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A Survey of Opportunities for Free Space Optics in Next Generation Cellular Networks

Frédéric Demers, Halim Yanikomeroglu and Marc St-Hilaire
Department of Systems and Computer Engineering
Carleton University
Ottawa, Canada
frederic.demers@ieee.org, halim.yanikomeroglu@sce.carleton.ca, marc_st_hilaire@carleton.ca

***Abstract*—Cellular wireless networks have consistently relied upon Radio Frequency (RF) channels to provide connectivity between users and base stations. RF channels have also provided, in large part, connectivity within the Radio Access Network (RAN) and the Core Network (CN) for the purpose of connecting mobile users to the Public Switched Telephone Networks (PSTN) and Internet. However, other methods may be necessary in order to provide the faster data rates required by many new and emerging applications. This paper provides a comprehensive overview of the potential role for Free Space Optical (FSO) communications within next generation cellular networks. The argument is made that the increasing number of base stations, as well as the advanced topologies supported by next generation cellular networks, pave the way for a growing reliance upon FSO communications, with a view to support the high bandwidth applications offered to mobile users.**

***Index Terms*—optical communication, land mobile radio cellular systems.**

I. INTRODUCTION

The exponential growth in the demand for high throughput and low latency applications for mobile users is forcing fundamental changes to cellular network topologies. Next generation cellular network deployments are converging to capacity-limited architectures in which radio resource reuse is optimized, often shrinking cell coverage (and thus the distance between users and network access) in order to provide high and constant signal-to-noise ratio [1]. Service providers increasingly rely on techniques such as cell splitting, sectorization, distributed antennas and relays, in order to improve frequency reuse and hope to deliver increasingly high aggregate capacity. These architecture changes may pave the way for a growing reliance upon FSO communication systems.

High-speed optical fiber networks have proliferated and carry the majority of telecommunication traffic today. Unfortunately, this cabled infrastructure does not reach many of the cellular infrastructure end points. The provision of escalating data rates to mobile users is creating the need for this high-speed bridging technology, one that will connect base stations to the fiber network. FSO communication systems have evolved in recent history; commercial systems are now available and are sufficiently reliable in their respective applications to be once again considered in next generation cellular network applications. Furthermore, as user mobility decreases, the demand for bandwidth increases. Nomadic users will ultimately expect and require bandwidths approaching what is currently available using fiber networks, but from a wireless connection [2].

Industry, standardization bodies and academia tend to diverge on the definition of next generation cellular networks. In this study, cellular networks that have not been widely implemented by telecommunication service providers are considered to be next generation cellular networks, namely 4G (defined as ITU-R IMT-Advanced compliant) and 5G. More specifically, the advanced network topology and radio interface features described in LTE/LTE-Advanced and IEEE 802.16m/WiMAX Release 2 are looked into and compared against recent FSO communication developments published in research literature.

For the purpose of this study, cellular wireless networks are divided into three components: User Equipment (UE), Radio Access Network (RAN) and Core Network (CN). The nomenclature and exact break down vary between standard families and Personal Communication System (PCS) generations. The RAN is responsible to provide connectivity between the mobile users and the CN. The RAN comprises elements such as base stations and base station controllers, managing the radio resources and handoffs. Until now, the RAN relied exclusively on RF channels in providing the air interface connectivity, linking the user equipment (e.g. smart phones) to the base stations. Connectivity between the base stations and base station controllers is also part of the RAN; it however uses a variety of communication channels, predominantly microwave RF, but also satellite communications (also RF based), or cabled infrastructure such as optical fiber where it is available.

The core network links the RAN to the Public Switched Telephone Network (PSTN) to provide seamless mobile-to-fixed telephony, as well as mobile-to-mobile telephony between cellular providers. With increasing importance, the CN also links the mobile users to the Internet in order to extend data connectivity seamlessly. For some service providers using carrier-class Voice-over-IP (VoIP) to encapsulate and carry voice traffic, the Internet is the only linkage to the PSTN. CN connectivity is most often achieved using microwave RF or optical fiber.

The purpose of this study is to investigate the opportunity for free space optical communications, also known as optical

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wireless communications (OWC), as an architecture component for next generation cellular networks. The most promising FSO communication systems are surveyed and presented as a viable solution to enhance or replace various components of emerging cellular network architectures.

