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Comparative study of the performance of analog fiber optic links versus free-space optical links

Hakki H. Refai, MEMBER SPIE
James J. Sluss Jr., MEMBER SPIE
Hazem H. Refai
The University of Oklahoma, Tulsa
School of Electrical & Computer Engineering
4502 E. 41st St.
Tulsa, Oklahoma 74135
E-mail: hakki@ou.edu

Mohammed Atiquzzaman
The University of Oklahoma
School of Computer Science
Norman, Oklahoma 73019

Abstract. Optical fiber offers many advantages over coaxial cable for the transmission of radio frequency (rf) signals in antenna-remoting applications, as well as cellular networks and cable television (CATV) signal distribution networks. Optical fiber shows significantly less loss, can support signals demanding much higher bandwidth, is immune to electromagnetic interference (EMI), and enables considerable size and weight savings when compared to coaxial cable. Free-space optics (FSO) communications is a technology that uses modulated optical beams to transmit information line of sight through the atmosphere. FSO can be deployed faster and cheaper when compared with optical fiber. Recently, FSO has been investigated by the telecommunications industry and research centers to transport digital signals for civilian "last mile" applications and military applications. We demonstrate the successful transport of modulated rf analog signals over an FSO link and compare key performance measures against a fiber optic link configured in an identical manner. Results of measurements of optical power, transmission response, reflection response, group delay that defines phase distortion, carrier-to-noise ratio (CNR), and dynamic range that defines nonlinear distortion are presented. Results from this comparative study indicate that FSO for rf applications is a suitable replacement for fiber optic transmission links over short distances. [DOI: 10.1117/1.2174623]

Subject terms: free-space optics; radio frequency; transmission response; carrier-to-noise ratio; dynamic range; cable television.

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1 Introduction

Free-space optics (FSO) communication uses modulated optical beams, usually generated by laser sources or light emitting diodes (LEDs), to transmit information line of sight through the atmosphere. Recently, there has been an exponential increase in the use of FSO technology, mainly for "last mile" applications, because FSO links provide the transmission capacity to overcome bandwidth bottlenecks.[1] The desire to develop high-speed Internet access has stimulated much of this growth and as a result, the major focus of most FSO research and development has been toward the transmission of digital signaling formats. Fiber optics has been traditionally used for transmission of both digital and analog signals. The transmission of rf intensity-modulated signals over optical fibers is well established.[2,3] However, the authors are not aware of any research work reporting on the effectiveness of FSO for transmission of analog signals. This paper investigates the effectiveness of FSO to transport modulated rf analog signals and compares it with that of fiber optics in a similar environment.

The advantages of transmitting modulated rf signals over FSO links are as follows:

1. FSO transmission links can be deployed quicker, and in some instances more economically, than optical fiber links.
2. When compared with wireless rf links, FSO requires no licensing and provides better link security and much higher immunity from electromagnetic interference (EMI).
3. FSO is highly invulnerable to interference from other sources of laser radiation.[4]
4. FSO can be implemented for portable applications, e.g., movable radar dish antennas.
5. FSO provides a viable transmission channel for transporting IS-95 CDMA signals to base stations from macro- and microcell sites and can decrease the setup costs of temporary microcells deployed for particular events, e.g., sporting events, by eliminating the need for installing directional microwave or connecting cable.[5]
6. FSO introduces a viable transmission medium for the deployment of cable television (CATV) links in metropolitan areas where installing new fiber infrastructure can be relatively expensive.[6]
7. Analog FSO can reduce the cost of transmission equipment as compared to a digital implementation.

