Ultra-short Pulsed FSO Communications System with Wavelet Fractal Modulation

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ABSTRACT

Wireless Free Space Optics (FSO) is one of the most promising candidates for future broadband communications, offering transmission rates far beyond possible by RF technology. However, free space wireless optical channel presents far more challenging conditions for signals than typical RF channels, making system availability and throughput a critical issue. A novel design for an FSO system based on integration of ultra-short pulse lasers and advanced signal processing techniques is presented. Simulations indicate that the novel design promises considerably improved availability and throughput compared to traditional FSO systems.

Keywords: Optical Communication, fractal modulation, holographic optical components.

1. INTRODUCION

As we continuously move into the modern warfare era, the ability to provide combatants with continuously updated data has become a crucial element in today's battlefield. In order to satisfy this need, huge amounts of data need to be securely relayed between the command and control centers, unmanned air vehicles and ground vehicles using wireless links, in order to adapt to the continuously changing demographics of the battlefield. 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 access enabling technology. Fundamental to the application 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 areas that do not allow high-quality 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 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 is organized as follows; in section 2 we present the outdoor wireless optical channel, in section 3 we provide a brief introduction to the advanced signal processing techniques used in our novel design and the rational behind it. The ultra-short pulsed FSO communication system architecture is introduced in section 4 alongside a performance comparison to conventional FSO systems in section 5, and finally our conclusions and remarks are presented in section 6.

2. WIRELESS OPTICAL CHANNEL

Properties of a transmitted light signal exciting a wireless optical channel are dependent on channel length and conditions. The presence of scatterers in the channel degrades the light signal properties; scattering medium density is directly related to signal degradation, additionally, increased channel lengths subject the signal to more degradation due to increased possibility of scattering.

Light propagation in an FSO channel is a multiple scattering phenomenon. Light undergoes many scatterings before arriving at the receiver. Analytical and Monte Carlo Simulation techniques have been used to characterize the channel [1-3], and light signal degradation is noticed in terms of spatial and temporal dispersion in addition to attenuation. A standard measure for the channel is the optical thickness τ defined by the equation:

$$\tau = L / d$$

where *L* is the physical thickness of the channel and *d* is the mean distance between the scatterers which is inversely proportional to the scatterer density. Small values of τ correspond to relatively clear channels, while higher values correspond to channels hindered by clouds. Temporal dispersion of the channel based on a receiver collecting 5% of the photons exiting the channel closest to the optical axis is shown in Fig.- 1.

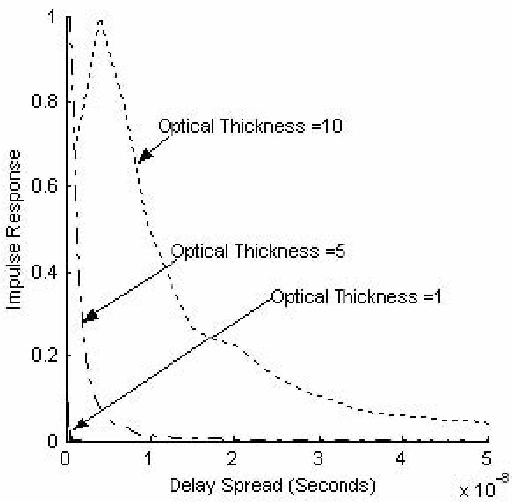

Fig.-1: Optical Channel Impulse Response

3. MULTIRATE COMMUNICATION USING FRACTAL MODULATION

As it can be seen from Fig.-1, the delay spread of FSO channel can vary considerably according to channel conditions, varying from nanoseconds to microseconds in clear and cloudy channel conditions, respectively. The change in channel conditions can occur gradually as in the case of a cloud overcast clearing off, or abruptly as in the case of scattered clouds. In order to maximize channel throughput and provide continuous communications, a modulation scheme that can adapt to various channel conditions needs to be employed. For channel conditions exhibiting delay spreads in the microseconds, transmission rates are limited to the order of megabits; while for nanosecond delay spreads, transmission rates in the gigabit regime can be achieved. Bursty transmissions at gigabit rates can achieve average bit rates several orders higher than continuous megabit rate transmission; thus employing modulation schemes that can take advantage of windows of good channel conditions, even for very short periods of time is highly desirable and beneficial. In conditions where channel availability and bandwidth vary randomly, complex adaptive schemes that follow channel variations can be adopted to maximize throughput, however this entails an increase in system complexity and requires a fast and reliable feedback channel which might not be available. A more viable approach is to employ a modulation scheme in which the data stream is spread across the time-frequency plane creating a multi-rate communication scenario, thus the transmitter is not required to adapt according to channel conditions, while the receiver would make the necessary adjustments by selecting the frequency bands appropriate to channel conditions. This is the basic idea behind fractal modulation, where transmission is over a broad range of rate-bandwidth ratios using a fixed transmitter configuration. A natural way to achieve this is to embed the data into a homogeneous signal [4], where such signals are well suited for noisy channels of unknown duration and bandwidth. These homogenous signals are known as wavelets. These wavelets present some interesting characteristics in terms of self-similarity and orthonormality with respect to translation and dilatation.

