WIRELESS WORLD
RESEARCH FORUM

Short-Range Optical Wireless Communications

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***Abstract*— It is commonly agreed that the next generation of wireless communication systems, usually referred to as 4G systems, will not be based on a single access technique but it will encompass a number of different complementary access technologies. The ultimate goal is to provide ubiquitous connectivity, integrating seamlessly operations in most common scenarios, ranging from fixed and low-mobility indoor environments in one extreme to high-mobility cellular systems in the other extreme. Surprisingly, perhaps the largest installed base of short-range wireless communications links are optical, rather than RF, however. Indeed, 'point and shoot' links corresponding to the Infra-Red Data Association (IRDA) standard are installed in 100 million devices a year, mainly digital cameras and telephones. In this paper we argue that optical wireless communications (OW) has a part to play in the wider 4G vision. An introduction to OW is presented, together with scenarios where optical links can enhance the performance of wireless networks.**

***Index Terms*—Optical wireless communications, wireless communications**

INTRODUCTION AND MOTIVATION

As the third generation mobile communication system (3G) is being deployed, manufacturers and scientific community are increasingly turning their research interests toward future wireless communication systems. It is commonly agreed that the next generation of wireless communication systems, usually referred to as 4G systems, will not be based on a single access technique but it will encompass a number of different complementary access technologies. Future systems will not only connect users and their personal equipment but also access to independent (stand-alone) equipment will be provided. Ultimately one would expect that everybody and everything will be wirelessly connected. This vision places short-range communications in a position of preponderance, as one could argue that most of the wireless links in future wireless communication networks will be established over relatively short distances. In addition, a significant proportion of these links will be characterized by high data throughputs. Probably the largest portion of practical applications of short-range communications take the form of WLAN, WPAN and WBAN (Wireless Local, Personal and Body Area Networks), covering ranges from a few tens of meters down to sub-meter communications.

In the context of short-range communications, two techniques have received increasingly attention in the last years, namely multicarrier (MC) and Ultra Wideband (UWB). These fundamental technologies for the physical layer have been extensively studied in the literature, for a comprehensive introduction and initial pointers[1, 2] [3, 4]. Application of these techniques in short-range environments will be considered in detail within the framework of WWRF [5].

In this paper we argue that optical wireless communications (OW) has a part to play in the wider 4G vision. The optical wireless channel has THz of unregulated bandwidth, and characteristics that are distinct from that of radio. It should be noted that our aim is to show that the optical channel has complementary characteristics and can, in certain situations, add to, but certainly not replace the capability of a RF 4G wireless system. Together these media might provide a broad spectrum of channel characteristics and capabilities that radio alone would find it difficult to meet.

The aims of this paper are to;

(i) Introduce OW and the components and systems used

(ii) Summarise the state of the art, and rich research community that exists

(iii) Compare the characteristics of OW with radio

(iv) Identify particular areas where OW can contribute to the 4G vision, and areas of future research

Optical Wireless Communications as a complementary Technology for Short-Range Communications

In this section an overview of Optical Wireless Communication systems is presented. The main emphasis in this paper is put on OW for indoor environments. Another important approach to OW, free-space optics (FSO), a point-to-point optical connection supporting very high rates in outdoor environments, will not be considered in this paper. We start with a brief introduction and classification of OW systems and then continue with different engineering aspects, including transmitters, receivers, the optical channel and other related issues. This introduction is based on the studies and reviews presented by [6],[7-9]. Comparisons to conventional radio systems are presented to give the reader a broader perspective of the possible baseband technologies. An up-to-date account of different techniques, practical systems and standards related to OW as well as future research issues complete the paper.

Basic system configuration

Figure 1 shows a number of different OW configurations. There are two basic configurations; communications channels either use diffuse paths (Figure 1 (a)) or Line Of Sight (LOS) paths (Figure 1(b)) between transmitter and receiver. In a diffuse system an undirected source (usually Lambertian) illuminates the coverage space, much as it would be illuminated with artificial lighting. The high reflectivity of normal building surfaces then scatters the light to create an optical 'ether'. A receiver within the coverage space can detect this radiation, which is modulated in order to provide data transmission. Diffuse systems are robust to blocking and do not require that transmitter and receiver are aligned, as many paths exist from transmitter to receiver. However,