This paper is organized as follows. The next section provides a comparison between the wireless optical channel and its RF counterpart, followed by a short discussion on the channel model in Section III. Section IV considers FSO within the CN whereas Section V focuses on the advent of free space optics within the RAN. Concluding remarks are gathered in Section VI.

II. CHARACTERISTICS OF FREE SPACE OPTICAL COMMUNICATIONS

As a communication channel, the advantages of free space optics are well documented. Matsumoto *et al.* list high bit rates, ease of deployment, license free operation, high transmission security, full duplex transmission and protocol transparency in [3]. Shielding from electro-magnetic interference should also be mentioned as a significant advantage in saturated RF spectrum environments.

However, a number of constraints have also been observed. FSO links have very stringent line of sight requirements, as they cannot propagate through obstacles, and rely on very narrow beamwidth to maximize gain. They also suffer from a high dependence on weather conditions (rain, snow, dust particles, and particularly fog), which can severely affect the reliability of the links. Furthermore, they are susceptible to atmospheric effects like scintillation and beam wander [4]. These atmospheric effects combined with vibrations and building sway need to be mitigated in commercial products using sophisticated tracking systems, in order to keep as much energy as possible onto the photodetector. In FSO communications, sources of background illumination such as fluorescent lamps and the sun have a fraction of energy in the infrared portion of the spectrum, introducing noise in the photodetector [5]. Lastly, signal attenuation is significantly higher than in typical RF-based communications systems, limiting the useful range of FSO products offered commercially. Chosen key characteristics of the communication medium are discussed in amplifying details next.

A. *High bit rate*

The most significant advantage of optical communications is their emplacement on the electromagnetic spectrum, offering unprecedented signal bandwidth. Optical communications rely on lasers and Light Emitting Diodes (LED) typically operating in bands in the wavelength range of 800–1700 nm, which provides several magnitudes of improvement in signal bandwidth over even the highest band signals operating in the RF environment. In practice, free space optical links in the order of 10 Gb/s have been achieved over reasonable distances (1 km). The tight beam confinement in FSO allows for beams to operate nearly independently, allowing for tight spatial diversity and providing virtually unlimited degrees of frequency reuse in many environments [6].

B. *License-free operations*

Unlike most of the RF spectrum that is subject to licensing by the nations' regulatory bodies, optical transmissions are not subject to licensing. Given the high attenuation of optical links through the atmosphere, and the high directivity required to achieve reliable point-to-point communications, FSO systems are unlikely to interfere with one another.

C. *Ease of deployment*

In addition to the cost savings over RF point-to-point links due to licensing, FSO communications are significantly easier and cheaper to install than their cabled counterpart. In war-torn countries for example, or during disaster relief, FSO communication systems are highly suited to jump start the establishment of a core communication infrastructure, particularly so if spectrum allocation authorities are not yet able to regulate the distribution of spectrum resources.

D. *Security*

Another advantage derived from the confined beam of FSO communications is the ability to provide a significant degree of covertness. A malicious eavesdropper would need to be located very near the direct path of the FSO beam, between the transmitter and receiver, to intercept sufficient energy and recover content. The eavesdropper's antenna is likely to cause link outage for the intended recipient due to beam obstruction. Only in unusual cases would eavesdropping be feasible. Jamming an optical receiver is also difficult because of the pointing capabilities required to accurately place optical energy onto the photodetector, without the luxury of a feedback loop to help tracking [6].

III. CHANNEL MODEL

Although optical communications generally obey known electromagnetic propagation laws, there are a number of factors which contribute more significantly to the path loss than geometric spreading inversely proportional to the square of the distance. Traditional analytical RF path loss models such as log-normal, Rayleigh, Rician, or empirical path loss models akin to Okomura-Hata, usually do not need to consider absorption, diffraction and scattering due to atmospheric gas molecules and airborne particles. These phenomena cannot be approximated out of optical path loss models due to the relative size between optical wavelengths (800-1700 nm), airborne particles such as contaminants (dust, pollen, large bacteria), water droplets (1,000-100,000 nm) and, to a lesser extent, the size of molecular atmospheric gases (~0.3 nm). Furthermore, atmospheric turbulence consists of moving eddies of varying refractive indices; this movement tends to bend the optical communication path, according to Snell's law, such that the incoming energy appears to dance around the optical receiver.

