

Accepted paper before reformatting and proofing **Transmitter and receiver technologies for optical wireless**

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Summary

Providing a reliable link, with sufficient signal to noise ratio and bandwidth to deliver high-capacity communications is a critical challenge for optical wireless communications (OW) and understanding and jointly optimising the performance of the transmitter and receiver subsystems is a key part of this. At the transmitter a source of light, either a Laser or an LED, must be modulated with the communications signal. The resulting emission must be directed, using optics or steering systems, as required for the particular application, and must be within any safety levels set by relevant standards. The receiver is the most critical part of any optical link, as its design is a dominant factor in determining the received signal to noise ratio, which determines the capacity and ultimately the utility of the link. A receiver must collect, filter and concentrate signal radiation, then detect and amplify the resulting electrical signal. This review surveys the state of the art transmitter and receiver technologies. Details of design constraints are discussed, and potential future directions discussed.

Systems considerations and overview

Optical wireless systems require a free-space link between a transmitter and a receiver, with sufficient received signal to noise ratio, and sufficient bandwidth to support communications at the desired rate, and

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with an acceptable error level. Figure 1 shows typical system configurations. Communications is achieved by modulating the transmitter source output intensity with an input electrical signal representing the information to be transmitted, and detecting the modulated optical power at the receiver, where it is converted into an electrical signal. The signal is then decoded to yield the transmitted information. The vast majority of OW links use this Intensity Modulation/Direct Detection approach, although there have been a number of coherent communications demonstrations (see for instance(1)) , where the amplitude and phase of the optical signal transmit information.

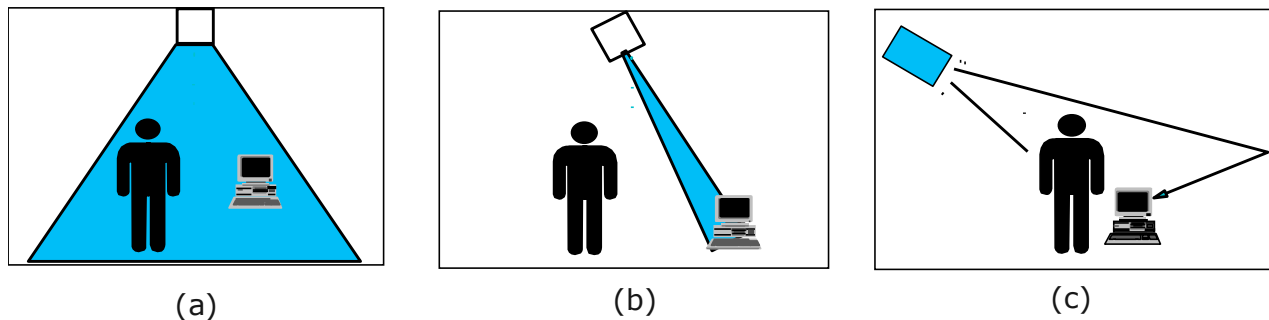


Figure 1. Optical wireless communications system (a) Wide Line of Sight (LOS) (b) Narrow LOS (c) Diffuse (non-LOS)

Links can be line of sight (LOS), or use non-Line of sight (nLOS) depending on the geometries used. For line of sight links, as shown in Figure 1 (a) and (b) there is effectively a single path between transmitter and receiver and all parts of the information signal transmitted at one instant arrive at the receiver at the same time, so dispersion of the signal is not an issue. For nLOS systems, as shown in Figure 1 (c) there are multiple paths between transmitter and receiver, so dispersion of the information occurs, limiting the bandwidth of the optical channel. This is a geometric effect, depending on the environment and the orientation and characteristics of the transmitter and receiver. Effects can be significant, with bandwidths of <100MHz being measured in a typical room(2).

Optical propagation models (see for instance (3)) can be used to determine the system loss for LOS links, and more sophisticated ray-tracing techniques(3) can be used to determine the characteristics of propagation. The path loss (defined as the ratio of average modulated optical power transmitted to that received) and the

impulse response of the optical channel are key characteristics that modelling determines. Path loss is a key challenge for OW, as receiver sensitivities are low compared with RF communications, due to the direct detection used.

OW systems have been developed over a wide range of wavelengths, and choice of wavelength is complex, depending on application, environment, link margin and safety considerations. Visible Light Communications (VLC) operates in the 400-750nm region of the optical spectrum and can combine solid-state (typically LED based) lighting and communications. The near infra-red region of the spectrum, from 750-1000nm is often used, as low-cost semiconductor sources (either lasers or LEDs) are available, and crucially low-cost, high bandwidth and large area photodetectors (required for reception) based on silicon can operate in this region. A major potential impairment to the operation of OW systems is additional noise due to ambient light, both sunlight and artificial lighting, which both have substantial energy in the same wavelength range as the communications signal.

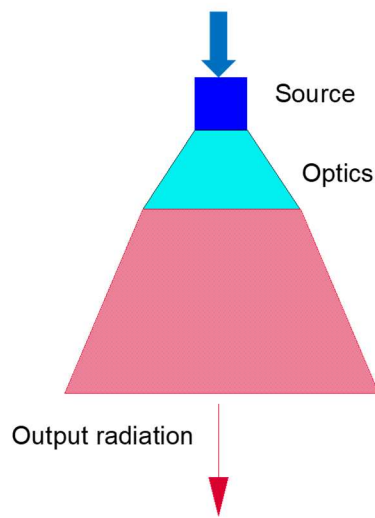
Systems operating in the 1500nm band used for fibre communications are attractive, as they can use components designed for optical communications, and for the more relaxed eye-safety regulations that exist. In addition, ambient light impairments are less substantial in both these IR regions, as artificial illumination and sunlight become less intense with increasing wavelength (See for instance (4)).