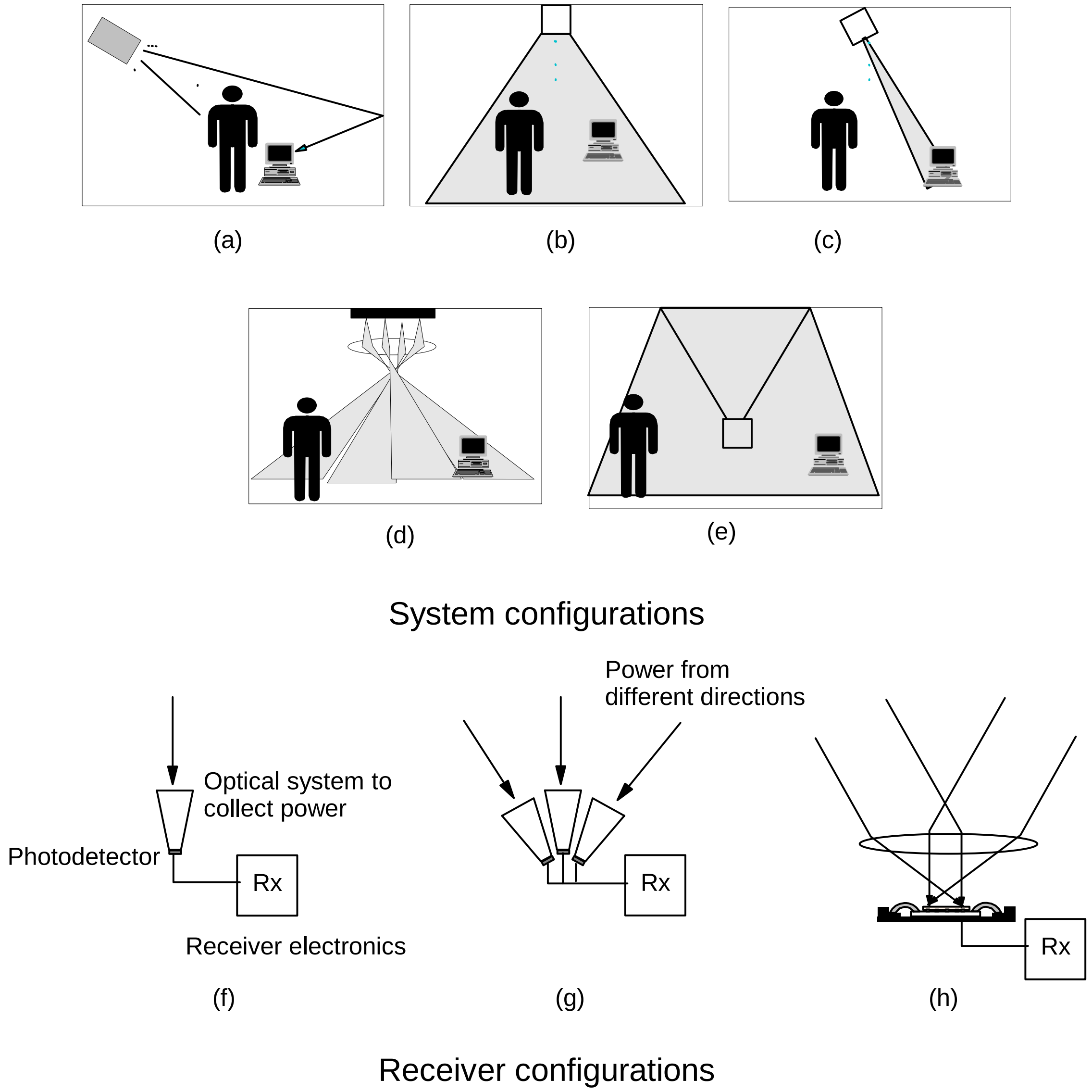


Figure 1. Optical wireless configurations. (a) Diffuse system. (b) Wide LOS system. (c) Narrow LOS system with tracking. (d)Narrow LOS system using multiple beams to obtain coverage. (e)Quasi diffuse system. (f) Receiver configuration: single channel receiver. (g) Receiver configuration: angle diversity receiver. (h) Receiver configuration: imaging diversity receiver.

multipath interference at the receiver can cause Inter Symbol Interference (ISI) and the path loss for most systems is high.

The alternative approach is to use directed Line of Sight paths between transmitter and receiver. Wide LOS systems such as that shown in Figure 1 (b) use ceiling mounted transmitters that illuminate the coverage area, but minimize reflections from walls, ensuring that a strong LOS path exists. The wide beam ensures coverage. As the beams are narrowed path loss reduces and the allowed bit rate increases, albeit at the cost of coverage. Narrow beam systems therefore either require tracking to allow user mobility (Figure 1 (c)), or some sort of cellular architecture to allow multiple narrow beams to be used (Figure 1 (d)). A third class of system also exists; quasi diffuse systems minimize the number of multipaths by limiting

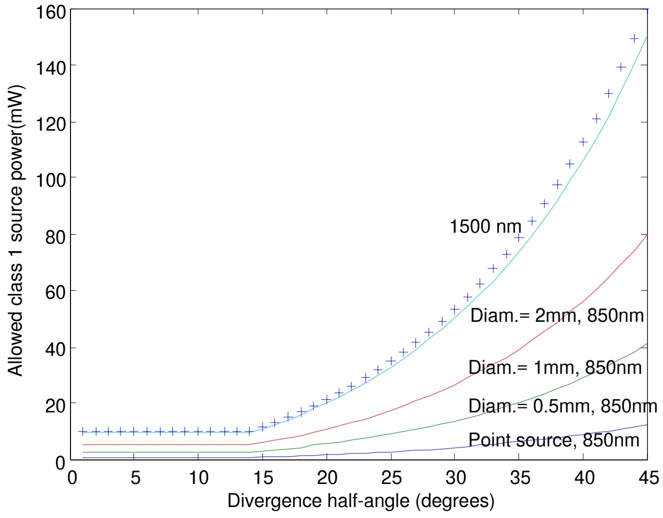


Figure 2. Allowed emitted power for class 1 eye safe operation of transmitter as a function of beam divergence.

the surface reflections, but allow robust coverage by directing radiation to a number of surfaces so that a suitable receiver may select a path from one surface only (Figure 1 (e)). Variants of this use structured illumination (perhaps using arrays of spots) [10, 11]. There is a large amount of simulation and more limited amount of measurement data that describes these channels in some detail. In contrast with radio frequencies simulation of indoor coverage spaces generally gives a good estimate of the channel characteristics.

System components

Transmitter

The transmitter consists of a single, or a number of sources, and an optical element to shape the beam and also render it eyesafe if required. The main element of the transmitter is the optical source. Light Emitting Diodes (LED) and laser diodes are employed as the optical radiating element, and their transmission power is limited by eye safety regulation. Figure 2 shows a plot of the allowed emitted power for class 1 (the most stringent eye safety regulation) operation vs. beam divergence. This is shown for an 850nm point source, different diffuse source diameters at 850nm, and for a 1500nm point source. Increasing the source diameter increases the size of the image on the retina of the eye, thus reducing the possibility of thermal damage. At 1500nm water absorbtion in the eye protects the retina, so the hazard is one of corneal damage, and therefore independent of source size. As might be expected more divergent sources are less hazardous as the eye, or an optical instrument such as binoculars or magnifier cannot collect all the radiation. The results in the graph are calculated using the test procedures and limits laid out in [12].

Sources of small diameter can be made diffuse using a ground glass plate, or more sophisticated engineered diffuser elements, including holographic [13] and reflective [14] examples. This latter device has been incorporated in a commercial optical link [15]. The effect of a diffuser is to increases the apparent size of the source, and the graph shows the benefit of this.

Most systems use laser diodes, due to their higher modulation bandwidth and efficiency. IR LEDs are also important optical sources being considered for establishing optical links. In addition, there is a small and growing interest in using visible LEDs that would be installed in a building to provide solid-state lighting for optical communications [16]. In such cases multiplexing of the low bandwidth devices might be used to increase data rates.

Receiver

A typical OW receiver consists of an optical system to collect and concentrate incoming radiation, an optical filter to reject ambient illumination, and a photodetector to convert radiation to photocurrent. Further amplification, filtering and data recovery are then required (Figure 1(f)).

Optical systems

Receiver optical systems can be characterised in terms of their angular Field of View (FOV) and their collection area. These are linked to the detection area by the *constant radiance theorem*. This states that;

$$A_{coll} \sin^2\left(\frac{FOV}{2}\right) \leq A_{\det},$$

where A_{coll} is the collection area and $A_{\det}$ is the photodetector area. This is important as it limits the collection area that is available for a given FOV and photodetector. For a truly diffuse channel the detector area sets how much power will be received. Any collection optical system changes the balance between field of view and collection area subject to the constraints above; however if the system is receiving light from a Lambertian source such as a wall or ceiling the amount of optical power that is collected remains approximately constant for a given detector area.

Both imaging and nonimaging optics [17] can be used to collect and focus radiation onto single element detectors. Recent designs of optical antenna [18] show good performance in compact form, although this cannot exceed that predicted by constant radiance. Various different receiver topologies have been investigated in order to circumvent these constraints. In angle diversity systems a number of single channel receivers are combined, so that each faces in a different direction. This allows multipaths to be resolved and collection areas for each receiver to be increased [19] (Figure 1 (g)). Imaging receivers, as developed at Oxford [20]and Berkeley [21] can also carry out this function (Figure 1 (h)). These use a large-area pixellated detector array and an optical imaging system. Light from narrow range of directions is collected by a single pixel, and together the array of pixels offers a large overall field of view. It also allows multipaths from different directions to be resolved as they are imaged to different pixels on the array. The array also allows the large detection area to be segmented, reducing the capacitance on each of the receiver front ends. Both of these topologies can to some extent resolve multipaths, and this may offer some means to reduce the effect of shadowing, by selecting an alternative non shadowed path. It is also possible to use a combiner/equaliser to maximise the received signal and BER [21].

