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Smart multiple-mode indoor optical wireless design and multimode light source smart energy-efficient links

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Abstract. We present the design of a smart multiple-mode indoor optical wireless system that combines line-of-sight (LOS) and non-LOS optical wireless methods to smartly adapt to changes in environment and application. The proposed design is able to operate in three optical wireless modes called directed LOS, non-directed LOS, and diffuse non-LOS. These modes smartly accommodate for changes in the number of users and their mobility, along with providing optimal light coverage area and increased robustness to receive light blocking. Experiments for the first time demonstrate the use of multimode light sources in the proposed smart links using electronically controlled variable focal length lenses. Specifically demonstrated is a visible 670-nm multimode laser-based directed LOS link with variable range of 0.2 to 1.5 m and a 650-nm LED-based nondirected LOS link with variable range of 0.2 to 1.1 m. Compared to nonsmart links, these smart links demonstrate an improvement in the received optical power of 1.7× and 2.1× for the laser and LED links, respectively. © *2013 Society of Photo-Optical Instrumentation Engineers (SPIE)* [DOI: 10.1117/1.OE.52.5.055001]

Subject terms: optical wireless communications; optical communications; free-space optical communication; indoor wireless.

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1 Introduction

Indoor optical wireless communications is an attractive alternative to radio frequency (RF) wireless, including its ability to easily achieve high data rates within an unregulated spectrum.[1–6] Recently proposed is the concept of smart indoor visible line-of-sight (LOS) optical wireless links.[7–9] The idea behind the smart designs in Refs. 7 to 9 is to use the electronically controlled variable focal length lenses (ECVFL) to form a 3-D laser beam so that the receiver captures as many transmitted photons as possible.[10] Thus issues of poor use of limited light energy and limited range are relieved, enabling the optical wireless link to smartly adapt to changes in range to allow for a higher signal-to-noise ratio (SNR) or a reduction in the transmitted optical power. However, since these previously suggested smart link designs are LOS, they are prone to physical blocking. While increasing the number of LOS transmitters[11] does reduce the probability of blocking in a wireless system, it does not achieve the robustness to blocking inherently provided by diffuse or spot-diffused[12,13] light optical wireless links. Non-LOS links also have the advantage in terms of connecting moving users.[14] Additionally, in today's environment where the number of mobile users and bandwidth of content is increasing, reliable nonblocking high data rate links are increasingly important.

To address these issues, recently proposed is a smart dual-mode energy-efficient optical wireless data link.[15] While the proposed dual-mode optical wireless system can smartly adapt to changes in link length, number of users, and bandwidth usage, it did not take full advantage of the robustness to blocking, control of bandwidth, or coverage area control that can be achieved using smart optical wireless systems. It would be beneficial if an optical wireless system could be designed that can smartly adapt to changes in its environment, i.e., link length and physical blocking, and the application, i.e., bandwidth usage, number of users, user mobility, and coverage area. Such a smart system would improve the quality of service and reduce the power consumption of optical wireless networks and is the first focus of this paper. Spatially multimode light sources, such as LEDs and lasers, are high-reliability economical components for large-scale deployment in industrial settings. Previously, the smart link[7] was demonstrated using single spatial-mode lasers. Hence, the second focus of this paper is to demonstrate the feasibility of using multimode LEDs and lasers with ECVFLs to implement 3-D optical beamforming required to implement smart energy-efficient links.

2 Proposed Smart Multiple-Mode Optical Wireless Design

Figure 1 shows the proposed smart multiple-mode optical wireless system design that can operate in two modes simultaneously or switch between modes depending upon application requirements and/or changes in the environment. Figure 1(a) shows the optical transmitter on the roof of the room operating simultaneously using a diffuse non-LOS mode and an LOS mode. A diffuse non-LOS mode can be created with an LOS beam striking an optical scattering element $S1$ so that light spreads in a particular area of the room. Other scatterers or optical antennas (e.g., $S2$ and $S3$) can be placed in the room (and adjacent LOS zones) to have a variety of coverage areas of the non-LOS mode. In effect, less optical power is wasted as only the areas

