WIRELESS OPTICAL COMMUNICATION SYSTEMS WITH MIMO –AN OVERVIEW

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Abstract:
Free Space Optical (FSO) communications has the potential of providing virtually unlimited bandwidth. Cellular wireless networks have consistently relied upon Radio Frequency (RF) channels to provide connectivity between users and base stations. This paper provides an overview of the potential role for FSO communications within next generation wireless 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 wireless users. Multiple transmitters and receivers can be used to combat the interference induced fading and to compensate for pulse attenuation and broadening caused by scattering. FSO-based mobile sensor networks can potentially be used in a battlefield where security of communication, including freedom from susceptibility to enemy-induced jamming, is important. Multi-Input Multi-Output (MIMO) transmitter and receiver designs for FSO communications are also discussed.

Keywords: *Free Space Optical (FSO), Multi-Input Multi-Output (MIMO), Atmospheric Turbulence, Registration*

1.0 INTRODUCTION:

In recent years, there has been a growing migration of voice communication to audio-visual communication with the introduction of 3G communication system. Devices such as digital still and video cameras, portable digital assistants, laptop computers, cellular communication sets offer users the ability to process and capture vast quantities of data. 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 limited 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. 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 [1]. 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 increasing data rates to mobile users is creating the need for this high-speed bridging technology. FSO communication systems have evolved in recent history. Future users will ultimately expect and require bandwidths approaching what is currently available using fiber networks, but from a wireless connection [2].

The use of multiple light sources allows the transmitter to produce a number of spatially separated channels which can be used to improve channel characteristics. Multiple receive elements afford a level of spatial diversity to the receiver. The spatial diversity allows the receiver to reject spatially localized noise sources and to separate multipath components spatially which can be used to improve channel reliability. One method to realize multi-element links is to construct multiple discrete transmitters and receivers. Space division multiplexing, employs multiple narrow beams to transmit data at high rates to various points. This system can be thought of as a MIMO optical channel in which different information is transmitted in different directions. In this case, the aggregate spectral efficiency is gained at the expense of requiring acquisition and tracking mechanisms.

The purpose of this study is to investigate the opportunity for FSO as an architecture component for next generation cellular networks. The most promising FSO communication systems are surveyed and discussed in simple language as a viable solution to enhance or replace various components of emerging cellular network architectures. The next section highlights the characteristics of FSO communications, followed by a short discussion on the free space optics within the core network in Section III. Section IV considers free space optics within the radio access network whereas Section V focuses on the advent of MIMO wireless optical channel model. Concluding remarks are given in Section VI.

2.0 CHARACTERISTICS OF FREE SPACE OPTICAL COMMUNICATIONS:

The wireless optical channel is a multi-element link which exploits spatial dimensions to achieve gains in reliability and spectral efficiency. These gains are achieved by implementing a transmitter which replaces the spatial repetition code with a more efficient code. The receiver is composed of a number of receive elements which detect the radiant optical power from a number of spatial modes. The gains in spectral efficiency can be realized by considering coding in time and in space. Such a communication channel has the advantages of high bit rates, ease of deployment, license free operation, high transmission security, full duplex transmission and protocol transparency [3]. Shielding from electro-magnetic interference should also be mentioned as a significant advantage over the 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 beam-width 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. 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 photo-detector. 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 photo-detector. Lastly, signal attenuation is significantly higher than in typical RF based communications systems, limiting the useful range of FSO products. 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 comparison between optical fiber and FSO communication system is shown in Table-1[4]. Chosen key characteristics of the FSO communication medium are discussed in details next.

