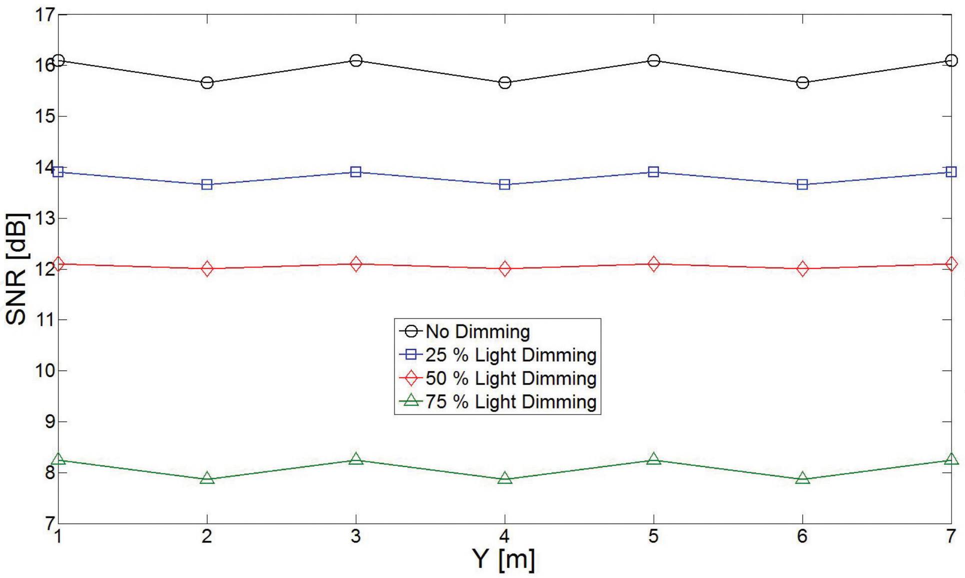

Figure 8. SNR of imaging LD-VLC system operating at 5 Gbps with different levels of dimming (25, 50 and 75%) when receiver moves at x = 2 m along y-axis.

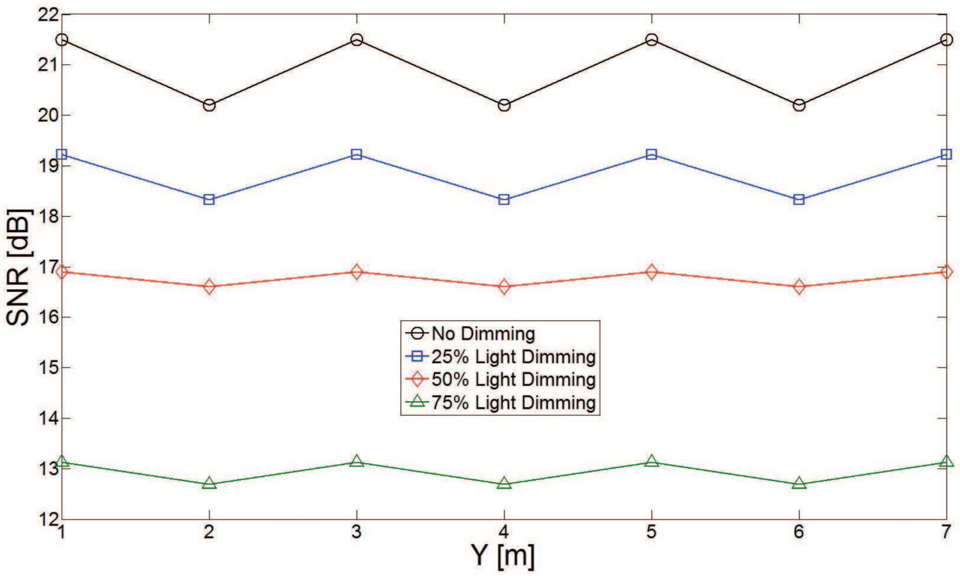

Figure 9. SNR of imaging LD-VLC system operating at 2.5 Gbps with different levels of dimming (25, 50 and 75%) when receiver moves at x = 2 m along y-axis.

wide range of rays with different path lengths from the transmitter to the receiver. In the HDIR system with an imaging receiver, the delay spread results are quoted when the system employs selection combining of the imaging receiver pixels where the pixel with the best SNR (note the SNR expression accounts for delay spread) is selected. The delay spread of our HDIR is reduced from almost 1.55–0.1 ns when an imaging receiver replaces the wide FOV receiver. This is due to the narrow FOV of each pixel, which limits the rays received by using 50 small FOV (about 21°) pixels and selecting the best imaging receiver pixel. The proposed BSIR