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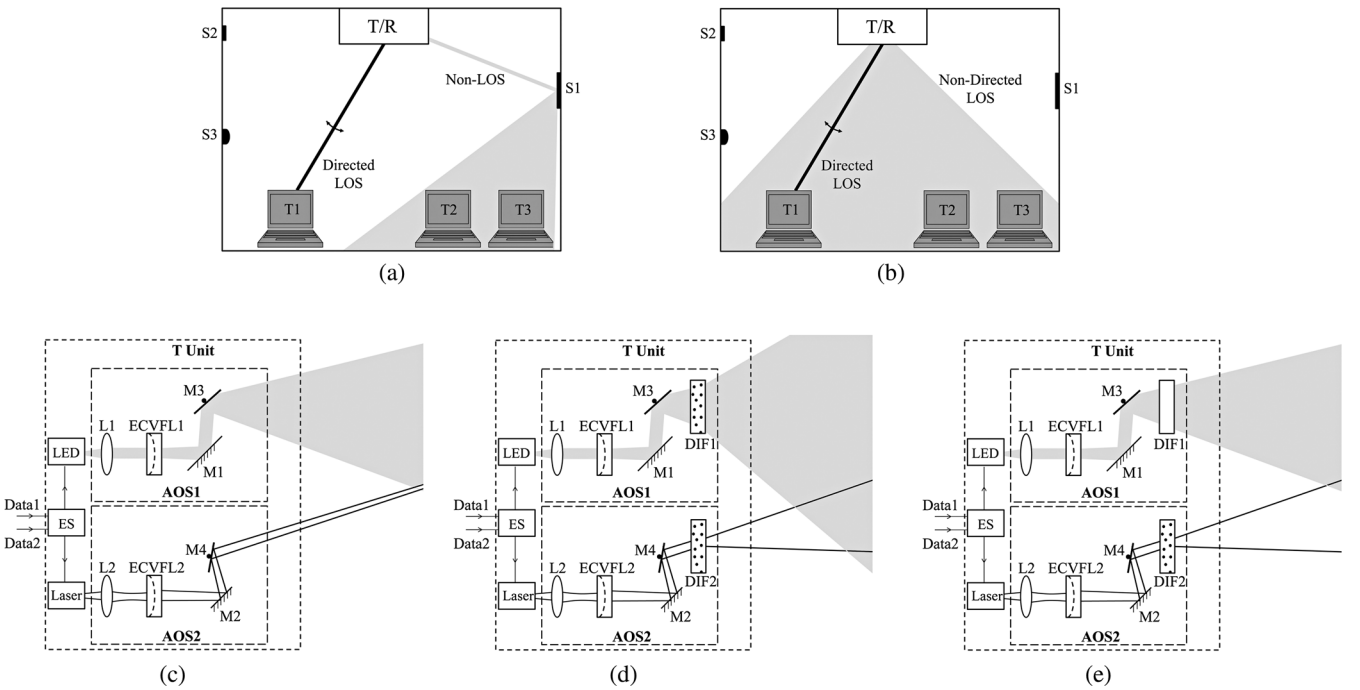


Fig. 1 Shown is the proposed smart multimode indoor optical wireless approach. Wireless operations are shown using (a) non-LOS diffuse mode and directed LOS mode and (b) directed LOS mode and nondirected LOS mode. (c) A dual-mode transmitter design is shown using a laser, LED, ECVFLs, and scan mirrors. (d) and (e) show advanced dual-mode transmitter designs using electronic diffusers. In (d), both electronic diffusers are on and diffuse the light while in (e) only DIF2 is on and diffusing light.

requiring wireless connections are covered intelligently via the chosen scattering/optical antenna. In Fig. 1(a), the diffuse non-LOS link is used to create a nonblocking optical wireless network that can serve multiple stationary users or a moving terminal, while the directed LOS link configures itself to establish a high-speed link with a stationary terminal that requires additional bandwidth. Simultaneous operation of the mentioned wireless modes can be activated to enable user search or during handover while switching between the LOS and non-LOS modes. An example of the switched mode operation is to smartly switch from the directed LOS mode to diffuse non-LOS mode when physical LOS path blocking occurs. This action keeps communications active and when an LOS path again becomes available to reconnect communications via the high-speed LOS link. The proposed design can also switch between modes for changes in application, such as switching from one user $T1$ to multiple users $T2$ and $T3$ or vice-versa. Thus the proposed design in Fig. 1(a) takes advantage of the benefits of LOS and non-LOS diffuse methods since it is able to achieve both the high data rates and the robustness to physical blocking.