Eye safety is governed by two standards; EN 60825-1 (5) for lasers and EN 62471(6) for LEDs. For lasers and LEDs, safe emission power limits are wavelength dependent. For lasers in the visible wavelength range the natural human aversion to bright lights provides additional protection. The near IR region (~750-1400nm) has stringent limits, as the eye can still focus radiation, but there is no aversion response. The band above ~1400nm is less hazardous as the water in the eye absorbs the radiation before it reaches the retina, and the hazards become skin and corneal, rather than retinal. Source size can also affect the hazard, depending on wavelength, and whether it is an LED or laser. Broadly, diffuse large area sources are safer in that power cannot be so highly focused onto the retina as a point source, but this is not always the case, and the relevant standards provide detailed procedures for classification.

The following sections detail different transmitter and receiver technologies, and how they are used to provide communications. Table 1 shows a summary of different Visible Light and Infrared optical wireless systems demonstrated thus far.

Transmitters

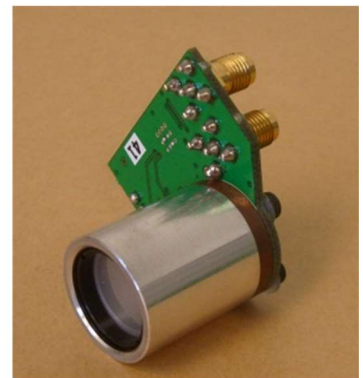
Modulated electrical driving signal



(a)



(b)



(c)

Figure 2. Transmitters (a). Block diagram. (b) LED based transmitter. (c) Laser based transmitter.

Figure 2(a) shows a typical transmitter. An electrical signal, modulated with the data that is to be sent, is applied to a solid-state semiconductor-based source, either Laser or LED, and the intensity of the source is modulated according to the signal. The electrical to optical transfer function can be either linear or non-linear depending on the electrical driving circuits, and requirements of the modulation scheme used for communications. A further optical element can then be used to control the shape of the emission from the source, and also enhance its safety.

Laser transmitters

Semiconductor lasers offer a wide range of different wavelengths and powers, with the potential to modulate with high bandwidth electrical signals. Lasers are current controlled devices and above a certain threshold current there is typically a region where light output is linearly proportional to the input current, up to some current where the output power saturates or increases little with increasing current. If a linear electrical-

optical transfer function is required the device will be biased in the middle of its operating regime, and modulated about this operating point. For pulsed based modulation schemes devices are biased at the laser operating threshold, with a modulation signal then turning the laser on, thus creating an output pulse of radiation.

Typically, laser sources use collimating optics to control beam divergence, and a diffusing element to destroy source spatial coherence. Lasers are effectively point sources, and the diffuser ensures that anyone viewing the source cannot see a sharp image of the point source- the effective source becomes the spot formed by the laser beam on the diffuser. This increases the safe emission power substantially, as optical power cannot be focused onto the retina. Early diffuser demonstrations used ground glass(7), but holographic diffusers(8, 9) allow the divergence of the beam from the diffuser to be controlled and shaped. Figure 2(c) shows a laser transmitter that uses a holographic diffuser at its output to control beam divergence and increase transmitted power(10). As can be seen from Table 1 a number of visible light communications demonstrations use lasers, and here the quality of the white light is effected by the narrow linewidth of the laser sources, and their coherence (see (11) for a discussion of this).

LED transmitters

The revolution in solid-state lighting, driven by the development of the Blue LED, has led to the development of Visible Light Communications. This was pioneered in Japan(12), and is now a substantial research area. Figure 2(b) shows a typical white LED, used as a transmitter. Figure 3(a) shows the emission spectrum of such an LED. Blue light is generated by a blue Gallium Nitride LED, and this is coated with a phosphor layer that absorbs some of the blue radiation and emits yellow light. The combination of the residual blue light that is not converted and the yellow from the phosphor together produce white light. Some luminaires combine red green and blue emitters to allow colour tunable emission, but this is not widely used for general lighting. Figure 3(b) shows the optical response of the LED when driven by a short electrical pulse for cases when the white response is measured, and when the yellow response is blocked using an optical filter. It can be seen that the blue emitter has similar turn-on and turn-off characteristics, but the phosphor causes a long turn-off response. The modulation bandwidth of the emitter is typically 10-20MHz (13), whereas the white LED might have a bandwidth of ~5MHz(13), due to this slow phosphor response.

1 There are a number of different approaches to increasing LED bandwidth. Pre-equalising the driving signal
2 (effectively increasing the driving signal at higher frequencies) either using analogue circuits, compensating
3 the signal, or using an array of sources to create an aggregate response (14) have all been demonstrated.
4 The large area and high capacitance of the LED limits the modulation bandwidth, as does the current density
5 at which the device is driven. Small area micro-LEDs, driven at high current densities, with bandwidths up to
6 several hundred MHz have been demonstrated, with growing research into such structures (see (15) for a
7 review paper on this subject). Arrays of such LEDs can be used for transmission of different data from each
8 LED, as described later in this paper, or aggregated to provide increased source power. As examples, in (16,
9 17) arrays of LEDs are used to create sources that convert digital signals directly into light levels. Resonant
10 Cavity LEDs incorporate a lower finesse cavity than a laser structure in order to enhance efficiency and
11 modulation bandwidth, and high data rates have been demonstrated with these devices (18).
12 High bandwidth colour converters have been also been developed, using polymer (19), perovskite (20),
13 quantum dot (21) and semiconductor (22) approaches, with high data-rate white light sources demonstrated
14 using such approaches.
15 The choice of Lasers or LEDs for VLC depends on a number of factors. Lasers are more efficient and have
16 higher modulation bandwidth than LEDs, but lighting using such sources is at an experimental stage, whereas
17 LEDs are widely deployed for lighting systems. Analysis of the application and the environment, including
18 eye safety considerations, are required to determine which approach is best.

