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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.**

***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 part 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. 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 vision and areas of future research

Optical Wireless Communications as an Alternative 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 configurations

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, 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 show 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 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. In the near IR region (between the visible and 1400nm) the limit for point sources is less than 1mW. Beyond 1400nm this limit increases by a factor of 20 or so. However in both cases much higher powers are available by diffusing the sources, thus increasing their apparent emitted areas. Several types of engineered diffuser have been developed, including holographic [12] and reflective [13]. This latter device has been incorporated in a commercial optical link [14]. Most systems use laser diodes, due

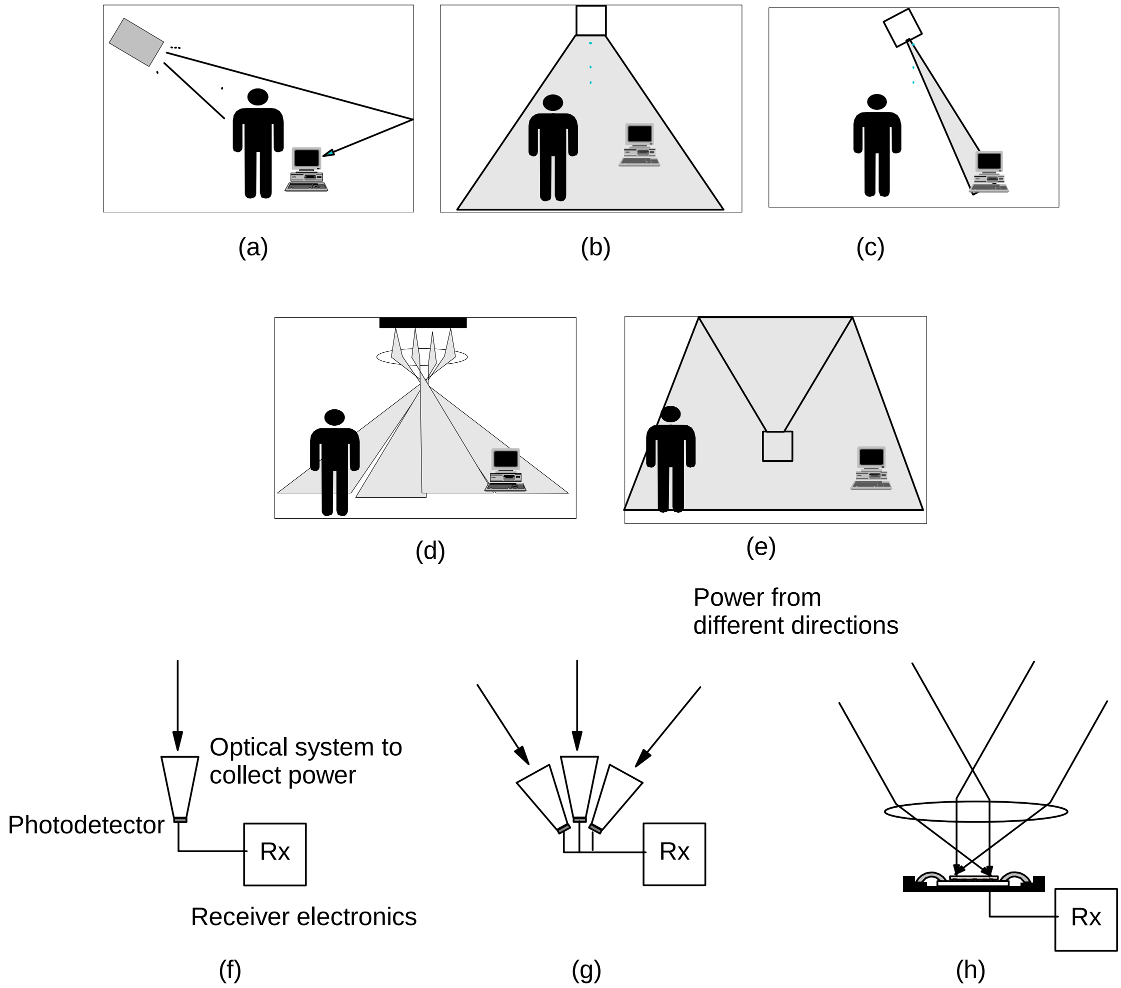

Figure 1. Optical wireless configurations. (a) Diffuse system. (b) Wide LOS system (c) Narrow LOS system with tracking (d)Narrow LOS system using multiple beams to obtain coverage (e)Quasi diffuse system (f) Single channel receiver. (g) Angle diversity receiver (h) Imaging diversity receiver.