Figure 1(b) shows an optical transmitter that is operating in two different LOS modes. Here, the nondirected LOS mode (i.e., wide-coverage beam) is used to serve multiple user terminals $T2$ and $T3$, while the directed LOS mode (i.e., pencil beam) link configures itself to establish a high-speed link with the $T1$ terminal that requires additional bandwidth. Hence, the ability to smartly adapt is achieved, giving an overall higher data rate to the users and/or reducing the amount of transmitted power as a smaller area is being covered by the transmitted light.

Figure 1(c) shows the design of a smart zero-propagation-loss directed LOS optical wireless transmitter[7–9,15] combined with a nondirected LOS transmitter. A 2×2 electrical switch ES routes the two possible electrical signals Data 1 and Data 2 to the respective transmitter. Both transmitters contain agile optical systems (AOS), which form their respective light beams. Specifically, the smart directed LOS link is designed to capture as many photons as were transmitted by the laser beam to produce a lossless transmission channel for communications and minimize the link gain margin due to laser beam propagation.[7–10,15] AOS2 performs 3-D beamforming using a bias lens L2 and ECVFL2 to adapt to changes in link length, while mirror M2 is used to direct the light to mirror M4, which is used for scanning in the xy plane. An example experimental implementation of a mechanical tracking system using a rotating mirror was demonstrated to have a bit error rate (BER) $<10^{-9}$ for 1 Gbit/s.[16] The beam analysis for the smart directed LOS transmitter has been previously analyzed in detail.[7]

In Fig. 1(c), AOS1 is used to change the divergence of the LED source so that there can be control over the tradeoff between coverage area and irradiance using ECVFL2 and the scatterers (e.g., $S1$, $S2$, $S3$). As scatterers/optical antennas can be of different sizes, shapes, scattering properties, and distances from the transmitter, the ECVFL can also provide the optimal beam size illuminating the optical scatterer/antenna for desired illumination of the selected zone. Mirror $M1$ is used to direct the light to the xy scanning mirror $M3$ that directs the light to a chosen scatterer (e.g., $S1$) to make a non-LOS diffuse mode as shown in Fig. 1(a) or make an LOS link as shown in Fig. 1(b). M3 can also be swept across the room for search operations or to keep link connections to mobile targets moving too quickly for the directed LOS link.

Figure 1(d) and 1(e) shows novel transmitter designs, where electronically controlled optical diffuser devices DIF1 and DIF2 are used within the AOS. In Fig. 1(d),

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both DIF1 and DIF2 are activated and cause both beams to spread over a wider area. Figure 1(e) shows DIF2 activated and DIF1 turned off. In Fig. 1(e), only the directed LOS beam is diffused, and the other beam passes through the diffuser unmodified. Similarly, DIF1 can be activated and DIF2 turned off. An example of an electronic optical diffuser is a liquid crystal (LC) diffuser similar to those used in privacy walls. AOSs can use any combination of agile optical elements (e.g., liquid lens, spatial light modulators, LC lens, deformable mirrors) and/or fixed optical elements (e.g., diffusers, scattering surfaces, lenses, mirrors, lenslet arrays, mirror arrays) for 3-D beamforming as long as they meet the specifications of the desired wireless application. An example AOS can use a deformable mirror as the ECVFL and the xy mirror so that a single reflective device performs both the scanning and focusing/defocusing operations.

3 Smart Link Beam Propagation Analysis Using Multimode Optical Sources

For the analysis of AOS1 using a nonlaser light source, one can use ABCD matrix analysis.[17,18] In a given cross-section along the optical axis (z-axis), a paraxial ray can be characterized by its distance from the optic axis (or its height) h and its ray divergence θ with respect to the optical axis. After traveling through an optical system, the input height and ray divergence are related by[17]

$$\begin{bmatrix} h_{\mathrm{OUT}} \\ \theta_{\mathrm{OUT}} \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} h_{\mathrm{IN}} \\ \theta_{\mathrm{IN}} \end{bmatrix}, \tag{1}$$

where A, B, C, and D are the elements of the ABCD matrix (ray transfer matrix) that characterize the system. The ABCD matrix of the system can be obtained by multiplying together the matrices for the optical elements comprising the system.