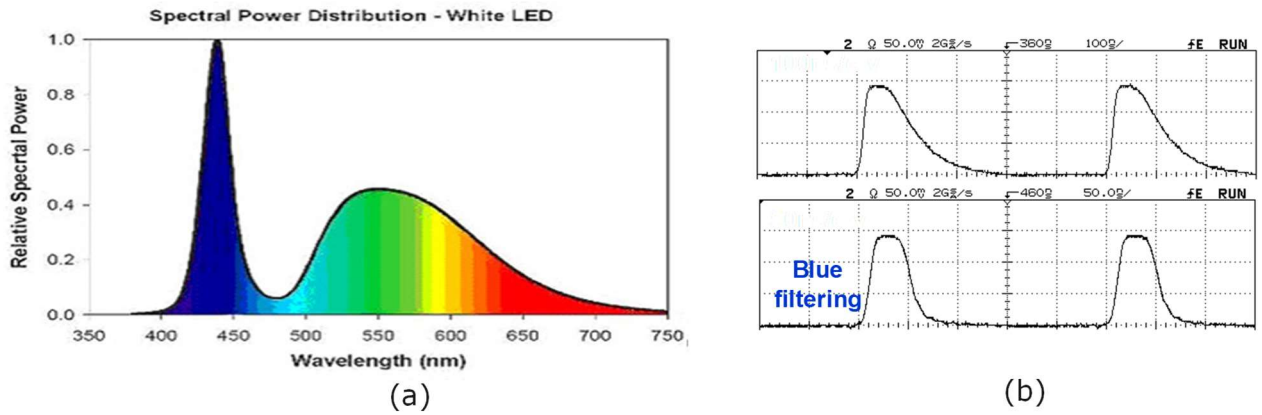


Figure 3. (a) LED emission spectrum. (b) Time response

For VLC the LED sources used typically have limited bandwidth but can provide high levels of signal at the receiver. Levels of illumination for different types of indoor space vary(23), but a well-lit space has levels of 4-500lux. For such illumination an extremely high Signal to Noise Ratio (SNR) can be achieved at the receiver. Figure 4 shows the measured response of a typical channel. It can be seen that the bandwidth of the channel (defined as the point where the response drops 3dB below its maximum) is a few MHz, but the response is free from noise up to several hundred MHz, at which point it is 50dB below its maximum. The choice of modulation scheme therefore needs to be optimised for what is a narrow bandwidth, very high SNR channel.

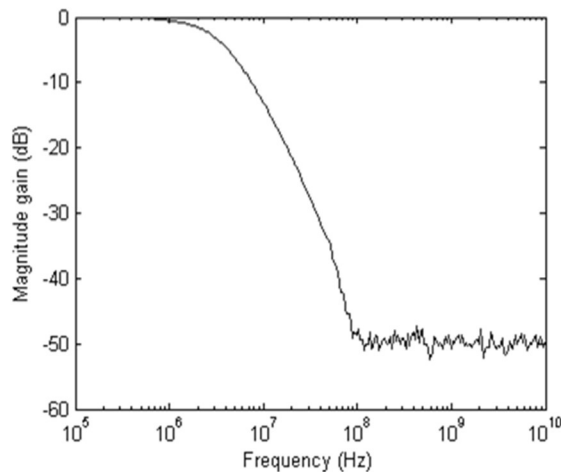


Figure 4. Measured Electrical Response of typical VLC channel

Multilevel modulation schemes are suited to High SNR channels as levels can be sufficiently well spaced to ensure they can be distinguished, and schemes such as m-level Pulse Amplitude Modulation (m-PAM) have been used to maximise the available data rate(24).

Equalisation schemes effectively flatten the channel response, extending the bandwidth at the cost of SNR, and PAM combined with digital equalisation is also effective(25). Orthogonal Frequency Division Multiplexing (OFDM) (26) combines a large number of low-speed data streams using a series of orthogonal carrier frequencies, and allows the modulation scheme of each carrier to be optimised for the available SNR. This has become a standard scheme for VLC, and for LED based communications links. There are several ways to implement the OFDM for IM-DD based optical systems: DC-biased optical OFDM (DCO-OFDM) (27), asymmetrically clipped optical OFDM (ACO-OFDM) (28) and their hybrids (29, 30). For intensity modulation, the time domain OFDM signal should be real and non-negative. DCO-OFDM applies Hermitian symmetry on the frequency domain signal to meet the real constraint and adds appropriate DC bias to satisfy the non-negative constraint. ACO-OFDM also uses Hermitian symmetry but modulates subcarriers in a way that clipping negative signal components to make a positive time domain signal does not affect the integrity of data. Using only half the available subcarriers for the special structure its spectral efficiency is half that of DCO-OFDM. However, as no DC bias is used, ACO-OFDM exhibits a high power efficiency.

A number of papers (31, 32) compare the power efficiency of m-PAM, DCO-OFDM and ACO-OFDM and show that m-PAM has the lowest and ACO-OFDM has the highest especially at low modulation orders. There are also hybrid optical OFDM schemes, which combine features of the DC-biased and non-DC-biased OFDM (29)(30). Considering the complexity of the receiver signal processing, OFDM techniques typically use Fast-Fourier-Transform (FFT) operations, and have complexities of $O(N\log_2 N)$ (33). Reference (34) details spectral and power efficiency of these optical OFDM schemes, considering the channel capacity and power allocation. Reference (35) showed a real time demonstration using OOK with 1Gb/s data-rate over 1.5m optical wireless link. Reference (36) demonstrated 4-PAM with 10Gb/s data-rates over 5m using a laser diode (LD). For optical OFDM, data rates of Gb/s has been achieved in using DCO-OFDM with lighting LEDs(37, 38), with higher rates for optimised micro-LED devices (39, 40) and lasers (41). ACO-OFDM is difficult to implement in a practical optical wireless channel with a limited linear dynamic range, but over an optical fibre (42)

demonstrated multi Gb/s. For the comparison between m-PAM and OFDM (43) numerically showed that m-PAM can outperform the OFDM for bandwidth limited channels, but that OFDM is superior in noise limited situations. A summary comparison of different schemes is shown in Table 2.

