MILCOM 2004 - 2004 IEEE Military Communications Conference

LASER COMMUNICATION SYSTEM USING WAVELET-BASED MULTI-RATE SIGNALING

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ABSTRACT

Free Space Optics (FSO) communication is a promising candidate for broadband applications, achieving bit rates far beyond possible by Radio Frequency (RF) technology. Communications via RF signals are generally reliable and well understood but cannot support emerging data rate needs unless they use a large portion of the precious radio spectrum. FSO communications offer enormous data rates but operate much more at the mercy of the environment. The perennial limitations of FSO communications are manifested in the channel attributes of scintillation (optical turbulence) and path obscurations. Both phenomena reduce the availability of the optical channel to support reliable communications. Since RF paths are relatively immune to the same phenomena, combining the attributes of a high data rate but bursty link (FSO) with the attributes of a low data rate (by comparison) but reliable link (RF) could yield attributes better than either one alone: high availability with high data rates. This transmission configuration is normally referred to as a hybrid RF/FSO wireless system [1-2]. Increased FSO availability can ease the design of a hybrid radio, significantly. The focus of this paper will be on a specific approach; Fractal Transmission on an FSO link, leading to improved availability of such links.

I. INTRODUCTION

Network-centric military operations require unfettered, high data rate connectivity among mobile combatants and command centers within and outside the combat theaters. Global reach is essential. Resources must concentrate on frequently changing crisis regions. Transmissions must be reliable, secure, and inconspicuous. Wireless mobile networks have global reach and can quickly focus resources on different regions. On the other hand, they are sensitive to jamming, electronic counter measures (ECM), and interception. The adoption of wireless technology for military use demands developing reliable communication systems and technology. Network must adapt at multiple layers and scales. Current technology is inadequate for military needs. Robust mobile military networks require advances in many areas of transmission and networking.

Indeed, as the wireless/mobile systems become more critical in their application, the possibility of intentional disruption becomes more likely, as well. Thus, such systems must cope with both natural and man-made interference, which take the form of benign co-channel transmissions and intentional jamming. Existing communication systems were designed with traditional forms of interference that occur as a result of natural phenomenon or other manmade communication systems.

In comparison to the radio frequency (RF) spectrum, the optical spectrum has the ability to provide unprecedented bandwidth capable of carrying huge amounts of data; outdoor wireless optical communications, conventionally known as Free Space Optics (FSO) communications has been attracting increased attention as a broadband communications technology. Fundamental to the study of FSO communications is the realization that channel conditions may vary widely and frequently due to fading and dispersion, and that the receivers may be located in the areas that do not allow optimal communications due to shadowing. In this paper, using a combination of advanced signal processing techniques and adoption of new optical methodologies, we present an ultra-short pulsed FSO communications system, operating with multi-rate parallel data streams capable of providing increased resilience to atmospheric turbulence effects of the wireless optical channel. Additionally, communications security is provided through a low probability of interception and immunity to jamming and interference for sensitive applications.

This paper proceeds as follows. In section II, we present the propagation characteristics of optical signals in cloud-obscured optical wireless channels. In section III, we discuss the reliability of optical wireless communications. In section IV, we introduce multirate communications via wavelet modulation, following which in section V; we discuss implementation via holographic spectral encoding. Finally in section VI, we present the performance of

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wavelet modulated multirate links through various channel conditions, and our conclusions are presented in section VII.

II. OPTICAL WIRELESS CHANNELS

Photons propagating in a free space optical channel are subject to multiple scatterings due to the distribution of scatterers within the channel [3-4]. Photon scattering within the channel induces temporal and spatial dispersion in addition to attenuation. The scattering regime observed is dependent on the relative size of particles distributed within the channel to the wavelength (λ) of the light used.

Particles with radius much smaller than λ exhibit Rayleigh scattering, while particles with radius comparable to λ exhibit Mie scattering.