An example ABCD matrix for AOS1 using the design of Fig. 1(c) with the method of Fig. 1(b) is given by

$$\begin{bmatrix} A & B \\ D & C \end{bmatrix} = \begin{bmatrix} 1 & d_{L1} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ -\frac{1}{f_{L1}} & 1 \end{bmatrix} \begin{bmatrix} 1 & d_{S1} \\ 0 & 1 \end{bmatrix} \times \begin{bmatrix} 1 & 0 \\ -\frac{1}{F_1} & 1 \end{bmatrix} \begin{bmatrix} 1 & L \\ 0 & 1 \end{bmatrix}, \tag{2}$$

where d_{L1} is the distance from the LED source to $L1$, f_{L1} is the focal length of $L1$, d_{S1} is the distance from $L1$ to the ECVFL, F_1 is the focal length of ECVFL1, and L is the distance from ECVFL1 to the receiver. Note that the ABCD matrix for deflection from a flat mirror is the identity matrix; thus it is not explicitly shown in Eq. (2) since it does not change the result. Notice that the AOS1 ABCD matrix is dependent on F_1, providing control over the ray height and ray divergence, thus enabling control over the coverage area. To find the relationship between the ray height, ray divergence, and F_1, substitute the results of Eq. (2) into Eq. (1).

$$h_{\mathrm{OUT}} = A\,h_{\mathrm{IN}} + B\,\theta_{\mathrm{IN}} \qquad \theta_{\mathrm{OUT}} = C\,h_{\mathrm{IN}} + D\,\theta_{\mathrm{IN}}, \tag{3}$$

where

$$\begin{aligned} A &= 1 - \frac{d_{S1}}{F_1} - \frac{d_{L1}}{f_{L1}}\left(1 - \frac{1}{F_1} - \frac{d_{S1}}{F_1}\right) \\ B &= L + d_{S1} + d_{L1} - \frac{L}{F_1}(d_{S1} + d_{L1}) \\ &\quad - \frac{d_{L1}}{f_{L1}}\left(L + d_{S1} - \frac{d_{S1}L}{F_1}\right) \\ C &= -\frac{1}{f_{L1}}\left(1 - \frac{1}{F_1} - \frac{d_{S1}}{F_1}\right) \\ D &= 1 - \frac{L}{F_1} - \frac{1}{f_{L1}}\left(L + d_{S1} - \frac{d_{S1}L}{F_1}\right). \end{aligned} \tag{4}$$

Thus using Eqs. (3) and (4), F_1 can be found to achieve the desired divergence and coverage area.

The smart indoor visible wireless LOS link has already been analyzed for single-mode Gaussian beam lasers.[7] This analysis can be extended to multimode laser sources for AOS2 by using the M^2 propagation parameter.[17–21] Specifically, ray optics ABCD matrix method[17,18] can be used to conduct smart link beam propagation analysis when using multimode optical sources for the link. The results of this analysis are presented here and details on derivations of the ABCD matrices are in Refs. 17 and 18. The relation between the multimode beam radii and M^2 propagation parameter can be written as[22]

$$W(z) = Mw(z), \tag{5}$$

where $w(z)$ is the beam radii of the embedded fundamental mode Gaussian beam at a distance z from the source. Thus the Rayleigh range is[22]

$$z_R = \frac{\pi w_0^2}{\lambda} = \frac{\pi W_0^2}{M^2\lambda}, \tag{6}$$

where λ is the wavelength of the laser beam, w_0 is the minimum beam radius of the embedded single-mode Gaussian beam, and W_0 is the minimum beam radius of the multimode laser beam. Assuming the same input and output media, the beam waist for a single-mode Gaussian laser beam at any location in the optical wireless link can be written as[7]

$$w(z) = \sqrt{\frac{\lambda}{\pi}\frac{(Az_R)^2 + B^2}{z_R}}, \tag{7}$$

where A and B are the respective elements of the ABCD matrix. The minimum beam waist size can be written as[7]

$$w_{\mathrm{Min}} = \sqrt{\frac{\lambda z_R}{\pi[(Cz_R)^2 + D^2]}}, \tag{8}$$

where C and D are the respective elements of the ABCD matrix. Substitution of Eqs. (5) and (6) into Eqs. (7) and (8) leads to

$$W(z) = M\sqrt{\frac{\lambda}{\pi}\frac{(Az_R)^2 + B^2}{z_R}}, \tag{9}$$

and

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$$W_{\mathrm{Min}} = M\sqrt{\frac{\lambda}{\pi}\frac{z_R}{[(Cz_R)^2 + D^2]}}. \tag{10}$$

Using Eqs. (9) and (10) instead of Eqs. (7) and (8), the optical link design can be analyzed using the method in Ref. 7. Following this method, one can compute the design parameters needed to achieve a low-propagation-loss link for a given maximum link range and maximum BER for an eye-safe maximum laser power level.