Table 1: Comparison between Optical Fiber and Free Space Communication

Factors	Optical Fiber	Free Space
Path Loss	$\approx e^{-\alpha L}$	$= 1/L^2$ (diffraction)
Chromatic Dispersion	Yes	No
Polarization Mode Dispersion	Yes	No
Nonlinearities	Yes	No
Modal Dispersion	Yes (in MMF)	No
Birefringence	Yes	No
Absorption	Yes	Yes (in earth atmosphere)
Scattering	Small	Yes (in earth atmosphere)
Clouds	No	Yes (in earth atmosphere)
Turbulence	No	Yes (in earth atmosphere)

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. Table-2 shows the attenuation in FSO communication links in different conditions [1].

Table-2 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

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

C. Eye Safety:

Most FSO communication systems use laser diodes as sources, and their transmission power is limited by eye safety regulations. Power density of about 100 mW/cm2 at 1550 nm, or 1 mW/cm2 at 780 nm is considered safe to the unaided eye. The maximum intensity that can enter the eye on a continuous basis depends on the wavelength 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 $I_0 = 2P/\pi\omega^2$. 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.

3.0 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. 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"). Dominating aspects of free space optics within the core network are discussed below.

A. Spatial Registration and Synchronization:

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. The divergence of the transmitted beam and the receiver field-of-view have to be greater than the beam jitter in order to provide accurate correction.

To detect the incoming images, the receiver must locate the transmitted in the field-of-view. The process of determining the location of an object in the field-of-view of a camera with respect to the camera coordinate system is known as registration. Image registration is typically done in machine vision applications during camera calibration. Although the receiver can infer the position and orientation of the transmitter from the captured images, it is not possible to adjust the phase or frequency of the spatial sampling.

B. Full-Optical Wireless Communication Systems:

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 enables several information carrying wavelengths to be transmitted simultaneously from the optical antenna, enhancing capacity.

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. 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. 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.The optical link is periodically blocked and the system switches to RF communications if these events last for a sufficiently long time. Hybrid FSO/RF links overcome the range restrictions imposed by the requirement to achieve link reliability in adverse weather conditions.

4.0 FREE SPACE OPTICS WITHIN THE RADIO ACCESS NETWORK (RAN):

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. This section investigates the suitability of free space optical links within the RAN.

A. Distributed Cell Sites:

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. 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). 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. The optical fiber offers very little attenuation, is immune to multipath fading, shielded from electromagnetic interference and independent of RF signal formats. RoF networks can be extended to Radio on Free Space Optics providing communication links for heterogeneous wireless services where it is not easy or feasible to install optical fiber.

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. 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 in a mesh topology than their RF counterparts because of the near infinite frequency reuse offered in optical communications. The mesh topology allows the overall network reliability to maintain carrier-grade figures.

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. 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. 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.

D. FSO in the Air Interface:

The air interface describes the interface between the user equipment and the access point or base station. 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. Spherical antennas and indoor diffuse optical wireless arrangement are found effective to enable optical communications to and from mobile users.

5.0 MIMO WIRELESS OPTICAL CHANNEL MODEL:

The MIMO wireless optical channel optical channel is a multi-element link which exploits spatial dimensions to achieve gains in reliability and spectral efficiency. The transmitter outputs a time-varying optical intensity image which is transmitted in free-space. The receiver produces an output signal representing the spatial distribution of optical power impinging on the device. A prototypical MIMO wireless optical channel is illustrated in Figure 1. A free-space optical communication system is composed of three basic parts: a transmitter, the propagation channel and a receiver. In our system, M lasers, intensity-modulated by input symbols, all point toward a distant array of N receiver apertures. Every laser beam width is sufficiently wide to illuminate the entire aperture array. The MN laser-receive aperture path pairs may experience fading and the amplitude of the path gain from laser m to detector n is designated as the random variable Anm . The channel is assumed to be frequency nonselective and slowly varying, i.e, constant over several symbol durations. The aggregate optical field from all the lasers is collected by a lens, coupled to a fiber and amplified by an optical amplifier, such as an Erbium doped fiber amplifier (EDFA), before being detected by a photodetector. We denote the total incident signal power captured by each receive aperture for a non-fading channel from all the lasers as Pr when a pulse is transmitted [8].