The objective of this paper is to characterize an end-to-end

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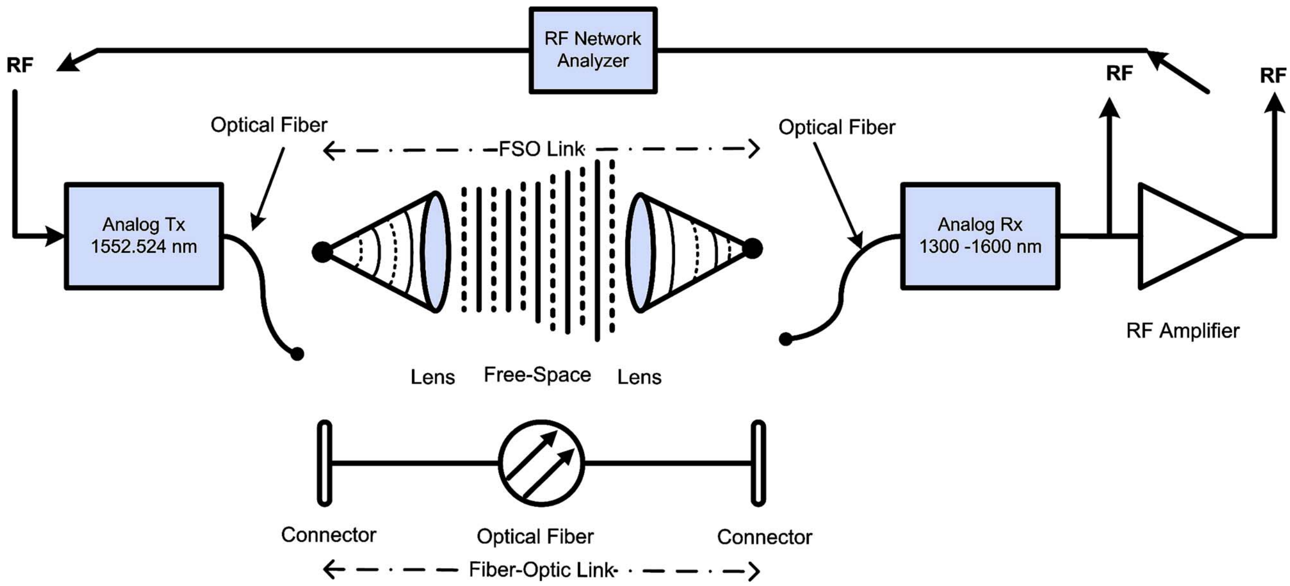

Fig. 1 Experimental setup for measuring transmission response, reflection response, and group delay.

communication channel for transmission of modulated analog rf signal transmitted over an FSO link, and compare with that using an identical fiber optic link. The motivation for comparing with rf photonic links is to obtain the same attributes as conventional rf over optical links, but with extended transmission distance, lower cost, improved performance, better operating frequency, and lower complexity and size. Therefore, it is important to evaluate the performance of rf photonic links in terms of the same generally accepted criteria typically applied to conventional rf links. Standard performance criteria for conventional rf links include rf loss and frequency response, with no attention given to nonlinear distortion or additional noise unless the signal is amplified. In rf photonic links, additional noise generated by the laser source and the photodiode can degrade the carrier-to-noise ratio (CNR), and nonlinearity of the modulation device can reduce the spurious free dynamic range. Therefore, the important rf performance criteria for rf photonic links are

1. the rf gain and frequency response
2. the additional noise and CNR
3. the spurious free dynamic range (SFDR)

The remainder of the paper is organized as follows. Section 2 describes the experimental setup to transmit modulated rf signals over fiber optics and FSO. The experimental results are reported in Sec. 3, which includes measurements of optical power, transmission response, reflection response, group delay, CNR, and dynamic range for rf analog signal transmission over both fiber optic and FSO links. Concluding remarks are given in Sec. 4.

2 Experimental Setup

Figure 1 illustrates the experimental setup used in transmission response, reflection response, and group delay measurements for both fiber optic and FSO links. An Aurora AT3510 analog laser transmitter, with an International Telecommunications Union (ITU) grid compliant output wavelength of 1552.524 nm, was fiber-coupled to either (1) a Dominion Lasercom DAViD® FSO telescope assembly or (2) a 3-m optical fiber. In the first case, the transmitting telescope was aligned line of sight with an identical receiving telescope that was approximately 3 m away. The distance between both telescopes was short, but sufficient to characterize the key performance measures of the channel between the optical transmitter and receiver. Deployed FSO systems will suffer atmospheric loss, but the atmospheric affects are beyond the scope of this paper. The receiving telescope was fiber-coupled to an Aurora AR4001 analog receiver. In the second case, the 3-m optical fiber was linked to the same fiber jumper that connected the receiving telescope to the AR4001, thus matching the same jumper and connector losses throughout the analog communications link.