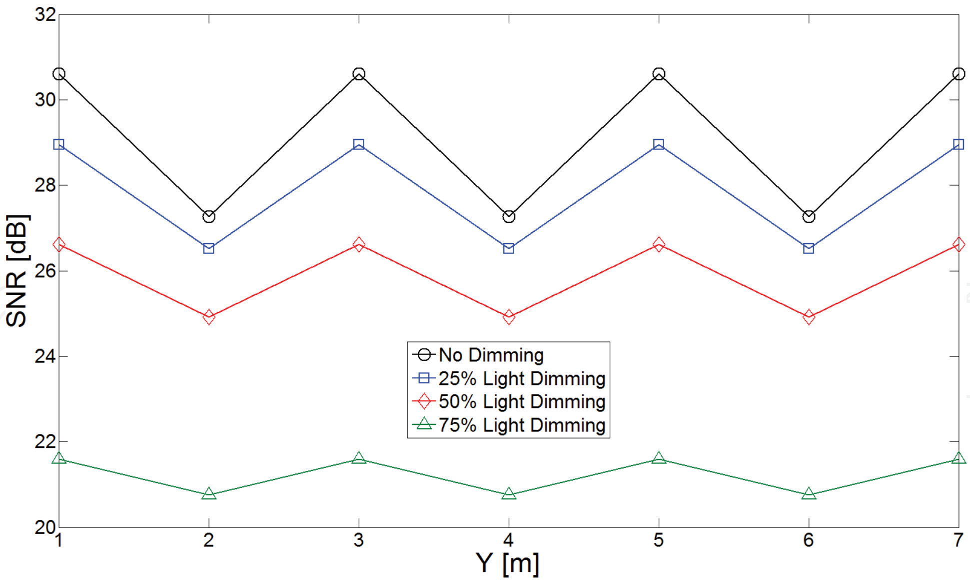

Figure 10. SNR of imaging LD-VLC system operating at 1.25 Gbps with different levels of dimming (25, 50 and 75%) when receiver moves at x = 2 m along y-axis.

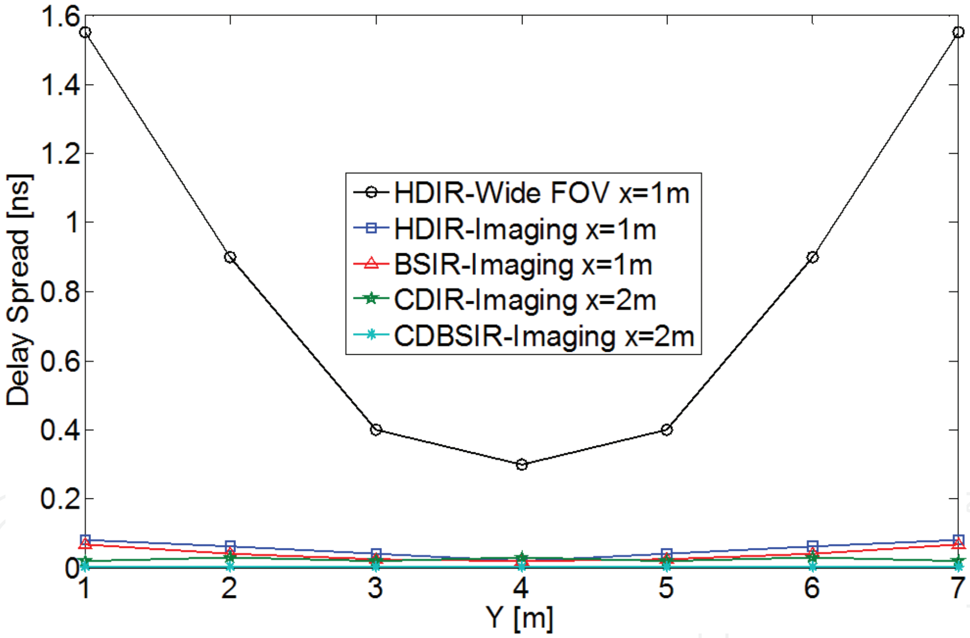

Figure 11. Delay spread of IROW proposed systems.

system coupled with an imaging receiver reduces the delay spread from 1.55 to 0.07 ns. This is attributed to two reasons: firstly, due to the narrow FOVs of each pixel in the imaging receiver, which minimises the number of rays accepted. Secondly, the use of beam steering helps reduce delay spread. It should be noted that steer the IR beam near to the receiver, not only improves the SNR, it is also decreases the delay spread by increasing the received power of LOS component. To further decrease the delay spread, the CDIR and CDBSIR systems are proposed. The CDBSIR system has the lowest delay spread compared to the other systems.