A. *Attenuation values*

The influence of meteorological conditions on the attenuation of FSO links is significant and is the chief limitation in preventing the wide deployment of FSO communication systems in some areas of the world. The safety margins that need to be built into the link budget calculations, in order to maintain carrier-class reliable communications, severely limit the effective range, or require power that is beyond eye safety regulations, notwithstanding implementation costs.

For FSO communication links operating in the infrared wavelengths, the attenuation contribution from the atmosphere is relatively low compared to the attenuation contribution from weather conditions, due to the close relationship between the wavelength and the particle size of fog droplets, cloud droplets, rain drops, haze particles and snow crystals [5].

Although rain and snow can cause attenuation up to approximately 40 dB/km and 100 dB/km respectively, fog is the largest problem by far. In extremely heavy fog, attenuation as high as 480 dB/km has been reported [7], [8]. Typical attenuation values from various publications were consolidated in Table I.

RF absorption through the atmosphere, on the other hand, is often insignificant when compared to the RF energy dissipation due to geometric spreading and other phenomenon such as diffraction, reflection and scattering on large objects. The attenuation is negligible for frequencies up to 50 GHz (1 dB/km), but high capacity RF links in the millimeter wavelength (60 – 80 GHz) are significantly affected by the atmospheric water content. Seybold shows in [9] RF attenuation values as a function of frequency (Fig. 1).

B. *Atmospheric turbulence*

Atmospheric turbulence has a significant impact on the quality of free space optical beams propagating through the atmosphere over long distances. Atmospheric turbulence is also of concern because even in clear weather, local temperature gradients, pressure variations, and scattering by airborne particles produce a varying refractive index along the transmission path [6].

The major effects related to atmospheric turbulence include beam broadening, beam wander, intensity fluctuation (or scintillation) and angle-of-arrival fluctuation [3], [10], [11]. These phenomena cause the received signal to fluctuate in location, intensity, and phase, degrading the channel and resulting in poor transmission quality and outages [6].

TABLE I
ATTENUATION IN FSO COMMUNICATION LINKS

Condition	Typical attenuation (dB/km)
Clear atmospheric conditions	0.2
Urban	1
Rain	40
Snow	100
Fog	120
Dense fog	300
Coastal fog	480

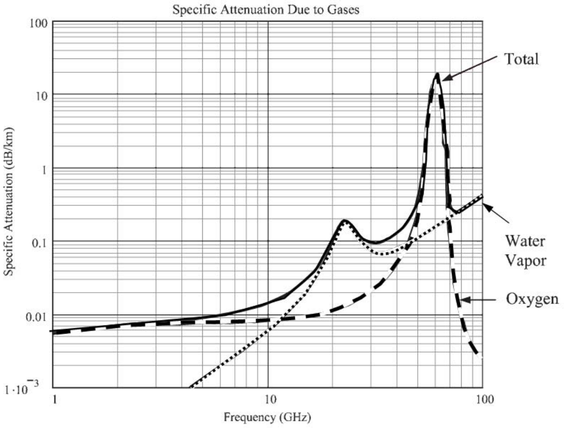

Fig. 1. RF attenuation due to absorption by atmospheric gases, for a standard atmosphere, as a function of frequency [9]

Matsumoto presents in Fig. 2 a simple illustration to show the effects of beam wander and scintillation on received signal strength [3].

Some techniques such as aperture averaging, adaptive optics, use of large receive apertures, diversity techniques (such as delayed diversity), fast tracking antennas and Fine Pointing Mirrors (FPM) help in minimizing the effects due to atmospheric turbulence. Although wave-division multiplexing approaches to this diversity scheme are satisfactory, orthogonal polarization channels offer a simple solution. Because the atmosphere is not intrinsically chiral (the phenomenon in which an object differs from its mirror image), left- and right-circularly polarized waves should be identically affected by turbulence, so no significant perturbation of the polarization state of a lightwave that has propagated through turbulence is expected. Indeed, the transmitted signal could be polarization-shift-keyed. This approach has not received much attention in optical fiber communication systems because of their depolarizing properties, and as such would not be applicable to full-optical FSO systems [12].