The rf frequency range of operation for the transmitter and receiver was from 46 to 870 MHz. The rf input signal to the transmitter was supplied by an Agilent 8712ET rf vector network analyzer. The rf output signal from the receiver was connected back into the network analyzer. For transmission response, group delay, and CNR measurements, a built-in rf amplifier inside the analog receiver and an Aurora OA4444T-42 RF amplifier were connected between the receiver output and the input of the network analyzer, thus providing rf signal gain.

Figure 2 illustrates the experimental setup used in the CNR measurements. Compared with Fig. 1, note that the only significant difference between these experimental setups is that, for the CNR measurements, the vector network analyzer has been replaced by a Rohde & Schwarz SMHU signal generator to feed rf signal to the transmitter. A Tektronix WCA280A wireless communication analyzer was used for rf output signal measurements. CNR measurements were made with and without the rf amplifier.

For the dynamic range measurements, the only signifi-

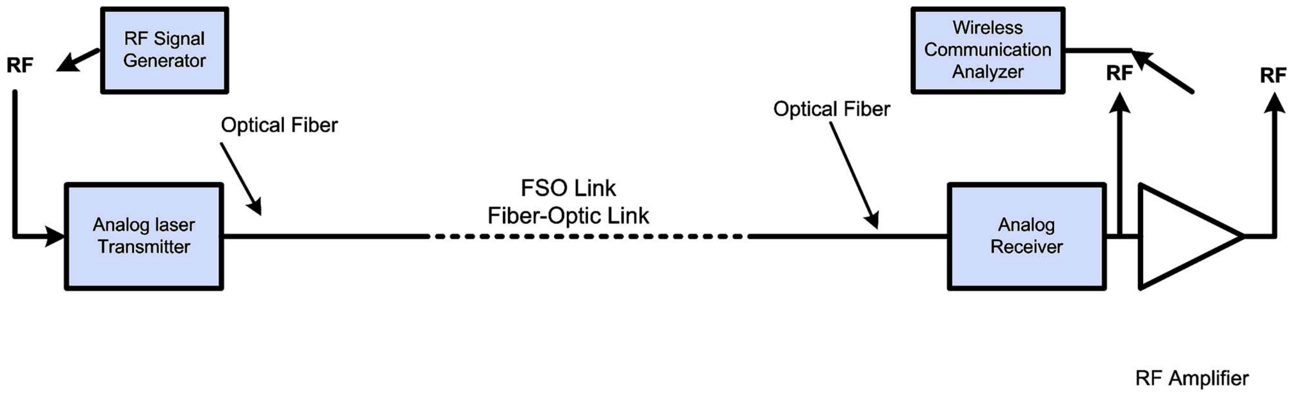

Fig. 2 Experimental setup for measuring CNR.

cant change in the setup (see Fig. 3) from Fig. 1 was that, on removal of the vector network analyzer, the Rohde & Schwarz SMHU and Agilent 8642A signal generators were connected to the transmitter input to supply the composite rf input signals.

The operating wavelength of 1552.524 nm is well matched with most commercial FSO systems that operate at or near 1550 nm. This wavelength range is of importance because, from a laser safety perspective, higher output powers can be used since the human eye is less vulnerable to injury at this wavelength. With these higher output powers, the FSO links can be longer and better able to operate in critical meteorological conditions, e.g., fog.[7]

3 Experimental Results

In this section, experimental measurements of optical power, transmission and reflection response, group delay, CNR, and dynamic range are reported. These measurements comprehensively characterize the communication channels.

3.1 *Optical Power Measurements and Analysis*

Investigation of the analog optical links must be addressed from two major criteria, optical and rf criteria. This subsection provides a complete study of the optical criteria, addressing the results of the optical measurements for both fiber optic and FSO links and illustrates the existing sources of optical loss that affect the optical power during its transmission through both links. The rf criteria are investigated in details in the upcoming subsections.