Optical filtering

Ambient light is the most important source of interference and it may greatly deteriorate link performance [22]. Constant ambient illumination will generate a DC photocurrent, and this will normally be blocked by the AC coupling of the receiver [23]. However the shot noise from the detection of this illumination cannot be filtered and can be large when compared with the noise from the preamplifier. Artificial illumination, particularly modern high frequency fluorescent illumination induces electrical harmonics in the received signal, with components up to 1MHz [24] and this can greatly effect link performance. Various studies of this have been undertaken, including [25, 26].

Optical filtering can be used to reject out of band ambient radiation and reduce the intensity reaching the detector. Various different filter types have been demonstrated; a longpass filter in combination with a silicon detector provides a natural narrowing of the bandwidth and absorbtion filters can be used to reject solar and illumination [27]. Bandpass interference filters can be used, although care has to be taken to allow sufficient bandwidth to allow for passband shifting with the varying angle of incidence. It is also possible to filter by incorporating appropriate layers into the photodetector . Holographic receiver front-ends also allow ambient light noise to be rejected [28].

Electrical filtering can be used to reduce the effect of the illumination harmonics, but at the cost of inducing baseline wander. Work on the optimal placement of the filter cut-offs for particular modulation schemes is reported in [29].

Detector/preamplifiers

The detector and preamplifier together are the main determining factor in the overall system performance. Both PIN structures and APDs have been used in single detector systems, whilst array receivers have tended to use PIN devices. Most of the detectors are designed for optical fibre systems, where capacitance per unit area is relatively unimportant, as areas can be small, and hence commercial devices are highly capacitive. Devices for OW should be optimized for low capacitance per unit area by increasing the width of the I-region, until this effect is balanced by the increasing carrier transit time. Detectors partially optimized for this application have been demonstrated [30] but further work is required in this area.

Various approaches to mitigating the effect of input capacitance on bandwidth have been taken. Bootstrapping [31], equalization [32] and capacitance tolerant front-ends [20, 33, 34] have all been investigated.

The Optical Channel

LOS optical channels are subject to path loss, and this can be modeled using either ray-tracing or analytical techniques. The diffuse channel has both high path loss (>40dB typically) and is subject to multipath dispersion. Both of these characteristics are dependent on the orientation of the source and receiver within the space.

There has been extensive work on predicting the characteristics of the diffuse channel, including [26, 35] [36] as well as analytical models of the channel impulse results. Most building materials are found to have a high reflectivity (0.4-0.9) and they can be approximately modeled as Lambertian reflectors. Ray tracing techniques therefore allow generally good predictions of the channel response, even in the presence of chairs and other objects. Depending on the balance of LOS and diffuse paths within a space channels can be modeled as Rician [37] or Rayleigh, with exponential impulse responses. Various measurements have also been made [38, 39]. Recent high-resolution data indicate that transparent 'unlimited' bandwidth diffuse channels are available in particular directions for most diffuse environments [40]. One of the major advantages of the OW channel is that there is no coherent fading, and the channel is therefore extremely stable when compared with its RF counterpart. Even though sources are coherent the size of detectors, and the scattering environment mean that any effects are removed by the spatial integration that occurs at the receiver.

Modulation schemes

Unlike in conventional RF systems, the optical channel uses intensity modulation and direct detection. The optical power output of the transmitting source is controlled according to some characteristics of the information bearing signal. The transmitted signal is thus always positive and its average amplitude is limited [41]. Analog and digital optical modulation is possible but, due to the intensity modulation, common modulation schemes employed in the radio frequency domain will perform differently when applied to optical systems.

The changes in optical power produced by intensity modulation are detected by direct detection, that is, a current proportional to the incident optical power is induced in the photodetector. As pointed out in [7] two criteria should be used to evaluate the feasibility of an optical modulation system; the average optical received power required to achieve a given target BER performance and the required receiver electrical bandwidth.

Three basic modulation schemes are usually used in OW systems, namely On-Off Keying (OOK), Pulse-Position Modulation (PPM) and Subcarrier Modulation (SCM). An extensive account of these and other techniques can be found in [41]. Other issues to take into account when considering optical modulation schemes are their robustness to multipath propagation and, in networks, their suitability to multiple access environments. PPM is very well suited to work in low signal-to-noise ratio scenarios, quite typical in optical channels due to blocking effects (shadowing) and ambient noise. However, multipath propagation induces intersymbol interference and PPM is particularly sensitive to these dispersive effects of the optical channel [41].

Many techniques have been considered in order to combat the deleterious effects of dispersive optical channels, among them the use of equalizers, angle-diversity and spread spectrum techniques. Different equalization approaches at chip or symbol rate have been studied for PPM based systems, including linear and decision-feedback equalizers [41].

Spread-spectrum modulation techniques can also be used to combat multipath distortion as well as to reduce the effects of interference, in a similar fashion as they are exploited with radio systems. Direct-sequence techniques are usually used in conjunction with optical links. Since bipolar spreading sequences cannot be used to modulate an always positive optical signal, a unipolar sequence is formed by biasing to the bipolar sequence with a fixed DC offset. This unipolar sequence preserves the correlation properties of the original sequence and it can be correlated with a bipolar sequence at the receiver. Several direct-sequence spread-spectrum approaches specially designed for optical systems have been proposed and studied, including sequence inversion keying modulation (SIK), complementary SIK (CSIK) and *M*-ary bi-orthogonal keying modulation (MBOK) [42, 43]. Sequences with low auto- and cross-correlation sidelobes are preferred in order to minimize the degrading effects of intersymbol interference.

Optical wireless vs. radio communications

Over the past decade the capacity of an optical fibre link has increased by several orders of magnitude, showing almost ‘Moore’s Law’ growth, largely due to the availability of optical spectrum. At the same time regulation of the RF spectrum limits available bandwidth to several orders of magnitude below this. The vision of a highly connected world is likely to require unaffordable amounts of the already scarce radio frequency spectrum. OW occupies fully unlicensed spectrum bands, and the possibility of using unregulated and unlicensed bandwidth is one of the most attractive characteristics of OW.

Unlike radio communications, the nature of the optical radiation is such that the transmitted signal is obstructed by opaque objects, and the radiation can have high directivity using sub-millimetre scale beam shaping elements. This combination of high directivity and spatial confinement gives optical channels an unmatched advantage in terms of security. Furthermore, these characteristics allow exploiting wavelength-reuse at room level, without taking special provisions for interference from and to neighboring rooms. Since the optical radiation produces no interference to electrical equipment, OW can be used in sensitive environments where conventional radio wave transmission is not allowed.

Another unique characteristic of wireless optical links is in the channel itself, and it is the fact that these links are not affected by multipath fading. This is because the dimensions of the receiver’s photodetector are many orders of magnitude larger that the wavelength of the optical radiation and thus, the spatial fluctuations in signal strength due to multipath are averaged over the large detector area, which acts as an integrator. For most of the cases, and as an essential advantage, optical components are small in size, low-cost and they have low power consumption. Furthermore, transceivers are relatively simple compared with their radio frequency counterparts.

There are several drawbacks, however; since IR radiation can reach the retina and eventually cause thermal damage, the maximum power that can be transmitted is limited by eye safety regulations and extra optical elements are required to render high power sources safe.