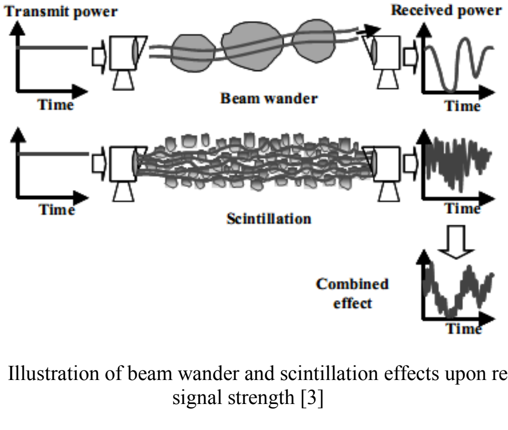

Fig. 2. Illustration of beam wander and scintillation effects upon received signal strength [3]

C. *Eye safety*

Most FSO communication systems use laser diodes as sources, and their transmission power is limited by eye safety regulations. In the United States, the Food and Drug Administration considers power density of about 100 mW/cm^2 at 1550 nm, or 1 mW/cm^2 at 780 nm safe to the unaided eye [2], [7].

The maximum intensity that can enter the eye on a continuous basis depends on the wavelength, whether the laser is a small or an extended source, and the beam divergence angle. The lasers used in free space optical systems generally emit beams with a Gaussian intensity profile. For a Gaussian beam at the transmitter with spot size w (in m) and total power P (in W), the maximum intensity at the center of the beam is given by

$$I_0 = 2P/\pi w^2. \tag{1}$$

In general, free space optical systems operating at 1550 nm are 70 times more eye-safe, in terms of maximum permitted exposure, than FSO systems operating below 1000 nm [12]. This attribute, as well as the ability to engineer full-optical communication systems compatible with existing optical fiber light sources, make the decision to use 1550 nm more practical in the majority of cases.

IV. FREE SPACE OPTICS WITHIN THE CORE NETWORK

Perhaps the most natural way to embed FSO products within cellular networks is to consider them as point-to-point replacements of terrestrial links within the core network. Commercial FSO products already exist with the benefits of requiring no cabling or spectrum licensing, whilst providing high speed links, on par with the capacity of optical fiber. For example, an FSO system with a capacity of 1.28 Tb/s over a range of 210 m has been realized by Ciaramella *et al.* in [13]. The main shortcomings of FSO communications used in this scenario are link reliability due to weather, and range. Indeed, in order to be a viable alternative to other communication means, FSO links need to achieve carrier-class availability, which is generally considered to be 99.999% (“5 nines”) [14]. This often constrains FSO links to sub-kilometer range.

A. *Pointing, acquisition and tracking*

A key property of lasers is their highly directional beams. FSO systems are often designed to have a divergence of a few milliradians or less in order to concentrate the optical energy on a receiver. Each “optical transceiver” must be simultaneously pointed at the other for communication to take place. Because of effects induced by atmospheric turbulence, wind and temperature loading on the mounting equipment and building sway, FSO links often need to use Pointing, Acquisition, and Tracking (PAT) subsystems. PAT in FSO communications is much more challenging than in RF communication systems in which the transmit and receive antennas may only be required to generally point at one another for communication to occur [6].

Tracking is non-trivial. The divergence of the transmitted beam and the receiver field-of-view have to be greater than the beam (or pointing) jitter in order to provide accurate correction [7]. Kazaura *et al.* used a quadrant photodetector for detecting and analyzing the beam position changes, and a Fine Pointing Mirror (FPM) to counteract the changes. A coarse 850 nm beacon was used in addition to the tracking of the main 1550 nm signal. The fast beam tracking and control mechanism of the FPM is able to both suppress atmospheric induced fluctuations and focus most of the received optical beam onto a 10 μm core of the single-mode fiber [4].

B. *Full-optical wireless communication systems*

In conventional FSO systems, a fiber transceiver converts an electrical signal into an optical signal. The electrical signal is amplified by a laser driver providing enough current to drive the laser diode. Modulated light from the laser diode or LED is directed through the channel to the corresponding receiver which focuses the beam onto a photodetector (PD). The PD converts the optical signal back into an electrical signal [3].