From the optical standpoint, the amplitude of the rf intensity modulated optical signal is much less than the intensity of the unmodulated optical carrier. Consequently, the link can be characterized using the small signal approximation. Beginning with analog fiber optic link, the peak optical power and output wavelength of the analog laser transmitter were measured using an Advantest Q8384 optical spectrum analyzer. The resulting measurements indicate that the peak power and output wavelength at the output of the analog transmitter were 9.49 dBm and 1552.530 nm, respectively. These values are shown in the lower table of Fig. 4.

Repeating these measurements at the input of the analog receiver shows that the peak power and output wavelength were 6.05 dBm and 1552.535 nm, respectively. These values are shown in the lower table of Fig. 5. The sensitivity

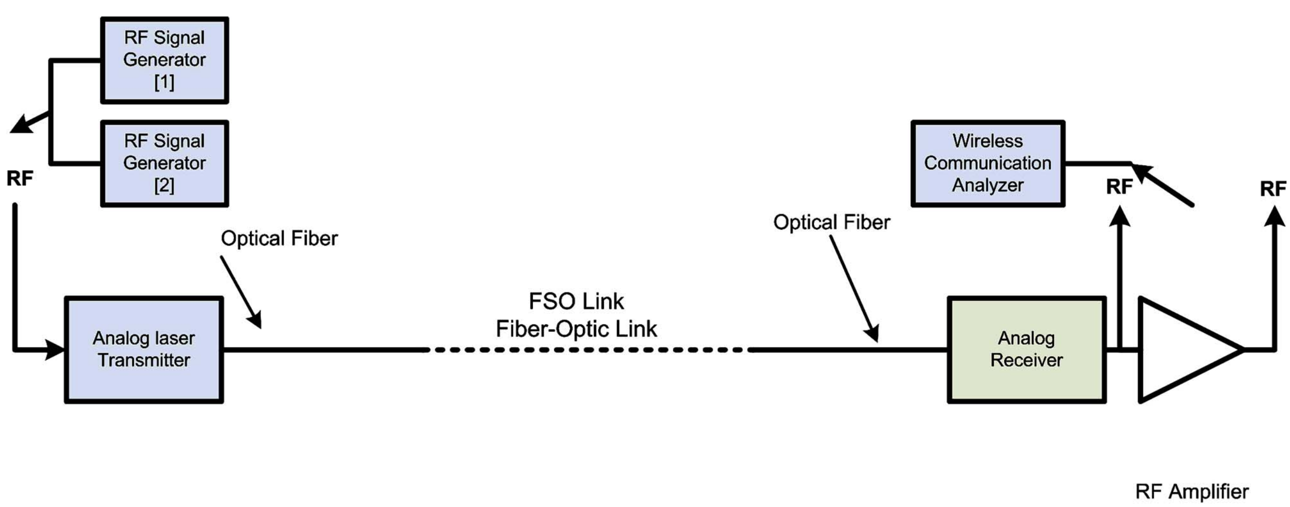

Fig. 3 Experimental setup for measuring the dynamic range.

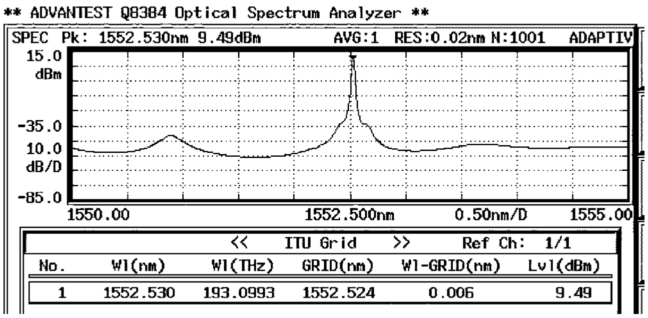

Fig. 4 Screen capture from the Advantest Q8384 optical spectrum analyzer illustrating the results of peak power and output wavelength measurements at the output of the analog laser transmitter.