Modulation Format	Spectral Efficiency	Power Efficiency	Receiver Complexity	Demonstrations (Data-rate, distance, source)
OOK	1	moderate	$O(N)$	1Gb/s, 1.5m, LED (35)
m-PAM	$\log_2(m)$	low	$O(N)$	10Gb/s, 5m, LD (36)
m-DCO-OFDM	$\log_2(m)$ *	moderate	$O(N \cdot \log_2(N))$	2Gb/s, 1.5m, WLED (38) 5Gb/s, 0.5m, μ LED (36) 6.5Gb/s, 0.15m, LD+phosphor (41)
m-ACO-OFDM	$\frac{\log_2(m)}{2}$	high	$O(N \cdot \log_2(N))$	3Gb/s, 20km fibre, LD (38)

* When single side spectrum is considered the used BW (31, 32)

Table 2. Properties and demonstrations of selected modulation schemes

Receivers

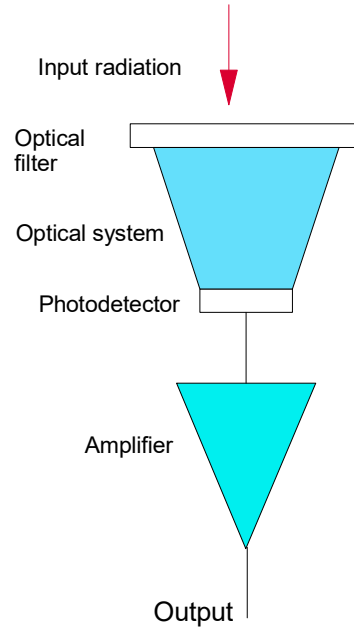


Figure 5. Receiver block diagram

Figure 5 shows a typical receiver. Light enters the receiver through an optical filter, which can be used to block unwanted ambient light, or in the case of VLC block the slow yellow light from the phosphor. Light is then collected and focused or concentrated onto a photodetector, which converts the optical power to an electrical signal. This is amplified, and the resulting signal is processed to yield a received data stream.

An ideal receiver would have a wide field of view, so that it does not need to be aligned with the transmitter, and focus light onto as small a photodetector as possible. Detector capacitance often limits the receiver bandwidth, and this is proportional to the area of the detector, so minimising detector size is a key goal.

Lenses, and any other optical elements used to achieve this optical concentration are subject to the limitations of etendue(44). Figure 6(a) shows a concentrating optical system, and for a lossless element

$$A_i \Omega_i \leq A_o \Omega_o$$

Where A_i , A_o and Ω_i , Ω_o represent the area and field of view at input and output of the system respectively.

For a typical planar photodiode area A its field of view is 2π Sr and its etendue $2\pi A$, and photodetector etendue ultimately limits the field of view and collection area of the receiver that can be achieved-both a wide

field of view and large collection area are typically not possible. The maximum gain G_{max} (the ratio of collection area to photodetector area) that can be achieved is

$$G_{max} = \frac{n^2}{\sin^2 \theta}$$

for a concentrator of refractive index n and full-angle field of view 2θ . It can be seen that a wide field of view can only be achieved at the expense of limited optical gain. In practice, Compound Parabolic Concentrators (CPCs) and variants thereof can achieve gains approaching this limit(45), and such a device is shown in Figure 6(b). More compact optical structures, including holographic elements (46) have also been proposed and demonstrated.