In diffuse optical communication systems, multipath propagation caused by the dispersive optical channel will introduce pulse spreading and intersymbol interference (ISI), much as would be experienced by a radio channel, although the process is due to incoherent, rather than coherent fading. Systems above 50Mb/s or so might typically require some form of equalisation.

Perhaps the major difference for the optical wireless channel is the detection process is usually incoherent, so that the detector responds linearly with power, rather than amplitude, as is the case with a radio receiver. Receiver sensitivity is therefore substantially lower than for radio channels, and therefore systems are more susceptible to path loss, especially in the case of diffuse systems. More complex receiver and transmitter structures can be used to reduce this, and the effect of noise from ambient illumination. As the detection process is incoherent there is no inherent rejection in the detection process, so filtering mechanisms must be introduced, as mentioned earlier.

The wavelength of optical radiation makes directive channels easy to implement, and system design often leads to asymmetric channels [44]. Such directive channels are necessarily subject to blocking, which is again distinct from radio applications [9, 44]and [45].

Link budget models

In this section simple models of the RF and optical channels are developed, in order to compare the performance (A similar analysis is undertaken in[44], albeit with different emphasis).

Radio communications

There are many models of the path loss of a radio link, depending on environment, and on link distance. In this case a simple set of limiting cases is considered.

If (i) the transceivers lie in each others far-field, so that Fraunhofer diffraction can be assumed, and (ii) a line of sight exists between transmitter and receiver the link loss can be estimated using the standard Friis' equation. In most indoor environments the antenna will be approximately isotropic, and have transmitter and receiver gains of unity. In this case

the link loss L_{link} can be approximated by;

$$L_{link} = \left(\frac{\lambda}{4\pi}\right)^2 \frac{1}{r^2} \qquad (1)$$

where r is the link distance and λ is the wavelength of the radiation. The minimum link distance at which this occurs is the Fraunhofer distance d_f and can be estimated as;

$$d_f = \frac{2D^2}{\lambda} \qquad (2)$$

where D is the largest dimension of the antenna.

In a real environment the situation is more complicated however. At distances greater than a reference distance d_{ref} from the antenna (d_{ref} is greater than the Fraunhofer distance) multiple paths from transmitter to receiver interfere and cause a path loss that varies as $r^{-\gamma}$ where γ is the path loss exponent. This gives rise to a 'dual-slope' path loss, with an r^{-2} loss at distances less than d_{ref} (but greater than d_f) and an $r^{-\gamma}$ loss beyond this.

The link loss then becomes

$$L_{link} = \left(\frac{\lambda}{4\pi}\right)^2 \frac{1}{r^2} \quad \text{for} \quad d_f \le r \le d_{ref} \qquad (3)$$

and

$$L_{link} = \left(\frac{\lambda}{4\pi}\right)^2 \left(\frac{1}{d_{ref}^{\;2}}\right)\left(\frac{d_{ref}}{r}\right)^{\gamma} \quad \text{for} \quad d_{ref} < r \qquad (4)$$

Both the position of the break-point and the slope beyond it can therefore vary widely, and the model above is at best an indication of the loss. The methods used to estimate d_{ref} and γ are detailed in each of the scenarios described later in the paper.

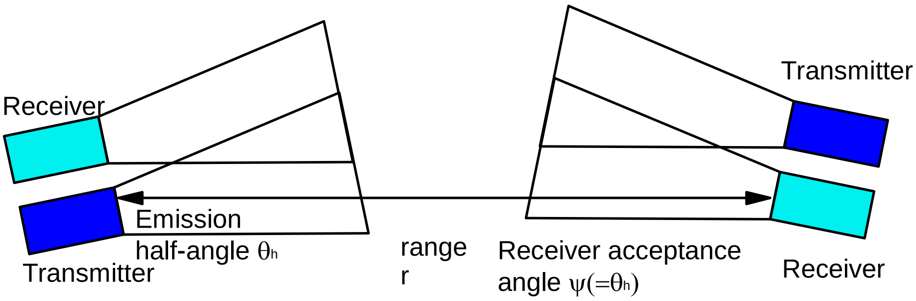
Assuming the receiver antenna is at the standard temperature, and feeds a matched preamplifier with noise figure F then for a transmitted signal power P_t the signal to noise ratio S/N at the receiver is;

$$\frac{S}{N} = \frac{P_t L_{link}}{FKTB} \quad (5)$$

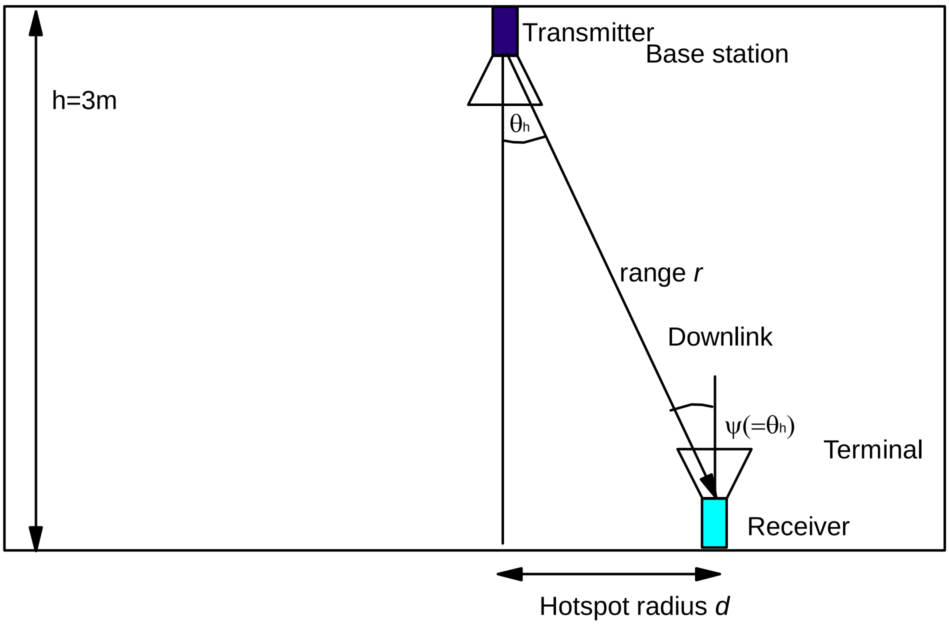
where K is Boltzmann's constant and T is the temperature in Kelvin. For a bit-rate R_b average energy per bit E_b and Noise power density N_o

$$\frac{E_b R_b}{N_o} = \frac{P_t L_{link}}{FKT} \quad (6)$$

This expression allows the bit-rate available R_b to be related to the range for a given required E_b / N_o. The value of E_b / N_o required for a particular Bit Error Rate (BER) is determined by the modulation and detection scheme used.



(a) Link geometry for 'point and shoot' optical link, showing 'worst case' alignment for correct operation.Transmitter and receiver are both oriented at θh to 'boresight' alignment.