4 Smart LOS Links Using Multimode Sources: Experimental Demonstration

Spatially multimode optical sources, such as multimode lasers and LEDs, are cost-effective, high-reliability light sources suited for large-scale industrial deployment. Hence, it is important to demonstrate the operational principles of the ECVFL-based smart LOS link using multimode lasers and LEDs. Using the dual-mode link transmitter design shown in Fig. 1(c), a proof-of-concept link is implemented for a visible laser and a visible LED source. The purpose of this paper is to demonstrate a new indoor optical wireless approach that combines current optical wireless methods into one smart system that takes advantage of the benefits of each method. The focus of the paper is on improving the optical design of the smart system. There are several well-known data modulation methods for lasers and LEDs. Optical wireless links have been demonstrated based on intensity modulation and direct detection using visible lasers (by Vixar) and LEDs producing data rates of 10 Gbps and 500 Mbps,[3] respectively. For a particular modulation technique, a certain average transmitted optical power is needed to achieve a given BER.[14] Using agile optical beamforming to increase the amount of received optical power from the transmitter means that the BER (or SNR) can be improved or the same BER can be achieved with a lower amount of transmitted power. The specific increase in BER is dependent on the data modulation technique chosen. Thus, it was decided to use only analogue modulation for this demonstration. The laser deployed is a Global Laser Beta-Tx Laser Diode Module with $\lambda = 670$ nm. This laser module has a built-in bias lens ($L2$) and is capable of being modulated at speeds up to 50 MHz. The 650-nm LED source deployed is the transmitter portion of the Firecomms FS-EDLT Evaluation Board transmit/receive (T/R) unit. This T/R unit was originally developed for short-range (<50 cm) optical wireless communication with a built-in bias lens ($L1$) and data rates <125 Mbps. It uses a silicon (Si) P-I-N photodiode in its receiver that has a responsivity of 0.3 A/W at 660 nm and 0.45 A/W at 850 nm. Typical responsivity curves for Si, germanium (Ge), and indium gallium arsenide (InGaAs) photodiodes versus wavelength are found in Ref. 23. Note that Ge and InGaAs photodiodes have much better responsivity than Si in the infrared region, so they are used in infrared applications. AOS1 is composed of an ECVFL placed at a distance of 5 cm from the LED module. AOS2 is set up using an ECVFL placed 8 cm from the laser source. No mirrors or diffusers are used in either AOS. The broadband visible light ECVFLs used in the system are Varioptic (France) Arctic Model 320 liquid lenses based on electrowetting technology. A Firecomms FS-EDLT Evaluation Board receiver is used as the photoreceiver in the experiment. For optical power measurements, a Newport 2931-C power meter is used with a 1 cm^2 active area Newport 918 photodetector. In the smart link demonstration, the laser is modulated at a lower speed than the LED since