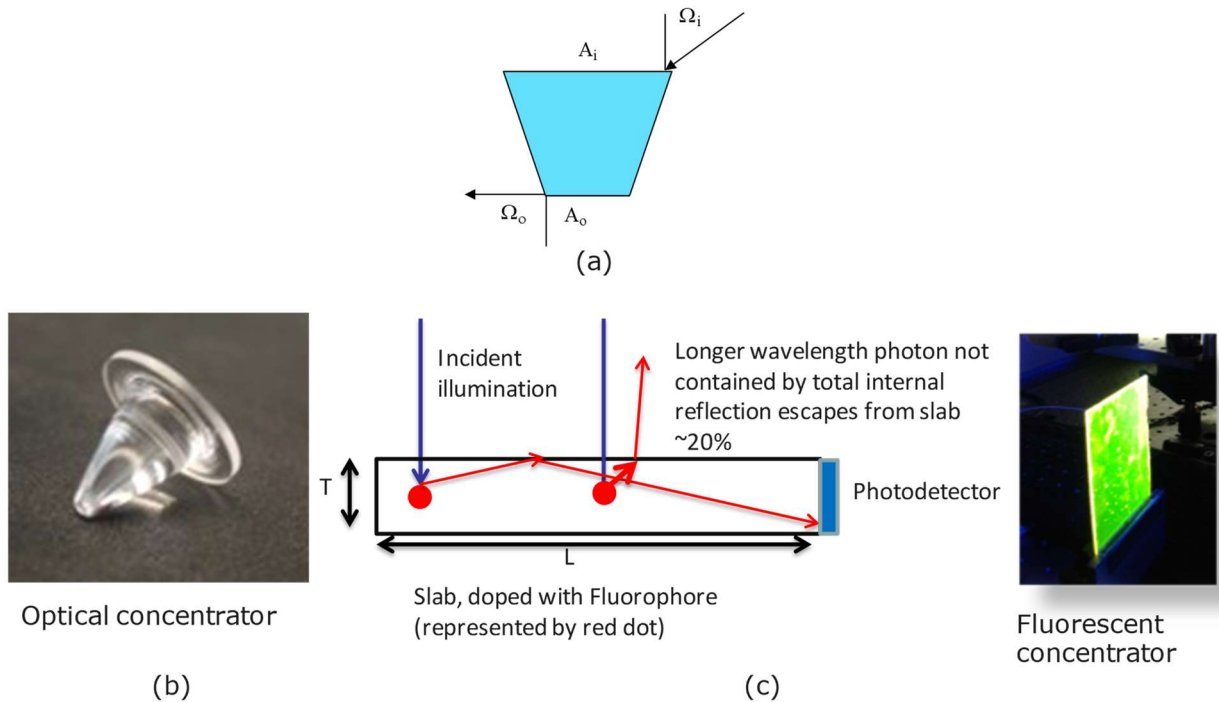


Figure 6. (a) Conventional Optical concentrator (b) Fluorescent concentrator.

Perhaps surprisingly, elements that do not preserve etendue can operate as effective concentrators.

Figure 6(c) shows a fluorescent concentrator based receiver, which operates using a similar principle to a luminescent solar concentrator(47). Light illuminates the concentrator, which is a slab of transparent material doped with a fluorophore. The fluorophore absorbs incident photons and reemits them, omnidirectionally, at a longer wavelength. Total internal reflection within the slab traps these photons and they propagate to an

1 edge where a photodetector is situated. This effect can be seen in Figure 6(c), where the edges of the
2 concentrator are brighter than the faces. The field of view of the device is determined by the reflection of the
3 incident illumination, rather than etendue, and the overall efficiency of the device is determined by a number
4 of factors, including the conversion efficiency and reabsorption of the photons within the slab. The use of such
5 a device in communications was proposed and modelled in(48) , and reported in(49-51). Gains of ~10 have
6 been measured in such concentrators, compared with a theoretical maximum of ~4 for a conventional design
7 with similar field of view(49).

8 Close integration and co-design of the photodetector and subsequent amplifier are required to obtain the best
9 performance from a receiver. This combination of amplifier and detector determines the bandwidth and noise
10 performance of the receiver. Design is a complex subject (52, 53). Both PIN and Avalanche Photodetectors
11 (APDs) are used as detectors, and the capacitance per unit area (and hence achievable bandwidth which is
12 reduced as capacitance increases), noise and in the case of APDs, gain, are key parameters. OW has distinct
13 requirements from optical fibre based systems, in that the power collected is proportional to the detector area,
14 making the capacitance of the detector a key consideration, whereas in a fibre system the detector simply has
15 to be large enough to capture light from the fibre, and increasing the size has no benefit. PIN devices are
16 typically used for lower performance links, whilst APDs provide additional gain by including a region in the
17 device structure which promotes semiconductor avalanche breakdown. This creates signal gain albeit with
18 attendant noise

19 For VLC and near IR wavelength systems silicon based devices are dominant, with Indium Gallium Arsenide
20 (InGaAs) devices preferred at longer wavelengths. Transimpedance amplifiers, which convert the
21 photocurrent from the detector into a voltage are predominantly used as the initial preamplifier in any
22 receiver. There has been some work on optimising receivers for OW. In work reported in (54) low capacitance
23 detectors were grown and combined with CMOS preamplifiers design to be tolerant to high input capacitance,
24 and in(55-57) high data-rate designs have been pursued. Integrated transceivers and high speed TIAs are also
25 reported in (58-60).

26 Single Photon Avalanche Detectors (SPADs) are detectors that are sensitive to single photons, and are thus
27 offer a route to high sensitivity receivers(61, 62). Each detected photon results in an output pulse from the

SPAD, and the detector must then be reset before detecting further photons, creating a ‘dead time’ where photons cannot be detected. Arrays of thousands of individual detectors can be fabricated (these devices are known as Silicon Photomultipliers), and at low levels of illumination only a proportion of the detectors are subject to this dead-time restriction at any one instant, leaving sufficient numbers of detectors active to receive a communications signal. Demonstrations of pulse-based (63) and more complex linear modulation schemes(64) have shown high-rates are feasible at levels of ambient light typical within rooms and buildings, with sensitivities exceeding those of conventional APD based receivers. A potential advantage of such detectors is that their bandwidth is independent of detection area, as increasing area is achieved by increasing the number of detectors, rather than the area of an individual device (65).

Overall, receivers that use APDs typically provide higher sensitivities (typically of the order of 10dB for a given link configuration), albeit at the cost of more complex biasing circuitry, and the highest performance links demonstrate thus far have used APDs. SPADs are a potentially attractive alternative to such linear APDs but have had limited use thus far.

The use of solar cells as both energy sources to remotely power receivers and as communications signals has also been investigated and demonstrated, with data rates of 0.5Gbps(66). In (67) a demonstration of a backhaul link for 5G wireless systems in a rural environment is reported. A significant challenge is the slow response of the solar cells due to their large area, bias conditions and structure, and this is mitigated by the use of bandwidth efficient modulation schemes.

Advanced configurations

Once the data rate of a single link has been maximised, techniques to multiplex data transmission across different channels can be used to further increase transmission capacity. Creating white (and other colour) light using a combination of LEDs offers the possibility of sending different data streams on each LED and separating them using optical filtering at the receiver. Data rates of up to ~15Gbits/s(68) have been demonstrated using red, green, blue and yellow LEDs and up to 35Gbits/s using red, green, blue, and violet lasers (69). Alternatively, the LEDs can be used together rather than as independent channels, and Colour Shift Keying (CSK) uses the colour sent as the data symbol. There is extensive research in this area(70, 71), and the technique is incorporated into an IEEE standard(68).