A family of orthonormal $\Psi_{n,m}(t)$ wavelets can be generated from a mother wavelet $\Psi(t)$ through dilatation and translation.

$$\psi_{n,m}(t) = \frac{1}{2^{m/2}}\psi\left(\frac{t - nT_m}{T_m}\right) \quad (1)$$

where T_m is the signaling interval in the m^{th} subband which is related to the zeroth order subband by $T_m = 2mT_o$, thus the data rate in subband m is double of that on sub-band m+1. Orthonormality of wavelets is achieved through dilatation and translation such that

$$< \psi_{n,m}, \psi_{j,k} > = \begin{cases} 1 & n = j \;\&\; m = k \\ 0 & otherwise \end{cases} . \quad (2)$$

A modulated signal *x(t)* can be generated and received using a synthesis/analysis approach

$$x(t) = \sum_n \sum_m d_{n,m}\psi_{m,n}(t) \quad (3)$$

$$d_{n,m} = \int \psi_{m,n}(t)\, x(t).dt \quad (4)$$

where $d_{n,m}$ is the data sequence modulating the m^{th} wavelet dilatation during the n^{th} signaling period. Several wavelet families have been proposed by researchers such as Meyer, Morlet, and Daubechies wavelets; for our application we focus our attention on the wavelets proposed by Meyer [5] due to their strictly bandlimited occupancy nature.

We direct the interested reader to [4-8] for a more comprehensive discussion of wavelets and to [9-11] for a few examples of the use of wavelets in communications applications.

4. ULTRA-SHORT PULSED FSO COMMUNICATION SYSTEM ARCHITECTURE

The novelty of our design lies in optical implementation of laser light ultra-short wavelet pulse shaping using holographic masks. Transmitted signals are extremely resilient against time impulse and tone jamming, additionally the signals are well suited to low-probability-of-intercept (LPI) and provide a cover of secrecy to the communication system. Transmitted signals are inherently suited to multi-access communications due to mutual orthogonality feature of wavelets. The multi-rate capability of wavelets is utilized to transmit the data streams over parallel fractal channels where each stream can be recovered from the aggregate signal by wavelet transform.

The use of wavelets in optical domain through optical wavelet transform provides significant advantages to implementing the wavelet transform given by (4) in digital domain. On-the-fly transform may be implemented in optical domain where any wavelet function can be encoded using either a computer generated hologram, or a complex amplitude modulation spatial light modulator. Adaptive wavelet transform can also be implemented, thus wavelet shape, dilatation and shift parameters can easily be varied to match the channel conditions. This can help to enhance the signal-to-noise ratio (SNR) [12]. Use of holography for ultrashort pulse shaping harnesses capability of filtering, thus, providing correlation and convolution operations capabilities for independently varying waveforms, matched-filtering and ultrashort waveform synthesis.

Our system design is depicted in Fig.'s-2 to 4; the transmitter is composed of an ultra-short pulsed laser followed by a pulse train generator used because each wavelet has a different duration, as there is a factor of 2 time-scaling difference between each two consecutively dilated wavelets. The pulses are then modulated via an external modulator with $d_{n,m}$, following which the modulated pulses are passed through a holographic wavelet generator shown in Fig.-3. In a holographic wavelet generator, the pulses spatially demultiplexed through a grating and then focused onto a holographic plate encoded with required wavelet shape, the exiting encoded spectrum light is focused with another lens onto a multiplexing grating. The receiver has a similar architecture to the transmitter, as shown in Fig.- 4. There are many ways to produce an ultra-short pulse shaping holographic mask. It can be fabricated by conventional optical means, utilizing a multiple-exposure technique or through the use of a computer. Holograms generated by a computer can produce wave-fronts with any prescribed amplitude and phase distribution.