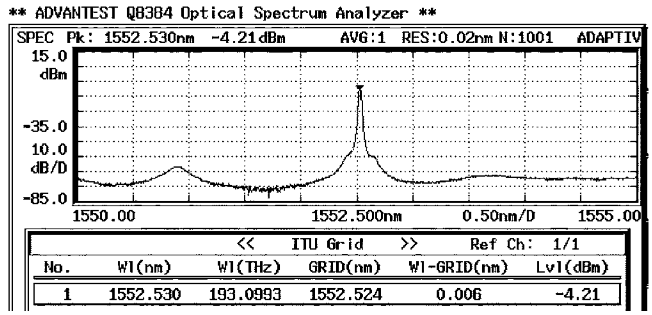

Fig. 6 Screen capture from the Advantest Q8384 optical spectrum analyzer illustrating the results of peak power and output wavelength measurements at the input of the analog receiver for FSO link.

of the photodiode is near 0 dBm, which indicates the presence of additional power that can be used to extend the link distance.

Clearly, there is a loss in the signal power of nearly 3.45 dB. The sources of loss are connectors, jumpers, and attenuation occurring during the transmission through the optical fiber. Since the total length of the fiber path from the transmitter to the receiver is 11 m, including the fiber jumpers connecting the transmitter and the receiver with the main fiber span, the optical signal incurs little attenuation. The major sources of loss in this case are therefore the connectors and jumpers—nearly 3 dB.

Applying the same optical signal measured at the output of the analog laser transmitter, as shown in Fig. 4, to the analog FSO link demonstrates the optical disparity between both fiber and FSO links. Using the Advantest Q8384 optical spectrum analyzer, a peak power of −4.21 dBm and output wavelength of 1552.530 nm was measured at the input of the analog receiver. These values are shown in the lower table of Fig. 6.

Clearly, there is a loss in signal power of nearly 13.70 dB. Major sources of optical loss are insertion, lens, geometric, and atmospheric losses. Figure 7 illustrates the sources of power loss throughout the FSO link.

Geometrical losses occur due to the divergence of the optical beam. These losses can be calculated using the following formula[8]

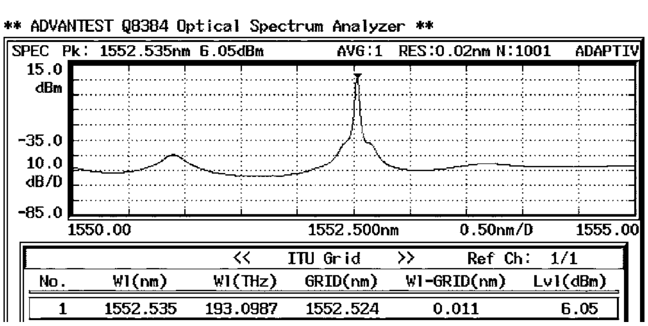

Fig. 5 Screen capture from the Advantest Q8384 optical spectrum analyzer illustrating the results of peak power and output wavelength measurements at the input of the analog receiver for fiber optic link.

$$\frac{A_R}{A_B} = \left(\frac{D_R}{D_T + 100 * d\theta} \right)^2, \tag{1}$$

where D_T and D_R are the diameters of the transmitting and receiving lenses measured in cm, both 5 cm in this case. The distance between the FSO transmitter and receiver is d, measured in kilometers, d=0.003 km in this case, and θ is the divergence of the transmitted laser beam in milliradians, θ=2 mrad in this case. Using Eq. (1), the calculated geometrical loss for this experimental setup is approximately 1 dB. This loss is low because the space gap between the FSO transmitter and receiver is only 3 m. Therefore, it does not add significantly to the overall loss of 13.70 dB.

Atmospheric losses are due to absorption, scattering, scintillation, and weather conditions. Since these experiments were conducted in a laboratory environment over a short distance, atmospheric losses are negligible and beyond the focus of this paper.