Wireless optical channels are characterized by their optical thickness (τ) given by:

$$\tau = L \cdot k_s \tag{1}$$

where L is the physical thickness of the channel and k_s is the scattering coefficient given by

$$k_s = \int_0^{\infty} C_s(r) n(r).dr \tag{2}$$

where $n(r)$ is the particle density distribution within the scattering medium and $C_s(r)$ is the scattering cross section per unit volume obtained from solving Maxwell's equations for spherical particles. Clouds of various optical properties such as Stratus and Cirrus usually obstruct free space optical channels in air-to-ground and air-to-air communications. Stratus clouds are classified as low altitude clouds, with a base altitude of 100m and a maximum physical thickness of 3.1 km [5]. The water droplet distribution within stratus clouds is given by a modified gamma distribution [6]:

$$n(r) = 27 \cdot r^2 \cdot exp(-0.6r) \tag{3}$$

where r is the particle radius. Using equations (1) and (2), the scattering coefficient at a wavelength of 1.55 μm is 56.8 km^{-1}; giving Stratus clouds maximum optical thicknesses of 176. Thin Cirrus clouds are high altitude clouds with a base altitude of 6.5 km and a maximum thickness of 13.1 km composed of ice particles having a modified gamma distribution given by:

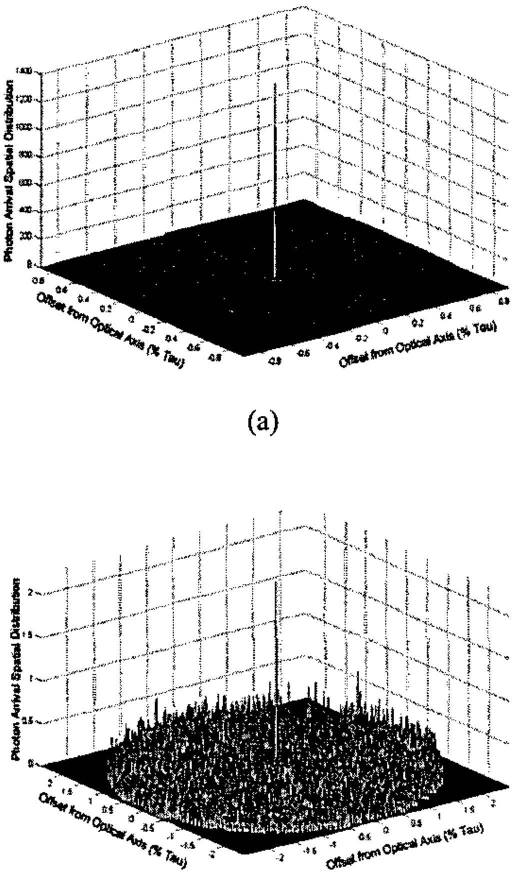
$$n(r) = .011865 \cdot r^6 \cdot exp(-1.5r) \tag{4}$$

giving a corresponding scattering coefficient of .0866 km^{-1}, and a maximum optical thickness of 1.13. Channel temporal and spatial responses are proportional to τ.

Figure-1 represents the temporal response and spatial distribution of arriving photons observed by a receiver collecting 10% of photons traveling closest to the optical axis. These are typical responses observed from a light impulse propagating through the Stratus and Cirrus clouds described previously.