(b). Link geometry for optical hotspot for worst case alignment

Figure 3. Optical communications link geometries

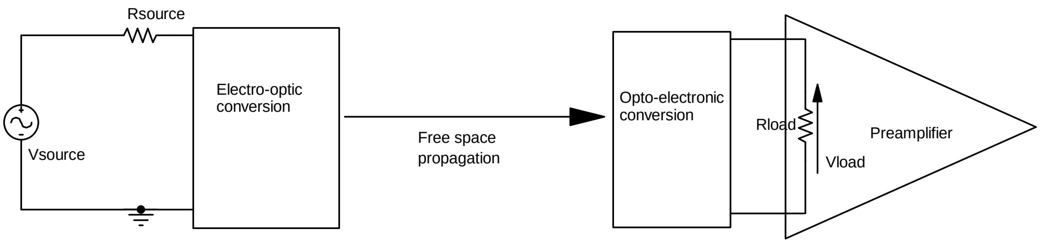


Figure 4. Communications channel model

Optical communications

Figure 3 shows the geometry of the optical links and Figure 4 shows an electrical model of the communications channel. Applying the Friis' formula for optical links creates results that are unrealistic in real situations, in that the diffraction limited transmitter beam that these simulate is very narrow, creating links that require very precise alignment. Two link geometries, for point and shoot links and a 'hotspot' geometry are shown in Figure 3.

The Intensity profile of the source is $I(r,\theta)$ where r is the link distance and θ is the angle measured from the optical axis, as show in Figure 3. In this case it is assumed that this is a constant value I_o so that $I(r,\theta) = I_o$ for θ varying from 0 to the beam half-angle θ_h. This is beneficial, compared with the more normal Lambertian pattern as the off-axis fall of in intensity is reduced. Such a distribution might be achieved by using a holographic diffuser to modify the source emission profile.

Normalising this by the power emitted by the source P_s yields;

$$I(r,\theta) = \frac{P_s}{2\pi r^2(1-\cos\theta_h)} \qquad (7)$$

This power is collected by a receiver with area A_{coll}, which in the worst case is oriented at an angle ψ from its optical axis, so the minimum power collected, P_{coll} is given by;

$$P_{coll} = \frac{P_s}{2\pi r^2(1-\cos\theta_h)} A_{coll}\cos\psi \qquad (8)$$

defining the optical loss, $L_{optical}$ as

$L_{optical} = \frac{P_{coll}}{P_s}$ leads to

$$L_{optical} = \frac{1}{2\pi r^2(1-\cos\theta_h)} A_{coll}\cos\psi \qquad (9)$$

In both cases shown in the figure the transmitter launches power within an emission cone with half-angle θ_h and receiver optical systems have acceptance angle $\psi = \theta_h$. The beam half-angle and receiver acceptance angles are matched as this is optimum for systems with paired uplinks and downlinks as shown in the figure. Any larger receiver acceptance angle is not useful as if light is entering the receiver at this orientation the transmitter within the same transceiver unit will then miss the receiver within the distant transceiver unit.

At the receiver the electrical power delivered to the load S is given by;

$$S = i_{optical}^2 R_{load} \qquad (10)$$

where $i_{optical}$ is the photocurrent. This is given by;

$$i_{optical} = RP_{optical} \qquad (11)$$

where R is the responsivity of the photodetector and $P_{optical}$ is the optical power incident on it.

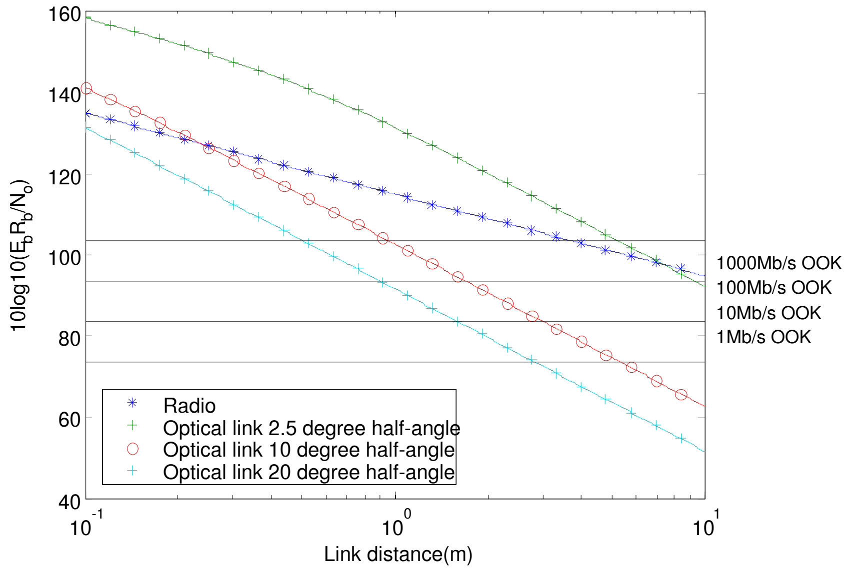


Figure 5. Comparison of RF and optical link performance for point and shoot links

The noise at the receiver consists of shot noise from the signal, shot noise from any DC photocurrent caused by ambient light and amplifier noise. The noise power delivered to the load is;

$$N = \left(2e\left(RP_{optical} + i_{Ambient}\right)B + i^2_{Amplifier}B\right)R_{load} \quad (12)$$

where $i_{Ambient}$ is the photocurrent due to ambient illumination and $i_{Amplifier}$ is the input referred noise of the amplifier.

The ambient light current can light current can vary over several orders of magnitude depending on the field of view and optical filtering[22]. The amplifier noise ranges from $1-10\,pA/\sqrt{Hz}$ [46] with a value of $5\,pA/\sqrt{Hz}$ typical for amplifiers with several GHz of bandwidth.

The overall signal to noise ratio is given by;

$$\frac{S}{N} = \frac{\left(RP_{optical}\right)^2}{\left(2e\left(RP_{optical} + i_{Ambient}\right)B + i^2_{Amplifier}B\right)} \quad (13)$$

which leads to;

$$\frac{E_bR_b}{N_o} = \frac{\left(RP_{optical}\right)^2}{\left(2e\left(RP_{optical} + i_{Ambient}\right) + i^2_{Amplifier}\right)} \quad (14)$$

This expression allows a direct comparison with the radio link to be made. In the case of RF the channel is subject to fading and both RF and the Non Line of Sight (NLOS) optical channel are subject to multipath dispersion. These expressions are therefore a simplification of the channel conditions, but are instructive as they allow a 'best-case' comparison. In the next section these expressions are used to compare the two media in typical scenarios.

Applications areas for optical wireless

'Point and shoot' and narrow FOV applications

Figure 5 shows a plot of $\frac{E_bR_b}{N_o}$ vs. range *r* for both RF and OW links with different optical link half-angles. The link geometry is that shown in Figure 3 (a).

The radio link model assumes an emitted power of –3.8dBm at a frequency of 3.975GHz, which is broadly representative of a UWB signal operating in the 'lower band' of the US frequency allocation[4]. This band extends from 3.1 GHz to 4.85 GHz, and the maximum emitted power is permitted is– 41dBm/MHz. The amplifier noise figure is assumed to be 6dB.

Values of path loss γ and reference distance d_{ref} are required for the RF model. There have been numerous measurements [47-49], and these show that $\gamma \approx 2$ for LOS environments and $\gamma \approx 4$ in Non-LOS (NLOS) situations for UWB systems. As the comparison is with an optical link the NLOS case is not relevant, so at the break point, there is no change of slope. The value of d_{ref} is therefore not required. (Measurements in [50] reinforce this assumption; a reference distance of 1m was chosen, and measurements at this distance closely matched the free-space Friis equation. Beyond this point a value of $\gamma = 1.91$ was found, making the assumption of $\gamma \approx 2$ for all distances from the source valid).