At the transmitter, arrays of lasers or LEDs offer the opportunity to either increase coverage area or transmit multiple data streams when compared with a single source and detector. At the receiver, arrays of detectors

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can enable large collection areas and high bandwidth, as each individual detector in the array can have low capacitance and thus high bandwidth. Examples of array receivers can be found in (72) and in (73). For both the transmitter and receiver the challenge is the implementation complexity, as individual drive circuitry is required for each source, and receiver circuitry for each detector in the respective arrays. Figure 7 shows different configurations that use such arrays.

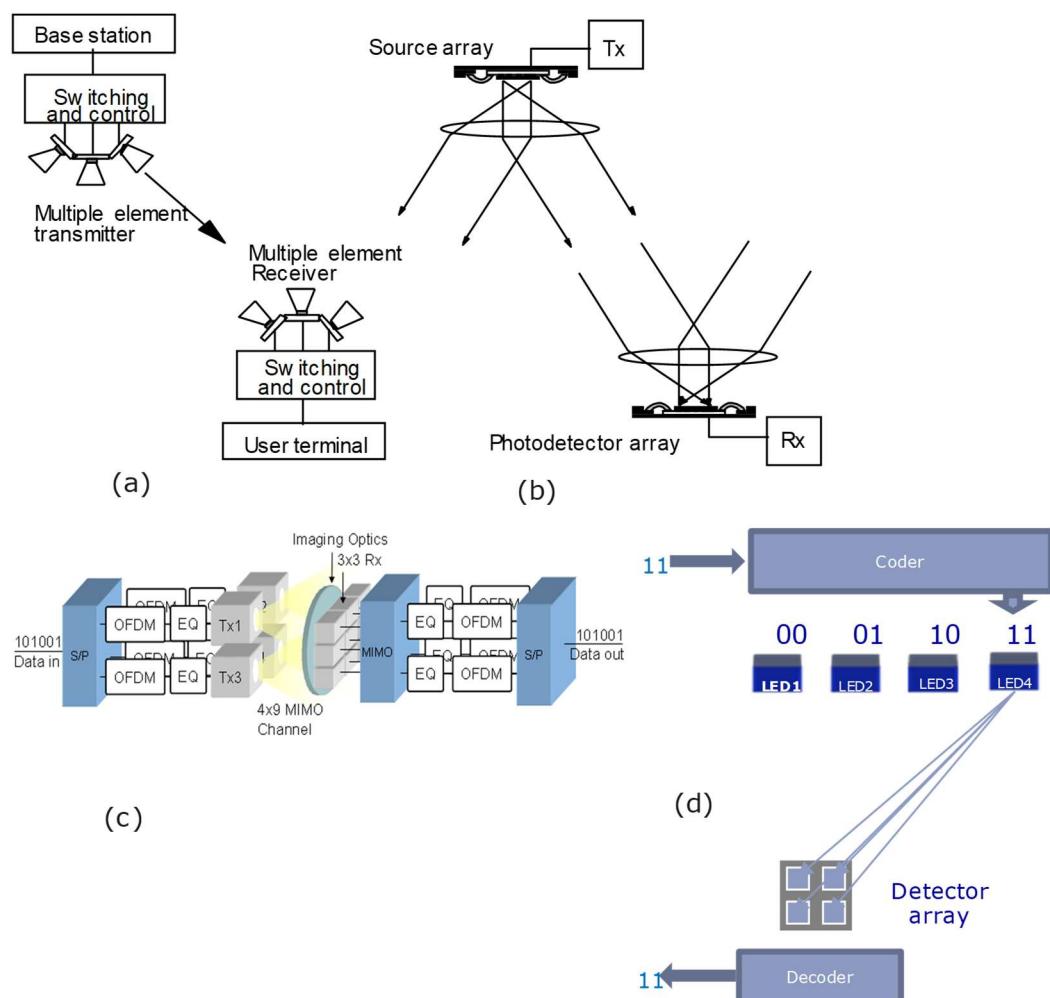


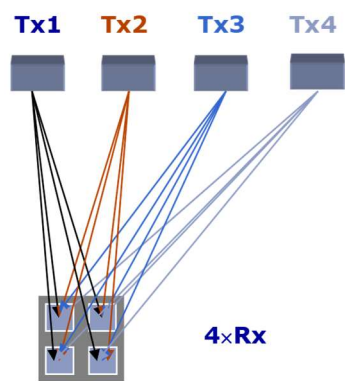
Figure 7. System configurations for multi-channel transmitter and receivers (a) Angle Diversity. (b) Imaging Diversity. (c) Imaging Multiple Input Multiple Output (MIMO) system (d) Spatial modulation system.

Imaging diversity transmitters(74) use an array of sources, each of which is directed to a particular range of angles, creating a ‘cellular’ coverage pattern. In angular diversity(75) individual sources are arranged to cover a range of angles. Both these approaches need information which allows appropriate transmitters to be activated, or sources to be directed to appropriate terminals. This is achieved either by monitoring the strength of the communications signal, or tracking using a separate optical system(76). Imaging diversity receivers can also be used to the angle of arrival of optical signals, which can form part of a position measurement system-see (77) for an example.