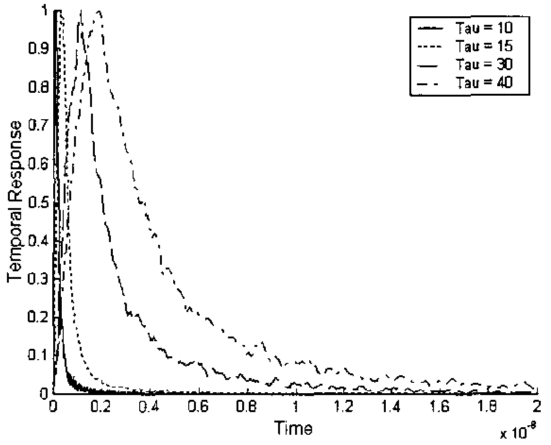
III. COMMUNICATIONS RELIABILITY IN OPTICAL WIRELESS CHANNELS

As shown in section II, optical wireless channels offer communication conditions that vary widely; from near ideal to highly dispersive channels with large temporal delay spreads. Additionally, the velocity of airborne nodes using optical wireless communications causes the channel conditions to vary frequently and widely. One solution for providing communications reliability (in terms of availability) is to limit the maximum bit rate to less than the coherence bandwidth of the maximally dispersive channel.



(a)

(b)



(c)

Figure 1: Optical Channel Response.
(a) Spatial Dispersion τ = 5
(b) Spatial Dispersion τ =10
(c) Temporal dispersion

In situations where channels present wide variations, and demand on bit rates and reliability is high, modulation schemes that take advantage of various channel conditions are highly desirable, this comes at the expense of increase in system complexity. Conventional adaptive schemes where adaptivity is incorporated into transmitter have been proposed and investigated, and proven their effectiveness in radio communications.

For optical wireless communications, wide and frequent variations of channel conditions, high bit rates, and long channel path, make the incorporation of conventional adaptive systems impractical; thus alternative solutions with a minimum level of complexity need to be used to provide communication reliability. Hybrid RF/FSO links have been proposed [1-2]. Such systems provide extremely high levels of availability. However, comparatively smaller available bandwidth of the RF link demands an increase in the optical channel availability in order to provide higher average bit rates.

To increase optical channel availability, we propose using a multirate signaling scheme, in which the data stream is spread across the time-frequency plane creating a multi-rate communication scenario in what is known as fractal modulation. According to the received signal quality, the receiver retrieves the stream(s) achieving an acceptable performance, with a higher priority for higher rate streams.

IV. FRACTAL MODULATION USING DYADIC WAVELETS

For a fractally modulated signal, the transmitted signal is spread over various rate-bandwidth ratios (fractal streams) using a fixed transmitter configuration. For a successful communication, at least one fractal stream has to be received with an acceptable signal-to-noise ratio.

Several authors have shown that transmission systems employing wavelets as basic signaling wave are well suited for utilization in multi-rate environments [7-8]. A family of orthonormal dyadic wavelets $\Psi_{n,m}(t)$ can be generated from a mother wavelet $\Psi(t)$ through dilatation and translation [8]:

$$\psi_n^m(t) = 2^{\frac{m}{2}}\psi(2^m t - nT_m) \tag{5}$$

where T_m is given by:

$$T_m = 2mT_o \tag{6}$$

such that:

$$\langle \psi(t)\cdot\psi(t-T_o)\rangle = zero \tag{7}$$

and

$$\langle \psi_{n,m}(t)\cdot\psi_{j,k}(t)\rangle = \delta(n,j)\cdot\delta(m,k) \tag{8}$$

It has been proposed in [8] that a sequence of data symbols $d_{n,m}$ modulating a set of m dyadic wavelets can act as a generating sequence for a waveform x(t).

$$x(t) = \sum_{m=0}^{m-1}\sum_{n=-\infty}^{\infty} d_{n,m}\psi_n^m(t) \tag{9}$$

By forming a x(t) in this fashion, redundant information can be incorporated in the transmitted signal such that multiple copies of a signal are interspersed in the time-frequency plane with the m^{th} subband data rate being double the rate of the $m+1$ subband. This scheme allows high bit rates when a suitably large time-bandwidth product is available; and gradual bit rate reduction when time-bandwidth product is reduced due to fading and shadowing.