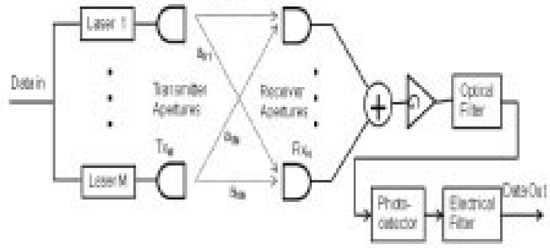

Fig 1. FSO MIMO system block diagram.

A. Transmitter Model:

In the transmitter, binary data bits are converted into a stream of optical pulses corresponding to binary on-off-keying (OOK) symbols described below, and sent to the M lasers. Since different lasers have independent phase processes, the M laser sources are non-coherent. This is different from using a single laser and beam-splitting optics to produce coherent optical sources. Here any time slot that a pulse is transmitted presented as an 'on' bit. If there is no pulse transmitted, it is an 'off' bit.

B. Channel Model:

Several models exist for the amplitude distribution of the channel gains. Most prominent among the models is the log-normal model, justified both by analysis in light turbulence and by empirical studies. As the clear-air turbulence increases, the log-normal model begins to deviate from experimental observation. In the log-normal model each path gain $A = e^X$, where X is Gaussian distributed with mean μx and variance σ^2_X. The scintillation index, used to measure the strength of fading, is defined as [8]:

$$S.I. = \sqrt{\frac{E\left[A^4\right]}{E^2\left[A^2\right]} - 1}$$

Where E[A2] is the path intensity. Typical values of S.I. are in the range of 0.4-1.0 for log-normal distributions.

C. Receiver Model:

The fiber amplifier scales the transmission signals in the optical domain and adds optical noise. EDFAs add unavoidable amplified spontaneous emission (ASE) noise to the signal channel due to *the spontaneous generation of photons. Assuming* a small input signal, the gain of the *EDFA can* be treated as fixed in a fixed single wavelength system. The free space optical system is a steady-state model where considers are given for only forward propagation of signals and noise. EDFA's noise models have been extensively investigated both experimentally and theoretically during the last decade. There are several amplifier models that are capable of approximating, to a reasonable degree, the ASE noise characteristics. The simplest approach is to model the ASE noise as a white Gaussian process with single-sided power spectral density

Sn(f)=nsp(G - 1)hf0 Watts/Hz

where G is the amplifier gain, nsp > 1 is the spontaneous emission factor, and f0 is the optical center frequency. This noise adds to the optical field and is filtered by an optical filter with optical bandwidth B0 prior to photodetection. The photodetector can be modeled as an ideal square-law device which adds thermal and shot noise to the mean photocurrent. The output of the photodetector is electrically filtered with electrical bandwidth Be and then sampled. The bit error probability for non-fading channels is given by [8]:

$$P_e = \frac{1}{2} erfc\left(\frac{Q}{2}\right) \quad \text{where} \quad Q = \frac{Ion - NI_{off}}{\sigma_{on} + \sqrt{N}\sigma_{off}}$$

Aperture gain (larger receiver surface area) can also be obtained by using multiple receiver apertures. Since adding more receiver apertures introduce more background noise, less than 3 dB gain may be achieved by doubling the receiver aperture, for a non-fading channel.

5.0 CONCLUSION:

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.

The MIMO wireless optical channel exploits spatial degrees of freedom inherent in the channel to provide gains in spectral efficiency. Pixel-matched systems provide a spatial multiplexing gain at the expense of requiring that all transmitters and receivers be in perfect alignment. The pixelated wireless optical channel with SDMT spatial modulation provides a means to generate spatial modulation which is well suited to the spatial frequency constraint. Additionally, the use of these bases eliminates the need for exact spatial alignment of the transmit and receive pixels and requires only that the spatial frequency resolutions be matched.

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