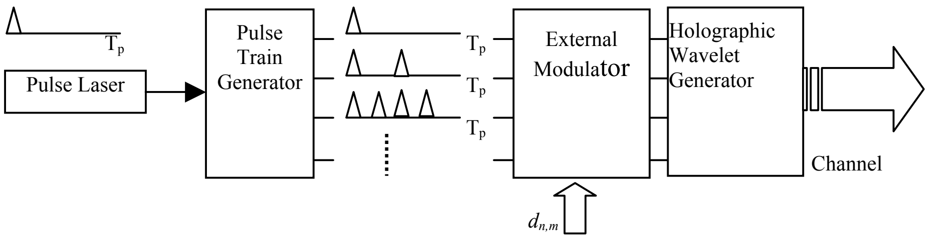

Fig.-2: Ultra-Short Pulsed FSO Transmitter

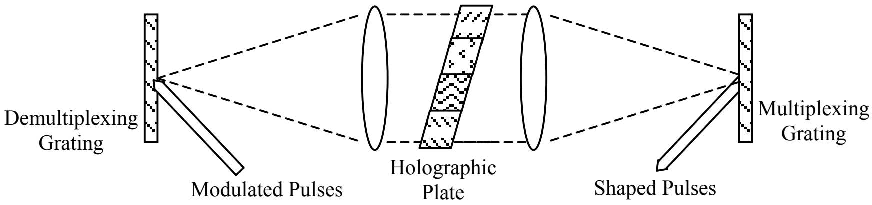

Fig.-3: Holographic Wavelet Generator

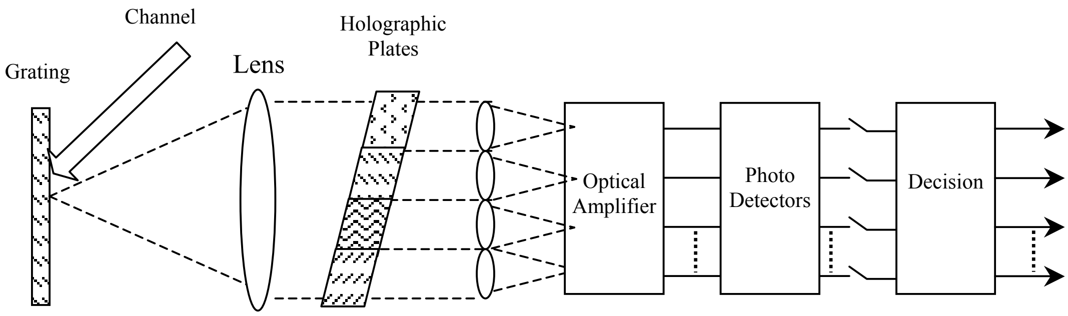

Fig.-4: Ultra-Short Pulsed FSO Receiver

5. SYSTEM PERFORMANCE

We have evaluated the system performance using a simulated test-bed, employing four fractal streams, with the highest stream rate of 2.5 Gbps, propagating through channels with optical thicknesses varying from 0.1 to 6, with equal-power channels. Wavelets were generated with an 8192 point resolution to assure orthogonality. System performance was compared to a single conventional FSO link operating at 2.5 Gbps using on-off keying (OOK) under the same channel conditions.

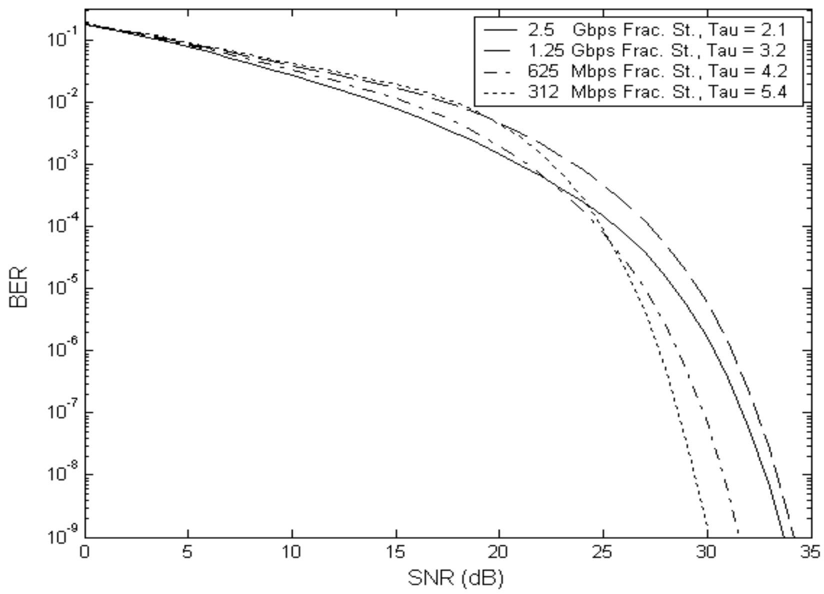

Fig.-5: Performance of Fractal streams and at maximum allowable optical thickness

The threshold for acceptable operation was set at a bit error rate (BER) of 10^{-6} , with the a higher bound of 45 dB on the SNR.