The optical link model assumes operation at 850nm, using a source 2.5mm in diameter. The optical link emits power levels allowed for class 1 emission, at each specific beam half-angle. The source aperture dimensions are large enough that it is classed as diffuse, thus allowing greater than point source emission. In addition at larger divergences greater power is allowed; for the 2.5 and 10 degree beams this is 12.2mW, which increases to 25.8mW for 20 degree half-angle.

The receiver collection aperture is assumed to be 5mm in diameter. This is chosen as the maximum practical area for a small portable terminal. A detector responsivity of 0.6A/W is assumed, and calculation suggests that a compatible receiver should be capable of Gb/s performance.

The amplifier noise density is assumed to be $5pA/\sqrt{Hz}$. The current due to ambient light $i_{Ambient}$ is a difficult quantity to estimate due to widely varying conditions. A value of 125 μA is used for the 10 degree FOV and scaled appropriately with for different FOV. This is equivalent to the maximum quoted in [44] when scaled for FOV and assumes coarse optical filtering. The required values of $\frac{E_b R_b}{N_o}$ for different bit-rates and incoherent OOK detection with a Bit-Error-Rate (BER) of 10^{-6} are plotted on the graph also.

The optical link is superior for narrow FOV applications up to approximately 10m, where for a FOV less than 2.5 degrees (half–angle) performance exceeds or meets that available using RF. For wider FOV the power density available at the receiver drops and the available range for a given bit rate reduces, whilst for the isotropic RF link this is not relevant, and performance depends only on range. Assuming that a FOV of approximately 10 degrees (half-angle) or so is required for a 'point-and-shoot' application a range of 1m or so can be achieved with an optical link operating at 1Gb/s. It should be noted that slightly better results-perhaps a 10% improvement in range- are obtained for an optical link operating at 1500nm. As can be seen from Figure 2 the allowed power emitted from such a source is similar (though slightly lower) to that from an 850nm source 2.5mm in diameter for all beam half-angles. This is more than compensated by the increased responsivity at the receiver however (1A/W compared with 0.6A/W) leading to the increase in range.

In this analysis 850nm is as an operating wavelength as components are available at low cost. It should also be noted that this calculation does not include detailed analysis of the effects of filtering and other impairments, but this is the same for the RF link budget, where effects such as fading are ignored, so the two are broadly comparable. In addition the results show marked differences, so that several dB is not of great importance to the overall conclusions.

From this analysis it seems that the most promising area of application, where optical links can offer a distinct channel with greater

Standard	Power consumption(W)	Bit rate(Mb/s)	Normalised energy consumption(J/Mb)
IEEE802.11(g)[51]	1.25	54	2.31E-02
Ultra-WideBand(UWB)[52]	0.75	114	6.58E-03
Bluetooth[53]	0.1	0.72	1.39E-01
Optical link[46]	0.3	150	2.00E-03

Table 1. Power consumption for different communications standards

range than the equivalent RF channel is where narrow FOV LOS channels are available.

Most of the links considered here will be used to connect portable terminals to data infrastructure, so power consumption becomes a consideration. Table 1 shows the power consumption of several short-range RF wireless communications standards normalised by the bit rate, and that for an optical link. The data shown are for particular products, although are broadly representative for examples of the same type.

The optical link is the most efficient, by a substantial margin. This is largely due to the baseband nature of the optical channel and the resulting simple transmitter and receiver architecture. In the case of the RF systems the complex transceiver structures dissipate substantial amounts of power. In all cases (both optical and RF) the link losses are a small part of the overall power consumption.

Within the 4G framework UWB is considered a likely solution for ad-hoc networks over distances <10m, and the example in table 1 offers data rates of 114Mb/s at ranges of up to 10m. However its energy consumption is a factor of three higher than the example optical link.

At distances <1m where there is a line of sight very high data rate (1Gb/s) optical links appear competitive with UWB, offering lower power consumption and better intrinsic security. Within the Infra-Red Data Association (IRDA) the IrBurst Special interest group has identified this area, and have specified links broadly in line with the results shown here.

The IRDA is promoting 'Financial Messaging', where a secure transaction takes place between a handheld and a retail terminal, albeit at low data rates [54]. Such a concept might be extended to retailing of high bandwidth content such as DVDs and CDs to portable players. In the future this might require several Gb/s in order to achieve reasonable download times (Samsung have recently introduced a telephone with a 3Gb disk). Theft of content would be limited by the confined nature of the optical signal, and extremely high spatial bandwidth could be achieved within the retail environment. This is relatively straightforward to achieve with a directed OW link used in a 'point and shoot' manner, or in a booth in which the link environment can be controlled.

Telematic applications

Over longer distances the superior link budget of narrow FOV systems makes OW attractive for telematic applications, such as road pricing and navigation. The German government has adopted an optical communications system for its tolling system for freight vehicles [55], and an International Standards Organisation (ISO) standard (ISO CALM 204) has been defined for such systems. Several train-operating companies are also investigating FSO for communications with trains, in order to provide broadband 'to the seat', and IRDA has formed The Travel Mobility Special Interest Group (IrTM).

Hotspots

In general, optical wireless suffers from low receiver sensitivity when compared with RF, but has the advantage of good spatial confinement, with the ability to maintain sufficient power density for good data reception over relatively small areas.

Optical wireless 'hotspots' that offer localised high bandwidth connectivity have been suggested[8] and the 4G model of heterogeneous standards allows this to be included, with the optical capacity augmenting that provided by RF. Figure 6 shows an example of this approach. Low bandwidth coverage is ubiquitous, and this is augmented at places where people congregate or lobbies of buildings so that large file transfers and tasks requiring high bandwidth can be undertaken. In 'regular' environments such as open plan offices the hotspots may provide complete coverage, with steps taken to ensure Optical LAN coverage.

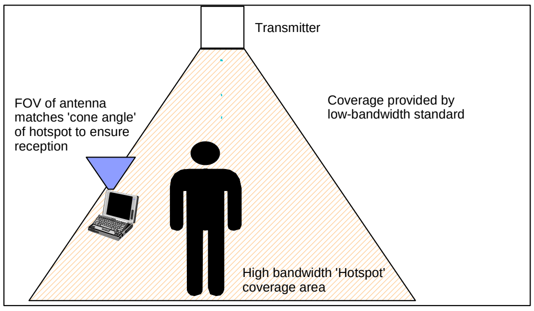


Figure 6. High bandwidth 'Hotspot'

Very simple hybrid approaches combining optical and radio frequency links have been proposed recently for short-range (indoor) communications [56, 57]. Reference [58] describes protocols that use RF signalling and reallocate the optical sources under blocking conditions.

Studies by Hou et al [59]have shown the advantage of this, especially in environments where the required capacity is asymmetric and the link capacity matches this. In the study a 100Mb/s optical downlink (from infrastructure to portable terminal) was combined with a 10Mb/s RF LAN. The optical link is subject to blocking, and depending on the duration of the blocking the system performs a vertical handover to an RF LAN. Downlink traffic is four times that of the uplink, a number that is typical within the Internet, and the decision to switch between standards is taken using a fuzzy inference engine.