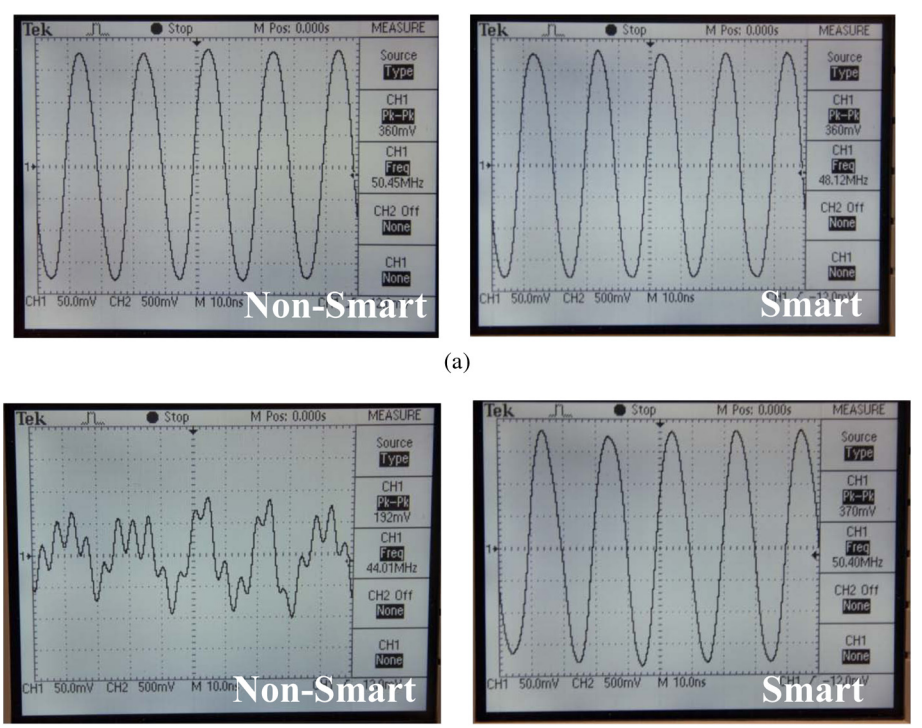


Fig. 2 The photodetected 50 MHz signals of the nonsmart 670-nm multimode laser-based and smart-directed LOS link at a distance of (a) 0.2 m and (b) 1.5 m.

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this specific laser module's bandwidth is lower than that of the LED module used. In practice, laser links can be modulated at higher data rates than LED links.

First, the directed LOS transmitter and nondirected LOS transmitter operating in separate switchable states is demonstrated. The photodetected RF signals are presented to visually show the improvement in signal quality that the smart link using the ECVFL provides over the nonsmart link. Figure 2 shows the performance of a nonsmart link and the smart LOS laser link for a photodetected signal at 50 MHz. As expected, Fig. 2(a) shows good performance for both the smart and nonsmart link at a short range of 0.2 m. Now note in Fig. 2(b) that as the link range reaches 1.5 m, the nonsmart link performance degrades drastically, while the smart LOS laser link continues to provide a good signal. In effect, the use of the smart link extends the LOS link range by a factor of 1.7, since the nonsmart link only worked up to 0.88 m. Longer link ranges can be achieved if a different bias lens or lens combination is used.[7] Figure 3 shows the photodetected signal for the nonsmart and smart LOS LED link operating at 100 MHz. Here again, the objective is to get the maximum amount of power achievable using the smart LED link. Figure 3(a) shows good performance for the nonsmart link at a short link range of 0.3 m. As shown in Fig. 3(b), the smart LED link continues to provide a good signal with link range of 1.1 m, a factor of two improvement in link range versus the nonsmart link, which only worked until 0.55 m.

Figure 4 shows the improvement achieved in received optical power at varying distances for the smart link versus the nonsmart link using the multimode sources. Specifically, Fig. 4(a) shows a 1.7× improvement (at 1.3 m) in received optical power for the smart laser link versus the nonsmart laser link. Similarly, Fig. 4(b) shows a 2.1× improvement (at 1.3 m) in received optical power for the smart LED link versus the nonsmart LED link. Note that even though the sources used had irradiance profiles that are not uniform with increasing link distance, link performance improvements are still achieved using the agile ECVFL optics. Additionally, higher received power means an improved SNR or BER. Also note that using a smaller active area high-speed photodetector compared to the Newport detector increases the smart link received optical power improvement factor.

Figure 5 shows simultaneous operation of the directed LOS laser link and the nondirected LOS LED link. Another feature of the Fig. 1 transmitters is that ECVFLs can be used to control the amount of RF power generated by the photoreceivers and thus operate with optimal photodetection power levels for best SNRs. Moreover, fine control of optical irradiance at a given range achieved via the ECVFL along with data signal coding methods can reduce the chances for eavesdropping by an unauthorized user. To demonstrate this variable optical attenuation/irradiance control operation, Fig. 5(a) and 5(b) shows a 2.7 dB difference in the received RF power levels at a range of 1 m for the nondirected LOS LED link for two different drive settings of the ECVFL.