The connectors and FSO telescope assemblies at the transmitting and receiving ends are responsible for a significant amount of insertion loss, nearly 12.70 dB in this case. Usual insertion losses for industrial FSO links are around 4 dB. The insertion loss was high in these experiments because the FSO telescope assemblies and connectors were not optimally manufactured to match the analog transmitter and receiver. Under typical operation, the Dominion Lasercom DAViD® FSO system offers an optical power at the transmitter output of around 20 dBm (100 mW), to overcome the propagation loss plus the insertion losses.

3.2 *Transmission Response Measurements*

The rf transmission response measurements provide the relative loss, or gain, in a communications link with respect to the signal frequency. The rf transmission response of a photonic link is frequency dependent. There are three key causes of frequency dependence: (1) the laser source, directly modulated or externally modulated, may have frequency dependent response; (2) the voltage or current delivered to the analog modulator may have frequency dependent features due to the electrical characteristics of the input circuit; and (3) the analog receiver, including its photodiode, may have frequency dependent characteristics. Any signal attenuation due to the communications link will

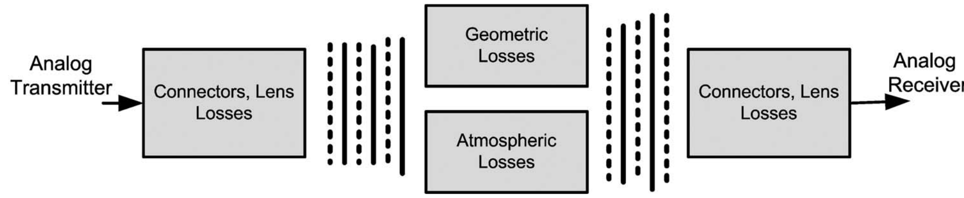

Fig. 7 Sources of loss in FSO link.

manifest itself in the transmission response measurement. The vector network analyzer computes the output measurement trace using

$$\text{Transmission(dB)} = 10 \log\left(\frac{P_{\text{trans}}}{P_{\text{inc}}}\right), \tag{2}$$

where P_{trans} is the rf power measured at the output of the receiver and P_{inc} is the rf power measured at the input to the laser transmitter. Results of the transmission response measurements, with and without the rf amplifier included, for the fiber optic link are shown in Fig. 8. There is a built-in rf amplifier connected to the output of the photodiode inside the analog receiver, which yields approximately up to 7.5 dB of gain, depending on the operating frequency. Consequently, the resulting gain can compensate the loss produced by the optical/rf conversion stage in the receiver. As mentioned previously, the received optical power at the input of the photodiode is still greater than the sensitivity, which eliminates the impact of the attenuation through the optical fiber.

Without the rf amplifier, the transmission response varied from 1.50 to 7.28 dB over the frequency range of 55 to 870 MHz. These measurements compare favorably with the −20 to −50 dB loss reported as typical for analog fiber optic links.[9] With the rf amplifier, the transmission response (gain) varied from approximately 13.69 to 18.34 dB over the same frequency range.

The results of the transmission response measurements for the FSO link, with and without the rf amplifier included, are shown in Fig. 9. Transmission response without the rf amplifier varied between −12.11 and −19.03 dB over the frequency range 55 to 870 MHz, while the transmission response with the rf amplifier varied between 7.65 and 13.53 dB over the same frequency range. The figure depicts a relatively smooth response over the measured frequency range. These measurements compare favorably with the previously reported measurements in this study, through the fiber optic link. Inclusion of the rf amplifier produced sufficient gain to overcome the FSO link losses, thus allowing the FSO signal to travel farther distances.

3.3 *Reflection Response Measurements*

Reflection response provides an evaluation of the amount of reflected power relative to the incident power versus frequency at the insertion input of the transmitter. The reflected power is predominantly due to impedance mismatch between the rf cable and the input to the analog transmitter, as well as reflections within the transmitter rf/optical con-