In full-optical wireless communication systems, an optical beam is emitted directly from a fiber termination to free space using an optical antenna. At the receiver, the transmitted optical beam is focused, using the receiver optics, directly to a fiber and then sent down the fiber for detection [3], [15]. The need to convert the signal from electrical to optical and back is eliminated which results in a bandwidth and protocol transparent communication link much easier to integrate with cabled infrastructure.

A Dense Wavelength Division Multiplexing (DWDM) extension to the full-optical wireless has been realized by Kazaura *et al.* in [4]. This important improvement enables several information carrying wavelengths to be transmitted simultaneously from the optical antenna, enhancing capacity. Matsumoto *et al*. succeeded in multiplexing 4 wavelengths to obtain 10 Gb/s over 1 km [3], whereas Ciaramella *et al.* used 32 wavelengths to achieve the Tb/s capacity over 210 m [13].

C. *Hybrid RF/FSO*

The combination of radio frequency and free space optical links has been studied for over a decade. Due to the complementary nature of radio and FSO communications, both in capacity and coverage, the combined use for data transmission suggests advantages over a single media [16]. FSO links are severely attenuated in foggy conditions, whereas microwave RF frequencies are significantly attenuated by rain, due to the close relationship between rain droplet size and millimeter wave transmissions wavelength (particularly for frequencies greater than 10 GHz) [14], [17]. For example, the blockage of an optical link running at tens of Gb/s may leave a backup RF channel running at hundreds of kb/s [6]. As optical wireless links allow very high data rates compared to RF links, even short periods of very high throughput could be beneficial in delay insensitive applications [8].

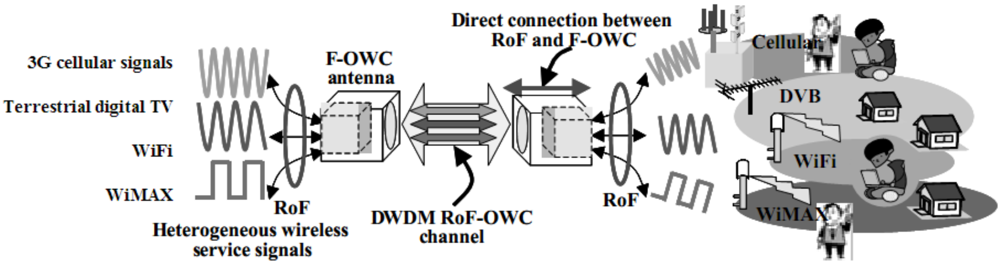

Fig. 3. Diagram representing the multiplexing of several RF signals onto optical fiber (RoF), used as a source to an optical wireless communications (OWC) channel [3]

Kim *et al.* show in [14] that hybrid FSO/RF system increases the availability of the link to 99.999% for all ranges up to maximum FSO range.

Hou and O'Brien implemented in [16] a 100 Mb/s optical bidirectional link used cooperatively with a 10 Mb/s RF LAN. The optical link is periodically blocked and the system switches to RF communications if these events last for a sufficiently long time. The decision to switch is made using a fuzzy inference engine. When the optical link is blocked 10% of the time, the combined system is approximately 12 times as efficient as the RF only LAN over a wide range of traffic loads [2].

Hybrid FSO/RF links overcome the range restrictions imposed by the requirement to achieve link reliability in adverse weather conditions [18].

V. FREE SPACE OPTICS WITHIN THE RADIO ACCESS NETWORK

The RAN fulfils requirements that are often competing: the need to extend the wired network's level of service to the wireless user, and maintain this connectivity in spite of user mobility and the lack of geographical boundaries. Mobile users increasingly expect levels of service commensurate with applications offered in nomadic wireless or wired applications, comparable to what is available at home, at work or on campus. Unfortunately, it is difficult for the RAN to provide both coverage and capacity given the finite radio resources. In previous personal communication systems generations, several base transceiver stations were connected to a Base Station Controller (BSC) in a hierarchical configuration. The BSC was solely responsible for Radio Resource Management (RRM). Within 3GPP's E-UTRAN however, enhanced Node Bs (eNB) form a mesh and are enabled to make RRM decisions. This section investigates the suitability of free space optical links within the RAN.