The results show that the CDBSIR system has a lower delay spread than the CDIR system at all the receiver locations considered. The delay spread for the CDIR system is relatively low (0.03 ns in the worst case), and this is attributed to two reasons: firstly, 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. Secondly, the IR transmitter is very close to the receiver (IR sources distributed on the ceiling see **Figure 4**). However, the delay spread can be further reduced (i.e. less than 0.03 ns) by employing beam steering. The CDBSIR system outperforms the CDIR system, as it dramatically decreases the delay spread from 0.03 to 0.003 ns (by a factor of 10) at the room centre. The minimum communication channel bandwidth of the CDBSIR was 29 GHz (where the delay spread is 0.003 ns at points $x = 2$ m, $y = 2$ m, 4 m, 6 m).

5.2. SNR

The SNR evaluation of the proposed backup VLC systems was carried out under the impact of receiver noise, multipath propagation, background noise and mobility. The proposed systems were set to operate at 2.5 and 5 Gbps. **Figure 12** shows the SNR of the proposed systems when operated at 2.5 Gbps. It can be noted that the HDIR system with wide FOV receiver does not have the ability to operate at a high data rate. However, when the imaging receiver is combined with this system, it can perform better than when using the wide FOV receiver. This is because the imaging receiver has ability to select the signals from the optimum pixels that monitor the best received signal during mobility. The imaging receiver uses a large number of detectors with a narrow FOV and small detector area. The HDIR system coupled with an imaging receiver provides around −2.3 dB at $x = 1$ m and $y = 1$ m (worst case), while the HDIR system with wide FOV can only achieve −24 dB at the same location. In OOK, a SNR of 15.6 dB is required to achieve BER of 10^{-9}. A considerable enhancement can be obtained by using the BSIR system, which offers a 33 dB SNR advantage above the HDIR wide FOV receiver at location $x = 1$ m, $y = 1$ m, $z = 1$ m. This enhancement in the SNR is due to the fact that the BSIR system has the ability to steer the IR beam close to the receiver position; hence, the received power will increase. Although improvements were achieved in the BSIR system SNR, a degradation in the SNR is noted when the receiver is on the move (mobile). Therefore, the effect of receiver mobility can be reduced by employing our CDIR system, which is capable of equally covering its environment through the use of a number of IR transmitters distributed on the ceiling.

From **Figure 12**, we can notice that the HDIR (with wide and imaging receiver) and BSIR systems do not able to transfer data higher than 2.5 Gbps; therefore, in **Figure 13**, we only present results for the CDIR and CDBSIR at 5 Gbps. **Figure 13** shows the SNR of the CDIR and CDBSIR systems when operated at 5 Gbps. It can be clearly seen that the CDIR system with imaging receiver does not have the ability to operate at a high data rate. However, when the beam steering technique is combined with this system, it can perform better. The significant improvement in the SNR level is attributed to the ability of the beam steering technique to steer the IR beam towards the receiver location and, thus, increase the power received by the pixels.

It should be noted that only CDBSIR can operate at 5 Gbps. Therefore, we suggested that this system can collaborate with VLC system.