Using the orthonormal properties of dyadic wavelets in equation (8), individual data streams can be recovered through use of an analysis approach, known also by the discrete wavelet transform:

$$d_{n,m} = \langle x(t)\cdot\psi_n^m(t)\rangle \tag{10}$$

Wavelet modulation is inherently well suited for military communication applications; wavelet modulated signals are resilient to impulse and tone jamming, and well suited to low-probability-of-intercept (LPI) thus providing a cover of secrecy and security to the communication system. Various wavelets have been proposed for use in communication applications; of special interest are the Meyer wavelets [9] with their strictly limited bandwidth occupancy.

V. HOLOGRAPHIC SPECTRAL ENCODING FOR MULTIRATE SIGNALING

FSO communications have the capacity to operate at rates exceeding multi gigabit per second, electronic implementation of transmitter/receiver architectures capable of supporting these rates becomes highly complex and may be beyond the level of maturity of available technology. Optical domain processing has long been seen as a key player in high speed processing applications, capable of performing filtering operations via passive elements such as holographic plates; thus correlation, convolution, matched filtering and pulse shaping operations can be conveniently performed at the required rates.

Optical encoding of wavelets can be performed through the use of holograms; spatial light modulators provide the capabilities of performing adaptive wavelet transforms, thus wavelets can be adapted to match channel conditions and thus enhance signal-to-noise ratio [10]. Application of holograms has been extensively researched in indoor wireless optical communications, and proven to be capable of increasing the received SNR by up to 18 dB [11].

By harnessing the capabilities of optical signal processing, and spectral holography, transmitter and receiver architectures can be greatly simplified, while maintaining processing speeds required by FSO communications. Waveform synthesis via spectral holography has been demonstrated as a powerful means for providing pulse shaping capabilities [12]; pulse trains with individually controlled pulses can be achieved from a single pulsed laser source [12]. Additionally, various pulse shapes can be recorded into holographic plates for later regeneration.

Our proposed system design is shown in Figures 2 through 4; the transmitter is composed of an ultra-short pulsed laser followed by a pulse train generator, with the pulse trains having a periodicity matching the signaling rate of the corresponding fractal stream. Pulse train generation can be achieved through spectral encoding as shown in Figure 3. Individual pulse trains are externally modulated; following which wavelet shaping is achieved through spectral holography.

As shown in Figure 4, the receiver has a similar architecture to the transmitter, where holography is used to perform the correlation operations, followed by a decision circuit for data stream recovery.