As shown in Fig.-5,6 and 7, OOK-FSO fails to operate in channels with τ greater than approximately 1.8, as the channel induced intersymbol interference bounds the BER. The proposed system offers increased resilience to channel conditions, as a gradual degradation in system performance with an increase in τ occurs rather than a complete system breakdown. The 2.5 Gbps fractal stream fails to achieve acceptable performance for τ greater than approximately 2.1, while the 1.25 Gbps stream fails for τ greater than 32. Similarly, the lowest rate streams are resilient to channels with τ up to 4.2 and 5.4, respectively. In order to assure continued communications for larger values of τ, lower order fractal streams can be employed in a similar fashion. Thus, continuity in communications is achieved throughout various channel conditions, without requiring additional feedback from receiver to transmitter. This is a "MUST" for longer communications paths.

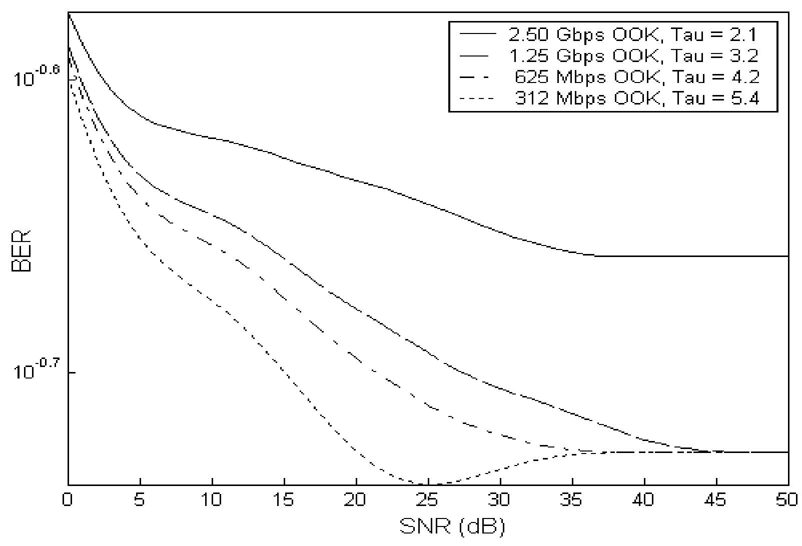

Fig.-6: Performance of FSO for same conditions of fractal streams

Overall, a higher average bit rate is achieved, in addition to an increased level of communications security by maintaining a minimum of one active link throughout most channel conditions. Additionally, this system is inherently suitable for use in imaging schemes that use a multi-resolution compression and coding [13]. To ensure system resilience to channel conditions, the number of fractal streams should be selected according to anticipated channel conditions at the location of deployment; the lowest rate fractal stream is upper bounded by the maximum anticipated τ to ensure continuous transmissions, while the number of fractal streams is determined by the required average bit rate.

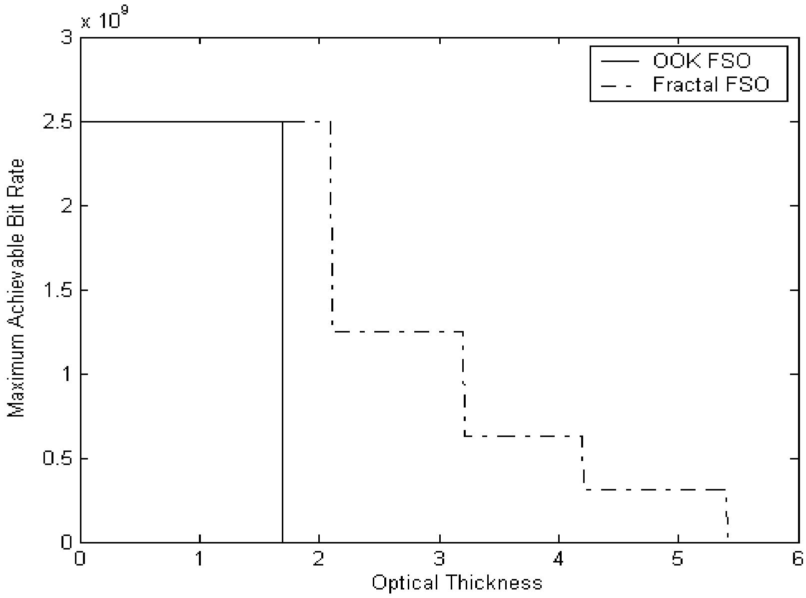

Fig.-7: Achievable bit rate during various channel conditions

6. CONCLUSIONS

We introduced a novel ultra-short pulsed FSO communication system architecture. The proposed system provides increased resilience to detrimental channel conditions through the use of fractally modulated multirate streams. Fractal streams are generated / recovered through the use of holographic optical elements that ensure an on-the-fly operation without the need for significant electronic processing. Due to the gradual degradation property of the system, a higher average bit rate is achieved, in addition to an increased level of communication security by maintaining a minimum of one active link throughout channel conditions.

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