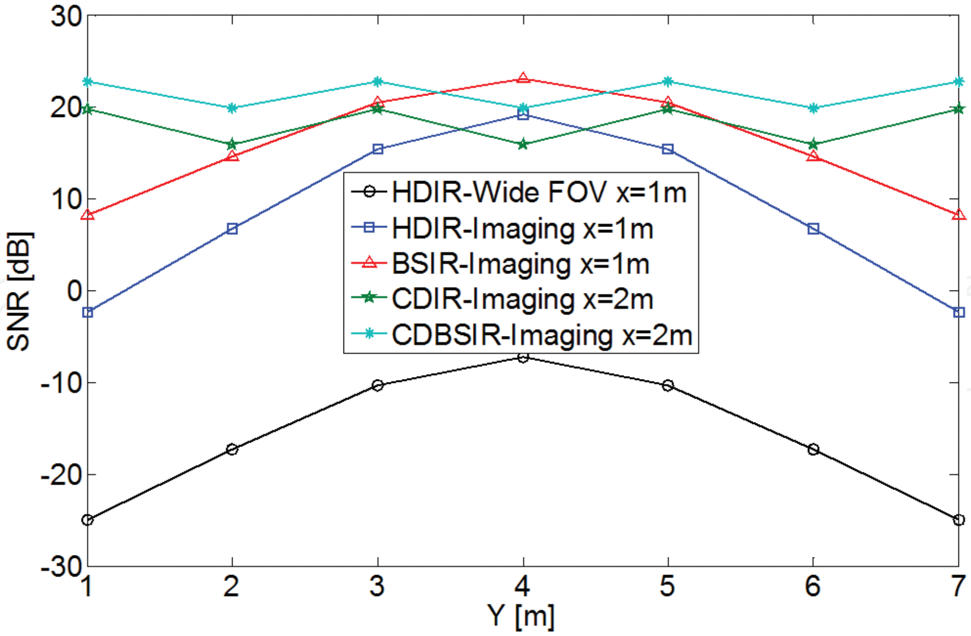

Figure 12. SNR of IROW proposed systems when operating at 2.5 Gbps.

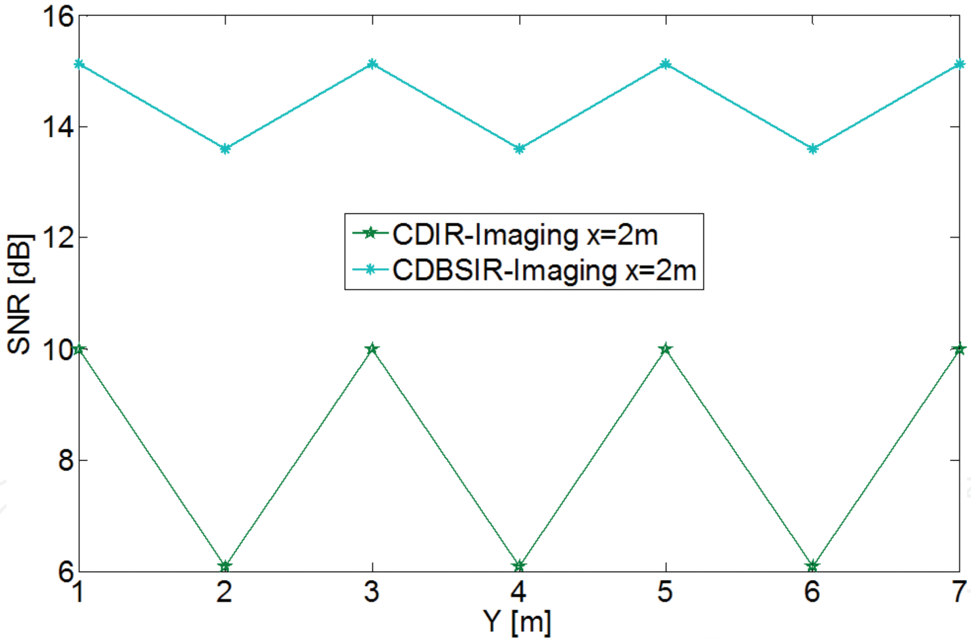

Figure 13. SNR of two systems operating at 5 Gbps when receiver moves at x = 2 m along y-axis.

6. Simulation results and discussion for collaborative VLC/IROW system

Dimming is an important feature of an indoor lighting system where the illumination level can be controlled by the user. One of the main issues in VLC systems is that the light unit should be “ON” all the time to ensure continuous communication. However, the user may dim the light at any time, and this will severally degrade the performance of the VLC system. In this section, collaboration between VLC and IROW systems (CDBSIR) is proposed to support the VLC system when the light is dimmed at different levels (25, 50 and 75%). An ART can be used with the VLC system to manage the reduction in the SNR due to the light dimming and to establish a high-quality communication link under the impact of dimming. To provide a high data rate service for an indoor user under different conditions (with\without dimming), an IROW (CDBSIR) system can be used to support the VLC system. **Figure 14** shows the SNR of the VLC system when the ART is carried out. It can be clearly seen that the data rate diminishes in a very graceful manner when the light is dimmed beyond 50%. However, when employing the CDBSIR system, the achieved data rates at the receiver will be 5 Gbps even though the VLC system is off. It means that the user can dim the lights and maintain a high quality communication service (5 Gbps and beyond). In the case of partial dimming (50 and 75%) in the VLC system, it can achieve 2.5 and 1.25 Gbps, respectively. Therefore, the collaborating system (VLC/IROW) can always achieve higher than the target data rate (5 Gbps). For example, 7.5 Gbps (2.5 Gbps from the VLC system and 5 Gbps from the CDBSIR) can be achieved when the light is dimmed by 50%. In the case of no dimming, 10 Gbps can be achieved by using both systems (VLC and IROW).