Under conditions of high blocking (the optical link is blocked 10% of the time) the combined system delivers a lower delay (by a factor of six) in packet delivery compared with the radio LAN alone, and the system is a factor of nine times as efficient.

In this case the optical link offers increased efficiency and capacity for the wide area coverage RF LAN by augmenting capacity when it is needed. Within the framework of 4G systems the optical link can be considered to be another channel with specific distinct characteristics.

There are several routes to Gb/s coverage in a hotspot. Perhaps simplest is the use of tracking narrow FOV links, as sold by JVC[60], but this requires mechanical steering mechanisms. A potential alternative is the multiplexing of narrow LOS channels using multibeam transmitters. Further potential gains are available using imaging, multichannel receivers[20, 21, 61]. These approaches use the spatial multiplexing available due to the high gain optical antennas (lenses) and the ability to do very precise beamforming and steering when compared with RF approaches. An architecture that uses wavelength to steer narrow beams to terminals within the coverage area is presented in[62]. This offers the potential for multi-Gb/s transmission to terminals using a simple passive base station. In this case there are formidable challenges in providing an uplink from terminal to base station, and this architecture is well suited to a broadcast 'hotspot' model.

As well as the fine control of narrow power limited channels an alternative approach is to increase the power transmitted, and a possible method may be enabled by a switch to solid-state lighting. The efficiency of solid state lighting using LEDs is increasing rapidly, and particularly in Japan there is an interest in using these for communications[63-65]. If illumination power is available for data transmission approximately 30-40dB more power is available than the case considered in Figure 5 (assuming LED lighting units of the type

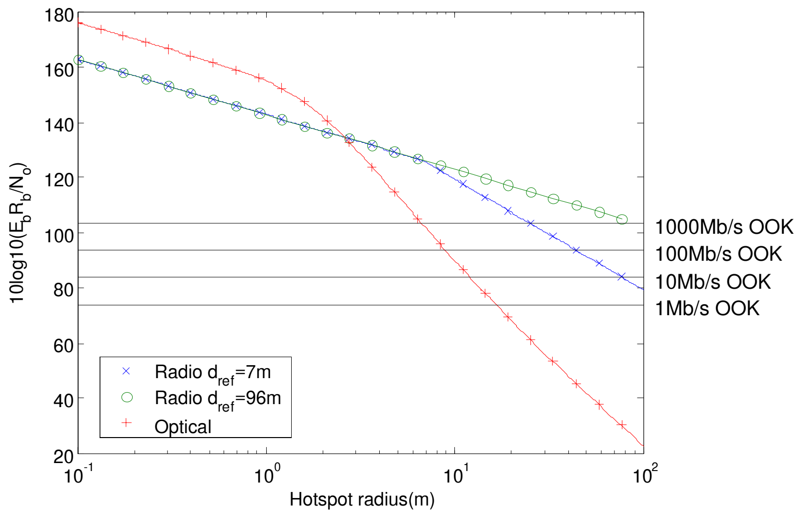


Figure 7. Comparison of RF and Optical communications for 'Hotspot' using solid-state lighting for communications.

in[63]). This would increase the available optical range for high data rates considerably.

Figure 6 shows a 'hotspot' geometry with a base station placed above a receiver plane within a room. The coverage area of the hotspot is of radius *d,* as shown in the diagram, and together with the height of the base station above the receiver plane *h* (in this case 3m) this sets the half angle of the hotspot θ_h.

The optical transmitter is assumed to be a 10W source, as would be provided by solid-state lighting, with an emission profile that is constant with angle, as was described previously. The beam half-angle is θ_h. The receiver aperture is 15mm in diameter and all other receiver parameters are as before.

The RF channel is considered to be provided by some 'future' LAN, transmitting in the 2.4GHz ISM band, at a power level of +15dBm with no antenna gain.

Values for d_{ref} and γ are required; measurements in [48] suggest that for link distances of up to 10m $\gamma = 1.91$ at this frequency in a LOS environment, so that an estimate of $\gamma \approx 2$ is appropriate. Assuming reflections can occur from ceiling and floor and that one may dominate leads to two separate two-ray estimations, depending on the reflectivity of the surfaces. For the geometry shown these yield d_{ref} in the range of 7-96m. In [66] a three-ray model is proposed, and this simultaneously takes into account reflections from ceiling and floor in order to estimate d_{ref}, but requires the base station to be mounted a distance from the ceiling that is equal to the terminal antenna height from the floor. Assuming this value is 0.7m d_{ref} is 30m. In order to present 'bounds' to the breakpoint in the figure curves are plotted for $d_{ref} = 7m$ and $d_{ref} = 96m$ with $\gamma = 4$ beyond these distances. This assumption agrees with [48] in that it is unlikely the effect of a breakpoint close to 10m would be observed in real measurements that were made up to a maximum link distance of this value.

Figure 7 shows $\frac{E_b R_b}{N_o}$ vs. the distance the receiver is from a base station situated 3m above the receiver plane. The geometry is that shown in Figure 3 (b).

The RF system shows superior coverage, but the optical system would provide sufficient

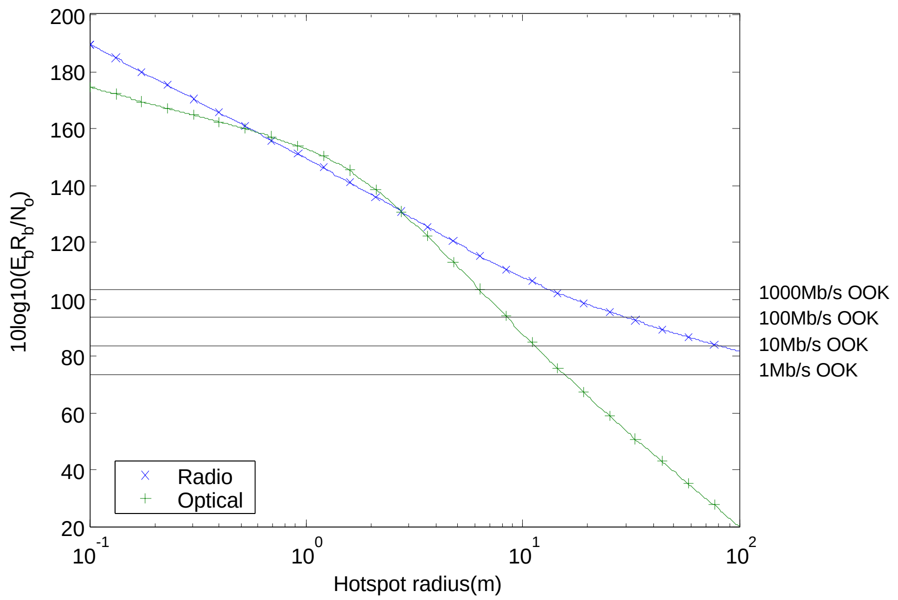


Figure 8. Comparison of 60GHz and solid-state illumination hotspot

coverage until the next lighting unit (as these must be placed frequently enough to provide illumination). In the case of the RF system the challenges are to provide sufficient bandwidth within the allocated spectrum, whereas for the optical link it is to modulate the LEDs at sufficient data rates. Research in this area is at a relatively early stage.