Multichannel transmitters can be used together with multichannel receivers to enable Multiple Input Multiple Output (MIMO) techniques(78), as shown in Figure 7(c) and Figure 7(d). Most OW demonstrations have focused on increasing data-rate, by using transmitter and receiver arrays to provide a number of independent channels between data source and destination, known as spatial multiplexing(79), shown in Figure 7(c). The principle of MIMO spatial multiplexing is shown in Figure 8. Light from a number of transmitters propagates to a number of receivers. The path loss for each of the potential transmitter/receiver pairs can either be estimated or calculated, leading to an equation relating the transmitted signal vector \mathbf{T} to the received signal vector \mathbf{R} . If the channel matrix \mathbf{H} is known, either by calculation or measurement, multiplying the received signal vector \mathbf{R} by its inverse yields an estimate of the data sent \mathbf{T} . Figure 9 shows an integrated MIMO demonstrator, fabricated as part of a UK EPSRC funded project including the Universities of Oxford, Cambridge, Strathclyde, Edinburgh and St. Andrews. This has 9 transmission channels and operates at $\sim 7\text{Gb/s}$ (73).

It is also possible to code information in the spatial position of the sources used to transmit information, as show in Figure 7(d). Here, four LED positions can encode two bits of information, and one source is activated at once. The receiver can be trained to distinguish light from different positions, allowing the information to be decoded. This is known as spatial modulation(80).

MIMO OW has also been used to communicate with an industrial robot, where the multiple paths are used to improve reliability by offering alternative paths if robot movement blocks data transmission(81). Multiplexing of spatial modes, including Angular Orbital Momentum has also been demonstrated(82), albeit for use in outdoor point to point communications. Finally, the use of multiple transmitters and receivers for multiple users (multi-user MIMO) is an area of active investigation (see for example (83))

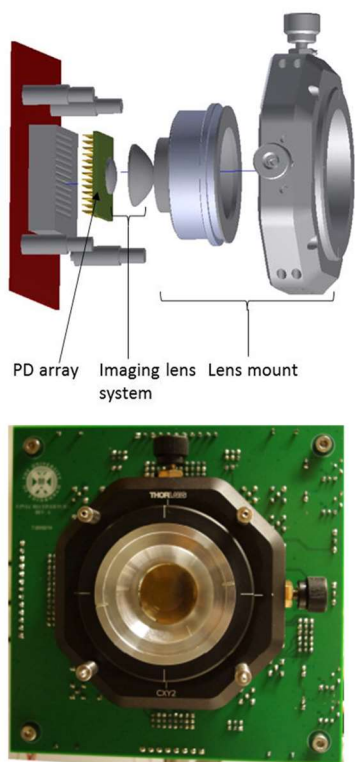


$$\begin{bmatrix} R_1 \\ R_2 \\ R_3 \\ R_4 \end{bmatrix} = \begin{bmatrix} H_{11} & H_{12} & H_{13} & H_{14} \\ H_{21} & H_{22} & H_{23} & H_{24} \\ H_{31} & H_{32} & H_{33} & H_{34} \\ H_{41} & H_{42} & H_{43} & H_{44} \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \end{bmatrix}$$

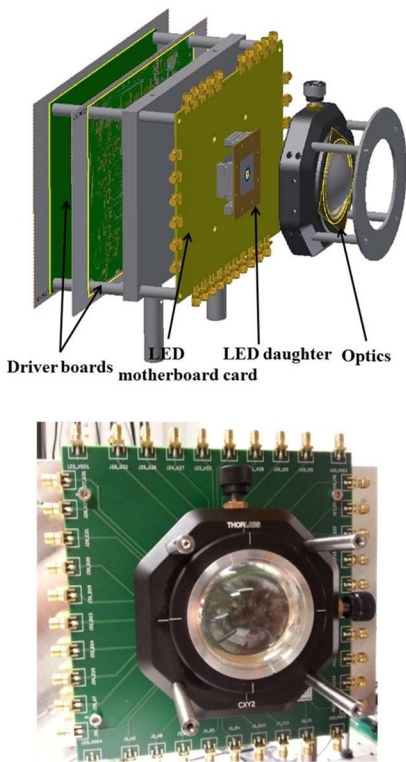
$$\mathbf{R} = \mathbf{H}\mathbf{T}$$

$$\mathbf{T}' = \mathbf{H}^{-1}\mathbf{R}$$

Figure 8. MIMO system principles



Receiver opto-mechanical assembly



Transmitter opto-mechanical assembly

Figure 9. Integrated MIMO demonstrator

The transmitters and receivers described so far use sources and detectors to convert electrical signals to optical for transmission, and back to electrical for detection. The use of arrays increases the capability of OW systems, but the cost is increasing difficulty in implementation.

Figure 1 (b) shows a narrow beam communications system, and to provide wide area coverage with such a system tracking and beamsteering is required. The steering of the beam can be achieved using a number of techniques, including mirrors(84-86), controllable prisms(87), or diffraction. For diffraction based steering a coherent optical source (a laser) is required, and there are two broad approaches. A fixed grating can be used with a wavelength tunable source so that the beam is controlled by tuning the wavelength(88), or a programmable phase grating can be used with a fixed wavelength(1). Tracking is required for these systems, so the beams of light can be pointed appropriately, and in (76) a camera based system is used, where an LED beacon identifies the position of a terminal and the camera image can be used to locate it. Beamsteering based systems can either use dedicated sources and detectors, or use light from an optical fibre as the transmitter source, and a fibre coupled receiver as the receiver. This fibre-wireless-fibre approach is attractive, as the beamsteering elements operate transparent to the data rate and modulation format of the transmitted signal, and such links can potentially operate bidirectionally(1).

Outlook and challenges

The challenges for any wireless communications technology include the availability of spectrum, the ability to create a link with sufficient margin for correct operation, and the ability to create suitable transmitters and receivers. As the demand for wireless communications grows conventional radio frequency approaches are experiencing a 'spectrum crunch', which has led to higher frequency bands being used. The available radio spectrum is in the mm-wavelength bands, where the propagation characteristics are similar to light, and the differences between the link margins available to the two technologies are closer. Thus, OW and radio frequency approaches face similar challenges.