As mentioned, the ECVFL can also be used to provide beam coverage area and irradiance (Watts/m^2) control in the receiver zones. Figure 6 shows LED light beam coverage area control via ECVFL at a link distance of (a) 0.9 m and (b) 2.5 m. Experiments indicate that despite the nonsingle spatial mode of the LED, the ECVFL is able to produce controllable size beam spots needed to form the smart link. Note that for zero-loss smart link operations, the ECVFL should be

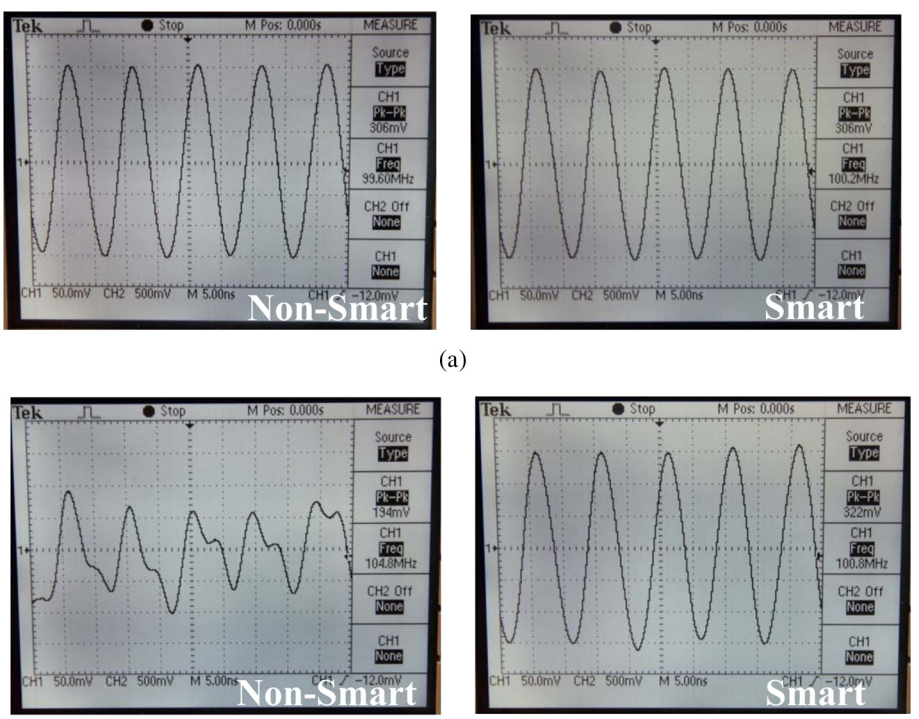


Fig. 3 The photodetected 100 MHz signals of the nonsmart multimode 650-nm LED and smart nondirected LOS link at a distance of (a) 0.3 m and (b) 1.1 m.

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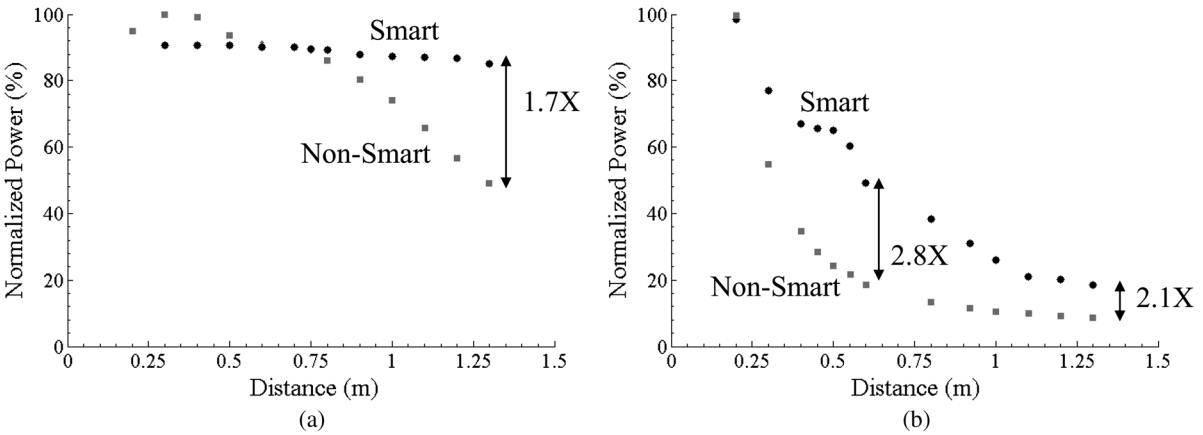


Fig. 4 The received optical power detected for the data modulated signals for the nonsmart and smart wireless links using (a) 670-nm multimode laser link and (b) 650-nm multimode LED.