A. Distributed cell sites, RoFSO

It is estimated that the number of base stations required to cover a given area in 4G systems will be four times greater than that of 3G systems for the same area [1]. Newer cellular architectures support different options in order to shorten the distance between the mobile users and the fixed networks. Examples are relay networks, distributed antennas and Coordinated Multipoint (CoMP) transmission and reception. These cost effective alternatives reduce the need to resort to cell splitting and sectoring as the only methodologies to increase the signal to noise ratio to and from mobile subscribers. The transmission of RF signals over optical fiber has been an attractive option to link wireless network facilities, particularly in designs employing distributed antennas, leaky feeders and relays. This technology is usually referred to as Radio over Fiber (RoF) or RF photonics. In RoF implementations, analog RF signals are placed on optical carriers and transmitted over high capacity optical fiber cables. The optical fiber transmitter modulates the optical carrier with the radio signal, instead of digital inputs which are commonly used in digital optical fiber communications [3], [15].

The optical fiber offers very little attenuation, is immune to multipath fading, shielded from electromagnetic interference and independent of RF signal formats [15].

The limited amount of installed optical fiber cables has highlighted the usefulness to FSO communication systems that are capable of replacing, or extending RoF links. The full-optical communication systems discussed in [3] are ideally well suited for this task. RoF networks can be extended to Radio on Free Space Optics (RoFSO) providing communication links for heterogeneous wireless services where it is not easy or feasible to install optical fiber. Kazaura *et al.* developed and demonstrated in [4] a full-optical FSO communication system operating using a 1550 nm wavelength capable of transmitting multiple RF signals (including W-CDMA, WLAN and ISDB-T) over an optical wireless channel using DWDM. The system demonstrated consistent performance in terms of the specified figures of merit for the various wireless services tested. A diagram of this topology is shown in Fig. 3.

B. Mesh topology and relays

The hierarchical tree-based access network topology suited for voice-centric low-bandwidth services is inflexible and cost-ineffective in 4G wireless systems with highly variable traffic characteristics and changing network requirements [1]. Mesh topologies consisting of short multi-hop links between network elements, favored in next generation cellular networks, are also well suited for FSO communications due to the path diversity opportunity. Also, FSO links are easier to implement and scale in a mesh topology than their RF counterparts because of the near-infinite frequency reuse offered in optical communications.

Ghosh, Basu and Das propose the FraNtiC mesh architecture using optical links in a multi-hop mesh scenario in [1]. In spite of typically low FSO link availability (e.g. due to adverse weather), the mesh topology allows the overall network reliability to maintain carrier-grade figures [1]. Safari and Uysal suggest relay-assisted transmissions as a powerful fading mitigation tool for free space optical systems operating in channels exhibiting atmospheric turbulence. Both serial (i.e. multi-hop transmission) and parallel (i.e. cooperative diversity) relaying coupled with amplify-and-forward and decode-and-forward modes were examined, explicitly taking into account both path-loss and fading effects [19]. Benefits from relays against fading due to atmospheric turbulence are explained because the fading variance is distance-dependent.

C. FSO and picocells

Picocells are characterized by small service areas and low transmit power from the pico-base stations. Picocells usually provide service to low mobility subscribers within or near buildings, often within a larger umbrella cell servicing outdoor subscribers with higher mobility. Unlike femtocells, which are connected to the cellular service provider using the PSTN or the Internet, cellular pico-base stations are connected to the network by the cellular provider.

Although telecommunication service providers have dedicated considerable financial resources in order to provide optical fiber connectivity between countries and cities, such connectivity remains unavailable for many buildings with high data throughput requirements. The “last mile” from the fiber backbone to the clients’ premises, or pico-base station, still represents a significant problem. It may not always be possible or practical to lay down optical fiber, and it is invariably costly and time-consuming [8]. FSO communication systems provide an attractive solution to the “last mile” problem, especially in densely populated urban areas. Similarly, FSO systems could be well suited to connect pico-base stations to the network, where optical transceivers could be installed in the windows or on the rooftops of buildings, and communicate with a local communication node [12].

D. FSO in the air interface

The air interface describes the interface between the user equipment and the access point or base station (e.g. eNB). The main challenges faced when considering FSO solutions to the air interface are rooted in user mobility, which often results in the obstruction of the optical link. In addition, the challenges of pointing, acquisition and tracking needed to compensate against building sway or atmospheric turbulence are pale in comparison to those experienced by a mobile user. A few solutions proposed to enable optical communications to and from mobile users are explored next.