For OW, there are a range of potential transmitter and receiver technologies that can provide high data rates, and the challenge is to optimise these, and their mass manufacture. At a systems level the challenges are associated with providing both coverage and capacity, which is likely to involve combining low-speed wide area coverage with high speed hot-spots, using both radio and optical wireless technologies. Integration of different wireless standards is being addressed under the developing 5G framework, and incorporating OW as 'another wireless technology' will allow very high bandwidth coverage to be provided to small areas, with

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little interference to neighbouring systems, thus augmenting capacity and allowing continued data rate growth.

Competing Interests

The author declares that he has no competing interests.

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Table of visible light communications systems

Year	Sources	Receiver	Modulation scheme	Multiplexing	Pre-equalisation	Post-equalisation	Link distance	System Bandwidth	Data rate (BER threshold)	Ref
2019	Laser diode	Photodiode	OFDM	WDM	-	X	4 m	-	35 Gb/s	(69)
2019	LEDs (RGBY)	Photodiode (1 GHz)	OFDM	WDM	-	X	1.6 m	300 MHz	15 Gb/s	(68)
2019	LD	Photodiode	OOK	--	-	-	2 m	65 MHz	4.7 Gb/s	(89)
2019	LEDs (RGBYC)	Photodiode	DMT	WDM	-	X	1.2m (underwater)	-	15.17 Gb/s	(90)
2019	RGB laser diode	Photodiode	OFDM	WDM	-	-	2m	-	40.665 Gb/s	(91)
2018	Laser diode	Organic Solar cell	OFDM	-	-	X	2 m	24.5 MHz	0.52 Gb/s	(66)
2017	LED	SPAD	OOK	-	-	X	45.640 m	-	20 Mb/s	(92)
2017	VCSEL	Photodiode (1.25GHz)	OFDM	-	-	-	3m	1 GHz	10.6 Gb/s	(93)
2017	RGB LEDs	Photodiode	OFDM	WDM+ Spatial	-	X	1m	-	6.36 Gb/s	(94)
2017	violet µLED	Avalanche Photodiode (1.6 GHz)	OFDM	-	-	X	-	655 MHz	11.12 Gb/s	(95)
2016	RGB LEDs	Photodiode (1 GHz)	OFDM	WDM	-	X	1.5 m	100 MHz	10 Gb/s	(96)

2016	μ LED	Avalanche Photodiode (90 MHz)	PAM-4	Spatial	-	X	0.5 m	50 MHz	7 Gb/s	(97)
2015	RGB laser	Avalanche Photodiode (1 GHz)	OFDM	WDM		X	0.2 m	> 1 GHz	12.4 Gb/s	(98)
2015	laser diode	Organic Solar cell	OFDM	-	-	X	1 m	1.3 MHz	42.3 Mb/s	(99)
2015	Organic LED	Organic Photodiode	OOK	WDM	-	X	0.05 m	600 kHz	55 Mb/s	(100)
2015	Blue Laser	Avalanche Photodiode (900 MHz)	OFDM	-	-	X	5m	900 MHz	9 Gb/s	(101)
2015	Blue laser + phosphor	Photodiode (1 GHz)	OFDM	Spatial	-	X	1 m	-	10 Gb/s	(102)
2015	RYGB	Photodiode	CAP	WDM	X	X	1 m	320 MHz	8 Gb/s	(103)
2015	Blue laser + phosphor	Avalanche Photodiode (1 GHz)	OFDM	-	-	X	0.5m	~1 GHz	4 Gb/s	(104)
2015	μ LED+ polymer colour converter	Avalanche Photodiode	OFDM	WDM	-	X	0.3 m	25 MHz	2.3 Gb/s	(105)
2015	White LED	Photodiode (300 MHz)	OFDM (bit and power loading)	-	X	X	1.5 m	28 MHz	2 Gb/s	(38)
2014	RGB LED	Avalanche Photodiode (100 MHz)	OFDM	Wavelength	X	X	0.1 m	156 MHz	4.22 Gb/s	(106)
2014	μ LED	Photodiode (1 GHz)	OFDM (bit and power loading)	-	X	X	0.05 m	60 MHz	3 Gb/s	(107)
2014	μ LED+ polymer colour converter (white)	Avalanche Photodiode	OFDM	-	-	X	0.03	>200MHz	1.68 Gb/s	(108)
2014	Polymer LED	Photodiode	OOK	-	-	X	0.05 m	270 kHz	10 Mb/s	(109)
2013	Organic LED	Photodiode	OOK	-	-	X	-	270 kHz	10 Mb/s	(110)
2013	Blue Laser	Photodiode (1.4 GHz)	OOK-NRZ	-	-	-	-	1.4 GHz	2.5 Gb/s	(111)
2012	RGB LED	Avalanche Photodiode (280 MHz)	OFDM(bit and power loading)	WDM	-	-	0.1m	130 MHz	3.4 Gb/s	(112)
2012	White LED	Photodiode (250 MHz)	CAP	-	X	X	0.23m	-	1.1Gb/s	(113)
2012	RGB LED	Avalanche Photodiode (80 MHz)	DMT-QAM	Wavelength	-	-	0.1m	15-20 MHz	1.25 Gb/s	(114)

2010	μ LED (blue)	Photodiode	OOK	-	-	-	-	150 MHz	1 Gb/s	(115)
2009	White LEDs	Photodiode	OOK-NRZ	-	-	X	0.1m	50 MHz	100 Mb/s	(13)
2007	White LEDs	Photodiode	DMT-QAM	-	-	-	0.01m	30 MHz	100 Mb/s	(116)
2006	White LEDs	Photodiode	OFDM	-	-	-	1 m		16 kbps	(117)
2002	White LEDs	Photodiode	BPSK	-	-	-			1 Mbps	(118)

Table 1. Summary of demonstration links and systems

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