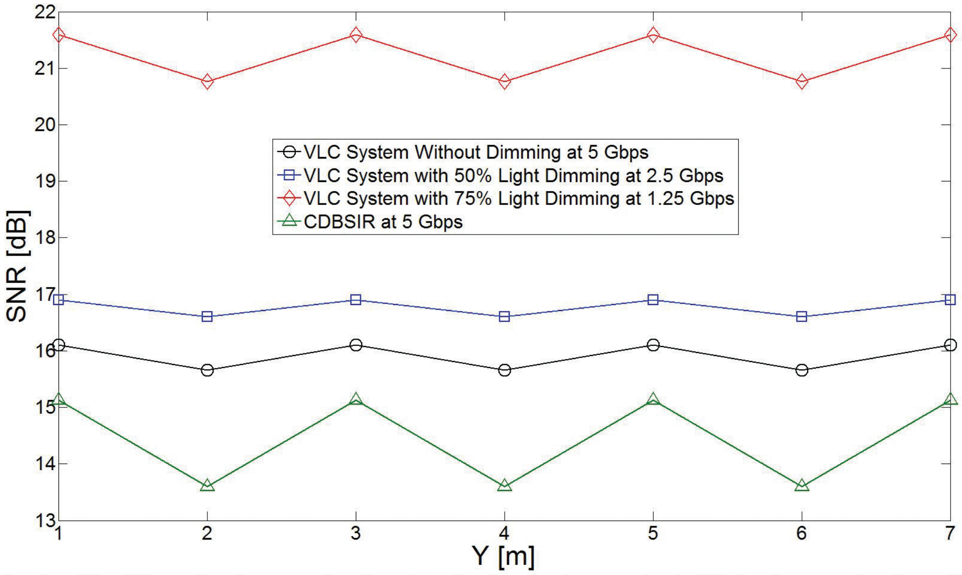

Figure 14. SNR of collaborative systems when receiver moves at x = 2 m along y-axis.

7. Conclusions

In this chapter, we proposed, designed and investigated the concept of a collaborative VLC/IROW system. In addition, we investigated the impact of partial dimming (25, 50 and 75%) on the performance of the VLC system. Moreover, we introduced a novel ART to reduce the effect of the dimming and to create an optimum communication link under the impact of partial dimming.

Five novel IROW systems (HDIR with wide FOV, HDIR with imaging, BSIR, CDIR and CDBSIR) were introduced to support and collaborate with the VLC system in the case of partial dimming or full dimming (i.e. lights off).

Simulation results show that the HDIR and the BSIR systems coupled with an imaging receiver achieved around −2 and 8.2 dB SNR at 2.5 Gbps, respectively. Further improvement in the SNR can be achieved by introducing a new CDIR system and employing more than one IR source distributed on the ceiling (attached to the VLC sources). The simulation results show that the CDIR system can significantly improve the SNR, as well as reduce the delay spread, compared to other systems. A beam steering technique is also proposed to further reduce the delay spread and increase the SNR by steering the IR beam nearer to the receiver at each given location. Simulation results show that the CDBSIR system has the ability to decrease the delay spread of the CDIR system by 90% from 0.03 to 0.003 ns at the room centre (x = 2 m and y = 4 m), which leads to an increase in the channel bandwidth by a factor of 5.5 from 5.5 to 29 GHz. The simulation results show that the CDBSIR system can significantly improve the SNR. The BER provided by the CDBSIR system is better than 10^{-6} at 5 Gbps in the worst case scenario. Therefore, we used the CDBSIR to collaborate with a VLC system.

Simulation results show that the collaborative VLC/IROW system has the ability to achieve 10 Gbps when dimming does not exist and 6.25 Gbps (5 Gbps from the IROW and 1.25 Gbps from the VLC) in the case of 75% light dimming (worst case scenario). It should be noted that in a collaborative system, the receiver should employ VLC and IR detectors connected through an electronic switching mechanism to control their functions.

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