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 [15]. 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;

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

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 [16] can be used to collect and focus radiation onto single element detectors. Recent designs of optical antenna [17] 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 [18] (Figure 1 (g)). Imaging receivers, as developed at Oxford [19] and Berkeley [20] 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 a combiner/equaliser can be used to maximise the received signal and BER [20],

Optical filtering

Ambient light is the most important source of interference and it may greatly deteriorate link performance [21]. Constant ambient illumination will generate a DC photocurrent, and this will normally be blocked by the AC coupling of the receiver [22]. 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 [23] and this can greatly effect link performance. Various studies of this have been undertaken, including [24, 25].

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 [26]. 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 [27]. Holographic receiver front-ends also allow light 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 [33-35] 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 [25, 36] [37] 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 [38] or Rayleigh, with exponential impulse responses. Various measurements have also been made [39, 40]. Recent high-resolution data indicate that transparent ‘unlimited’ bandwidth diffuse channels are available in particular directions for most diffuse environments [41].

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 [42]. 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 [42]. 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 [42].

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 [42].

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) [43, 44]. 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 [45]. Such directive channels are necessarily subject to blocking, which is again distinct from radio applications [9, 45]and [46].

Applications areas for optical wireless

There is little doubt that radio solutions will remain dominant for most applications, but there are several areas where OW is attractive.

Telematic applications

There is also a growing interest in optical communications between moving vehicles, and between vehicles and roadside hubs. These are being considered for telematic applications, such as road pricing and navigation, as indicated by the development of an ISO standard (ISO CALM 204) for such systems. The German government has adopted an optical communications system for its tolling system for freight vehicles [47]. Several train-operating companies are investigating FSO for communications with trains, to provide broadband 'to the seat'.

Secure wireless applications

There are a number of applications where OW can provide secure communications. The IRDA is promoting 'Financial Messaging', where a secure transaction takes place between a handheld and a retail terminal, albeit at low data rates [48]. 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. 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. There may also be other environments such as dealing rooms where secure wireless networks are required, and OW can easily provide this.

Ultra-high bandwidth wireless

Applications such as virtual reality suites, and wireless TV studios require multi Gb/s wireless communications with very high spatial bandwidth density. The directivity available with optical links, combined with tracking makes this feasible.

RF Hazardous environments

One of the major growth sectors in avionics is data and speech communications to aircraft. Satellite broadband is being added to aircraft, and many aircraft are equipped with telephone to the seat. The wireless link from the passenger to the data infrastructure is currently not possible, and OW represents perhaps the only allowable alternative. A mobile phone or PDA containing a radio and optical terminal could allow seamless communications with a local optical base station part of the aircraft infrastructure. Hospitals offer similar opportunities, both in wireless instrumentation and transmission of data. In sensitive environments, the access point or network could automatically disable the radio interface, enabling communications through the optical link.

Hybrid Wireless Systems

In broad terms optical wireless provides high bandwidth, and providing coverage is problematic, whilst for RF approaches the opposite is the case. Perhaps the key advantage of OW (in a general environment where security is unimportant) is the ease with which high bandwidth LOS channels can be provided, and the potential these have to decrease the load on the infrastructure.

Hybrid systems that can allow this are therefore attractive, and fit well within the 4G vision of heterogeneous wireless systems working together to provide a seamless infrastructure. Very simple hybrid approaches combining optical and radio frequency links have been proposed recently for short-range (indoor) communications [49, 50]. Reference [51] describes protocols that use RF signalling and reallocate the optical sources under blocking conditions.

Future research in this area is discussed in later sections.

State of the art

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 [52].

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 [53]. 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. Work on such standards is also being undertaken by IRDA [48].