High capacity 'future' LANs

It seems likely that RF LANs will migrate to higher frequency regions of the spectrum, as more bandwidth is required and the implementation cost falls, so it is instructive to compare high frequency RF approaches with OW.

There has been interest in 60GHz wireless systems over perhaps a decade or so or longer, with several demonstrators [67] and recently funded projects[68]. The prospects and challenges for this medium are discussed in[69]. The availability of a large region of spectrum is a major attraction, and the improvement in semiconductor device performance, and potential fall in infrastructure cost are seen as an important enabling factor in its future widespread use. There have been a number of propagation studies that have investigated various environments and the effect of shadowing of humans and other obstacles[70, 71]. The conclusions from these are generally that 'mostly LOS' environments are required to guarantee operation [69].

One of the major problems with the acceptance of OW has been the need for geometric control of the transmission paths in LOS systems and quasi-diffuse systems. There are a number of quasi-diffuse systems [72-74]that use novel schemes to mitigate this, but the general arrangement of RF access points has always been a minor consideration in indoor systems when compared with OW. As RF LANs move to higher frequencies this distinction is unlikely to remain, with the optical and radio channels becoming 'closer' in nature.

Figure 8 shows a comparison between a 60GHz RF channel with a solid-state illumination provided OW channel (emitting 10W as previously). The base station is 3m above the receiver plane, and the geometry is that shown in Figure 3(b). For the RF link 10mW transmitted power[69] is assumed. The transmitter gain is set to match the half-angle of the hotspot θ_h (as shown in Figure 3) and the receiver gain is set to the same value (This is different from the previous 2.4 GHz example, where RF antenna gain is much more difficult to achieve). The receiver noise figure is 6dB.

The path loss exponent and reference distance must be determined for this configuration. Assuming either a two or three ray model the values of d_{ref} far exceeds the range of interest, so the free-space equation holds and $\gamma = 2$ for the LOS environments considered.

The optical model used is the same as for the previous example, with a 10W emitter into a half-angle that is set by the hotspot geometry.

The optical and RF links are relatively close in performance, with the RF providing slightly improved coverage. The need to illuminate the room should mean that continuous coverage using a series of hotspots may be available in the optical case, however.

Both systems are affected severely by shadowing, and require some means to provide a predominantly LOS path for a high capacity link. It therefore seems likely that a 60GHz LAN will be used to augment that provided by the installed 802.11 infrastructure, as is likely to be the case for optical links. Despite the inferior link budget the optical system has the virtue of simplicity, being a baseband channel. It is also not susceptible to the fading of the RF channel, and does not require complex coding and modulation.

Outlook for optical wireless

Short term

The wide range of RF standards and the rapid increase in bit-rate available makes the adoption of large area coverage OW LANs unlikely in the short to medium term. However, within the broad range of strategies for 4G systems there is a common theme of heterogeneous wireless links, and there are situations where OW links can offer higher performance, or lower power consumption, or both than their RF counterparts. This is most likely where there are lines of sight or quasi line of sight. Links are likely to be narrow field of view and short range, or when the geometry can be controlled, such as in optical hotspots.

Medium term

The use of higher frequency RF approaches to obtain bandwidth requires path management, and makes the use of OW in 'managed' situations more likely given that the alternative has a similar requirement, and OW may offer a simpler solution with low power consumption.

Longer term

The results here show that the major long-term challenge for OW is to improve the link budget to that provided by RF systems, so that obtaining LOS geometries is less critical. Coherent systems offer a potential long term solution, albeit with formidable challenges in providing a stable low-cost geometry[75]. Vertical cavity amplifiers using modified laser structures have been demonstrated[76], although these usually operate with very small etendue, which is unsuitable for OW applications without modification. Substantial parametric gain [77] has been demonstrated over limited bandwidths, (although broadband operation is possible), as well as the use of Avalanche Detectors [78]. Detector geometry and optimized devices also offer potential for increased antenna size and hence link margins[20]. The optimum solution may well be a combination of these techniques, and further work is required to compare each of these approaches and determine the best future approach.

Research directions and conclusions

The distinct properties of the OW channel can add to the 4G vision, with the possibility of a future terminal having a number of interfaces, both radio and optical. In order to achieve this work in the following areas is proposed, although this is not an exhaustive list.

Link budget improvement: the major barrier to non-LOS systems is the power required at the receiver, and work to improve this should be a major focus.

More comprehensive performance comparisons between short-range optical systems and their counterpart based on conventional RF approaches; there is a need to understand the properties of both channels between the same points, so that alternative data paths can be modeled, and the performance of a network that chooses the optimum path be determined.

Network modelling: understanding how optical and radio communications might co-exist.
Signal processing: examination of radio processing techniques such as Multisensor (MIMO) optical systems exploiting space and angular diversity. Space-time coding for optical wireless channels. Some work in this field has already been recently introduced by [79], where space-time codes are designed specifically for optical channels, specifically in the context of free-space optics communications. A MIMO channel model applied to diffuse WOC has been recently presented by [80].
Hybrid optical-RF systems: determination of the optimum method of using the alternative resources under different conditions, and the resulting performance improvement.
Visible light communications: fundamental capabilities and limitations of communication systems based on visible light (combined with illumination).

Future wireless standards offer a good opportunity for the wider adoption of OW. In particular, as 4G networks will be highly heterogeneous, OW based air interfaces can be incorporated to terminals in addition to the conventional RF based ones. Considerable work is still needed to fully exploit the clear advantages of the optical solutions, as well as developing low-cost subsystems and components to implement them.

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Appendix: standards

IrDA

The IrDA (Infrared Data Association) is a worldwide organization that develops standards for point-to-point very short-range optical communications, with a sub-meter range. This optical wireless interfaces can be found nowadays in a variety of portable equipment, like mobile phones, laptop computers and personal digital assistants, among others. In its basic version this standard defines a very low-cost, low-power with a maximum operating range of 1 m and data rates of up to 4 Mb/s. High speed IrDA versions providing up to 16 Mb/s are also available. Various interest groups are working on financial messaging (IrFm), transport (IrTM), and higher data rates (IrBurst) and (UFIR).

It is noted that the IrdA optical air interface supports no mobility as it usually requires manual alignment between transmitter and receiver. The standard defines the physical layer as well as different protocols used by upper layers. An overview of IrDA can be found in [81].

The IR Physical Layer of the IEEE 802.11 Standard

The IEEE 802.11 standard, broadly known for wireless LAN radio based air interfaces, also includes an infrared based physical layer. This air interface was developed in parallel with the basic radio air interface and it exploits diffuse transmission to provide point-to-multipoint indoor connectivity. This WLAN IR physical layer was originally designed to support 1 and 2 Mb/s with inexpensive optical transceivers. The main application originally foreseen for the IR 802.11 was in establishing optical ad-hoc networks. An introduction to the IR 802.11 standard can be found in [82]. Unfortunately industry never was enough attracted to this standard with the consequence that no commercial products complying with this standard were ever launched.

ISO CALM TC 204

This supports communications over 100m (and may support longer distances) with closing speeds between vehicles of 200km/h. Data rates of up to 100Mb/s and beyond are specified.