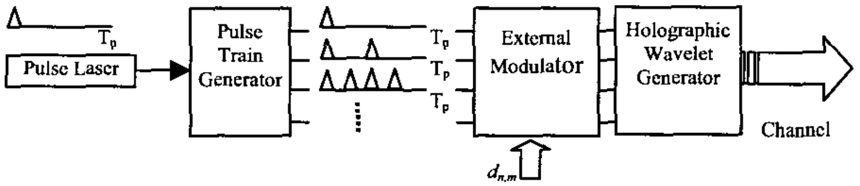


Figure 2: Wavelet Based Multirate FSO Transmitter

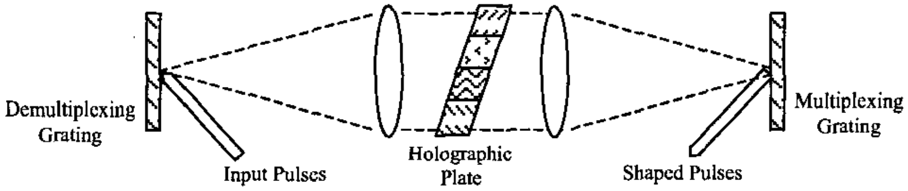


Figure 3: Pulse Shaping via Spectral Holography

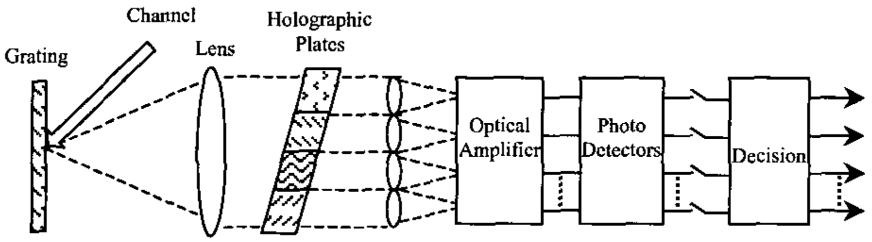


Figure 4: Wavelet Based Multirate FSO Receiver

VI. SYSTEM PERFORMANCE

Performance evaluation was performed through simulation over various thicknesses of Stratus clouds. Multirate communication was achieved through modulation of dyadic Meyer wavelets, with a maximum rate stream of 10 Gbps and 8 streams. The cloud thickness was gradually varied from 0 to 1.0 km; low altitude clouds have an average thickness of 0.6 km. Results in terms of achievable bit rate at an average bit error probability of 10^{-9} versus the cloud thickness are shown in Figure 5. As a benchmark, we compare the performance of individual streams to a single stream operating at the same rate, using raised cosine pulse shaping with a roll off factor of 0.5. Note that, the same shape is applied at both transmit and receive ends. Performance is shown in Figure 6.

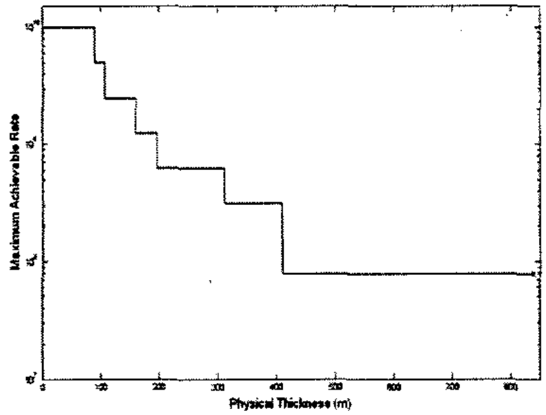


Figure 5: Achievable Bit Rate in Stratus Clouds

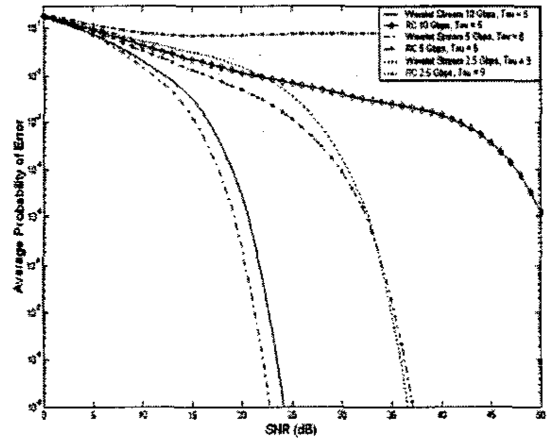


Figure 6: Probability of Error for Wavelet Streams and Raised Cosine (at transmit/receive ends) Shaped Streams

Gradual degradation of system performance is observed with an increase in cloud thickness. This is in contrast to the available / unavailable scenarios observed in a single link, operating at a constant rate. Wavelet streams performed better, as raised cosine rather than root-raised cosine is used here. This may be attributed to the relatively compact band occupancy of Meyer wavelets.

VII. CONCLUSIONS

In this paper, we introduced a wavelet based multirate signaling scheme for laser communication systems. Using holographic spectral encoding, system architecture can be simplified, and achievable rates will not be limited by the technological constraints of electronic processing. Multirate communications is suitable for long distance laser communication where channel variations occur widely and frequently, as in the case of cloud-obscured channels. Multirate signaling allows opportunistic high bit rates during windows of good channel conditions, and a higher tolerance to degraded channel conditions.

ACKNOWLEDGMENT

A DARPA Grant sponsored by the U.S. Air Force Research Laboratory/Wright-Patterson AFB Contract-FA8650-04-C-7114 and The Pennsylvania State University CICTR has supported this research.

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