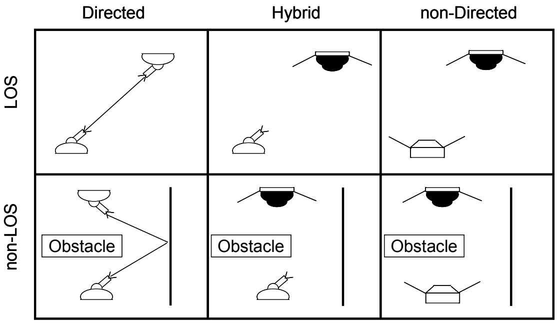

Fig. 4. Configurations for indoor infrared communications [23]

1) Spherical antennas: Akella *et al.* proposed in [20] a new design that employs spherical antennas covered with optical transmitter and receiver modules, in order to maintain connectivity even when antennas are in relative motion. Spatial reuse is achieved by tessellating multiple optical transmitters and photodectors on the surface of a sphere. The tessellation not only improves the range characteristics because every direction now has an inexpensive light source (e.g. LED), but also enables multi-channel simultaneous communication through each transceiver. Another significant advantage of high resolution tessellation on spherical surfaces is that it allows electronic tracking of the light beam coming from a mobile peer, enhancing the ability to maintain Line-of-Sight (LOS) condition, without the use of mechanical tracking [20]. A variant of this idea is suggested, as a proof-of-concept, in [21] and [22] using angle-diversity receivers and multiple-element transmitters to obtain LOS at rates of 1 Gb/s in nomadic applications. Unfortunately, neither of these two approaches, on their own, mitigate blocking due obstacles preventing the LOS. Interference from nearby spherical antennas, due to the relative wide angle of the tessellated transmitters and photodetectors proposed by Akella *et al.*, has not been discussed.

2) Indoor diffuse optical wireless: In indoor applications, free space optical communications offer broadband highly secure communication system in which a single wavelength can be used to cover a large area within the same room, taking advantage of the fact that optical signals cannot pass through opaque obstacle. As shown in Fig. 4, there are six configurations possible for indoor FSO communications. One of the most attractive is the non-LOS-non-directed configuration, also known as diffuse. Connectivity is possible even when obstacles are placed between the transmitter and receiver, because of the high reflectivity of walls [23]. As an alternative design to wide-angle transmitters often used in diffuse communications, quasi-diffuse transmitters create multiple narrow beams targeted in different directions. The development of a combined directed (for high-speed) and diffuse link (for connectivity) system was demonstrated achieving bit rates of 155 Mb/s over 2 meters, which could service users in a small classroom [24]. The indoor diffuse or quasi-diffuse model is interesting; however, the Inter-Symbol Interference (ISI) impairment and high path loss, resulting in relatively low bit rates (155 Mb/s), offers little advantage over RF approaches.

VI. CONCLUSIONS

Advanced radio access network architectures supporting mesh configurations are attractive from an FSO perspective. Mesh configurations generally provide shorter link distances between network elements, but also provide path diversity, which enhances link reliability in face of inclement weather and temporary obstructions.

The use of optical links in the air interface is more problematic. Whilst nomadic applications could be supported, true user mobility will continue to face significant connectivity issues due to obstruction. The spherical antennas proposed by Akella *et al.* are a step in the right direction, but size and complexity render this solution unusable in user equipment for the near future. The suitability of indoor diffuse or quasi-diffuse transmissions to provide connectivity to mobile users also needs further research.

In all, the research suggests that many engineering solutions exist to overcome common connectivity issues due to atmospheric turbulence, vibrations, wind and temperature loading and building sway. Whilst optical fiber cabling is still the preferred media for long haul, high-bandwidth transport, FSO systems can now be considered a viable alternative for short-haul access distances of 4 km or less [14]. With the densification of infrastructure access points, opportunities for short hop wireless connectivity will grow. We believe FSO links and hybrid RF/FSO links are well suited for next generation cellular topology models including mesh networks, CoMP transmission and reception, relays and picocell architectures.

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