Commercial systems and research state of the art

Traffic management

As mentioned previously there is both standards and commercial activity in this area. IRDA has formed The Travel Mobility Special Interest Group (IrTM) in order to develop a specification for toll payment. A standard also exists for longer-range communications (ISO TC 204 CALM). A major commercial amount of activity is by Efkon, who have won large contracts for payment systems worldwide, notably a German project for truck traffic tolling.

Ultra-high bandwidth wireless

JVC have recently introduced a tracking 1.5Gb/s link between a HDTV source and Flat screen TV [14]. This uses mechanically tracked terminals and a novel diffuser to achieve eye safety.

Secure applications

IrFM is a ratified standard and a number of point and shoot products designed for electronic funds transfer. The high speed Special Interest Groups (SIGs) (IrBurst and UFIR) are working on data transmission at 100Mb/s and greater, and a major applications area is secure downloading of multimedia files.

Networks

There are few low speed IR networks that are commercially available, and several in development. An LOS network was available from JVC [54], and diffuse LANs from spectrix[55]. The low cost and complexity of OW components also makes the attractive for relatively low speed home networks, and such networks are being developed by Infracom [56]. In the research area diffuse networks that operate up to 50Mb/s have been demonstrated [57]. A solid-state tracked link that operates at 155Mb/s has been fabricated [30] that uses components optimised for OW applications. This includes custom CMOS transmitter and receiver devices, and detectors optimised for this application.

Recent advances in LED technology has led to the fabrication of high efficiency white light devices. Even though the primary function of white LEDs was for illuminating and signaling purposes, some recent studies suggested and even demonstrated that such a LED can be used for establishing simultaneously a communication link [58, 59]. Achievable data rates depend on the angle of irradiance and field of view, and also on the use or not of tracking systems. In [59]data rates of few hundred Mb/s and even much higher are reported based on numerical results. This is a new emerging area for research and it has generated considerable interest, in especial in Asia. Recently the Visible Light Communication Consortium was created with the aim of investigating and promoting these techniques [60].

Future Perspectives and Areas of Research in Optical Wireless Communications

The part that OW might play in the 4G vision will be driven by different reasons in different applications areas.

Where directive links are required, for instance for reasons of security, power efficiency or a requirement for very high spatial bandwidth density OW has clear benefits over RF approaches. Low cost optical and electrical components can be used to provide high capacity links over a wide variety of distances, with data rates from Mb/s to greater than Gb/s.

Providing full coverage using LOS links is possible with some sort of tracking mechanism, and in cases where user density is low, and the environmental geometry is

controlled to manage blocking. These systems might find application where ultra-high bandwidth is required, together with mobility.
The most common use of LOS links might be to augment the capacity and capability of an RF network. Such links might offer (i) point-to-point capacity within a hybrid network (ii) high bandwidth between RF base stations (iii) optical hotspots with low latency data links and (iv) wireless access when RF systems are not desirable, such as medical or avionic environments.
Diffuse and quasi-diffuse channels can provide complete coverage without the need for RF channels, with varying degrees of complexity depending on the bit-rate desired. At low bit rates (~10Mb/s) diffuse OW can offer wireless connectivity with simple and therefore low cost components. This might find application in cost sensitive environments, such as the home, or in RF sensitive areas, such as hospitals, where wireless medical sensing is of interest.
At much higher bit-rates (10-100s Mb/s) the increased path loss of the optical channel makes achieving coverage challenging, and relatively complex systems are required to achieve this. In this regime, some of the signal processing techniques used for radio systems may be valuable, using different front-ends and a common electronic system.
RF is likely to be dominant particularly in this regime (as similar bit-rates may be available and allowed path losses are higher), with OW used in special situations, such as secure or RF sensitive environments.

Research directions

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.
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 modeling: 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 [61], 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 [62].
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).

The bandwidth and directivity of the optical wireless channel, together with the security and safety of the optical wireless channel in RF sensitive environments are useful and distinct properties that have a part to play in the wireless world. Together RF and optical approaches might significantly add to the capabilities of terminals, and there is a significant body of research effort that is working toward this.

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