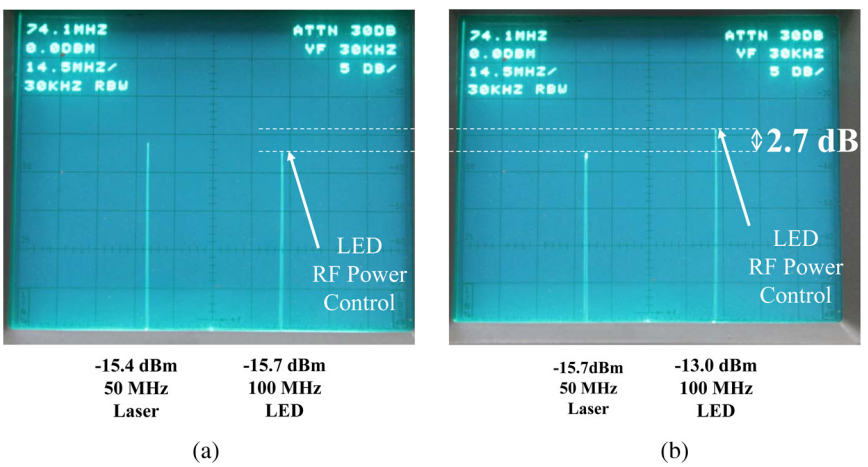


Fig. 5 Simultaneous LOS laser and LOS LED link operation demonstrating the use of agile beamforming to control the amount of optical irradiance and hence RF signal produced at a link distance of 1 m. The RF power control shown is for a change of 2.7 dB.

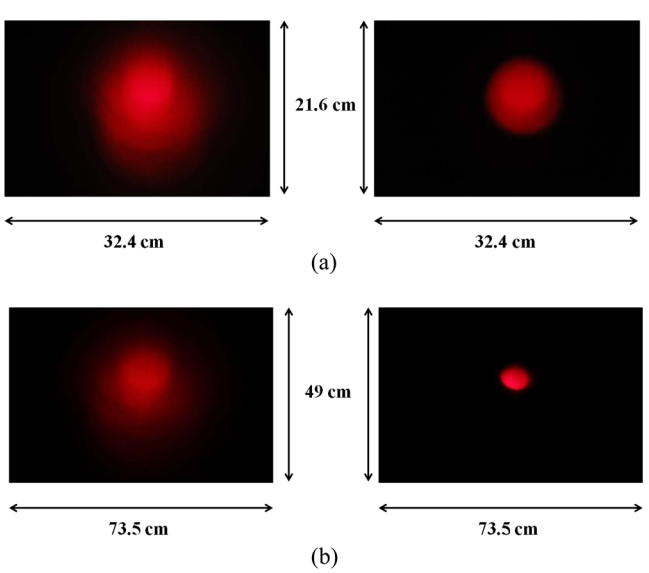


Fig. 6 Multimode 650-nm LED light beam coverage area control via ECVFL at a link distance of (a) 0.9 m and (b) 2.5 m.

configured to realize the smallest beam area (or achieve the highest irradiance) possible at the receiver.

Note that for networks with large information capacity that a single proposed transceiver is not able to handle, data transmission can be done using multiple transmitters, i.e., a transmitter array in conjunction with agile optic lens array, instead of single elements within the transceiver.

5 Conclusion

In conclusion, presented is the design of a smart multiple-modes indoor optical wireless system that combines LOS and non-LOS optical wireless methods to smartly adapt to changes in environment and application. The proposed design is able to operate in three optical wireless modes called directed LOS, nondirected LOS, and diffuse non-LOS. These modes smartly accommodate for changes in the number of users/user mobility and optimal coverage area, along with providing an increasing robustness to receive light blocking. By choosing the optimal coverage area and optimizing the transmitted power, the optical wireless system is made energy efficient. Experiments conducted demonstrate for the first time that economical high-reliability multimode visible light sources, such as lasers and LEDs,

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indeed have the spatial properties to implement proposed 3-D beamforming required for energy-efficient smart optical wireless LOS links. Applications for the smart multiple-mode wireless system includes mobile computing, medical monitoring, data center computer communications, and wireless sensor networks.

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