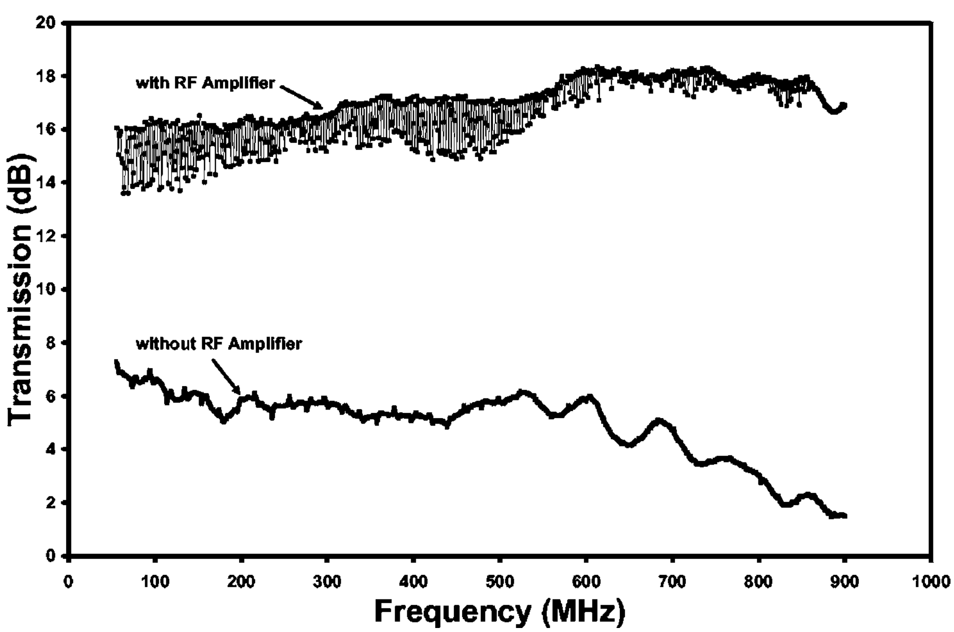

Fig. 8 Transmission response measurements for fiber optic link.

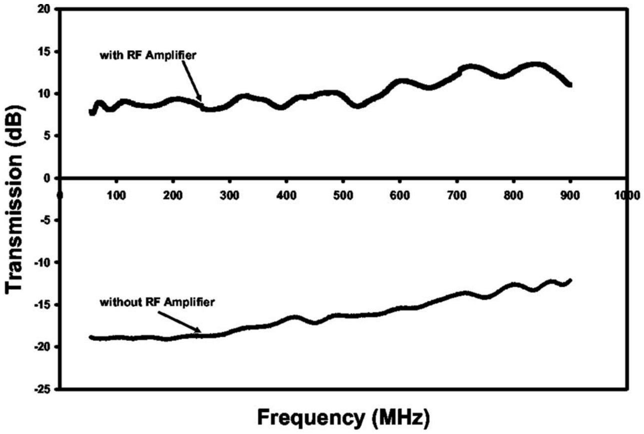

Fig. 9 Transmission response measurements for FSO link.

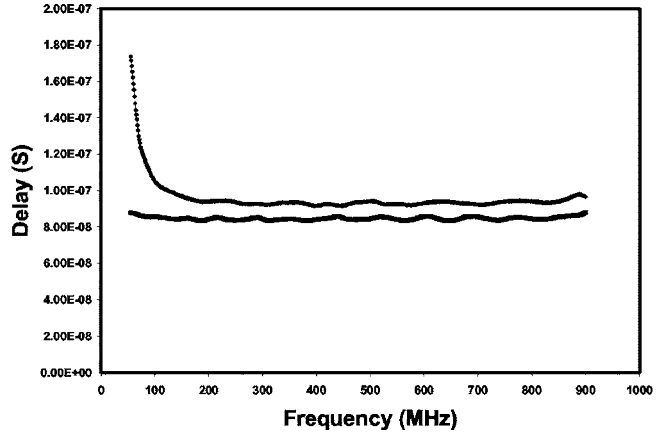

Fig. 11 Group delay measurements for fiber optic link.

version circuitry. In determining the rf reflection response, the network analyzer calculates the output measurement trace using

$$\text{Reflection(dB)} = 10\log\left(\frac{P_{\text{refl}}}{P_{\text{inc}}}\right), \quad (3)$$

where P_{inc} is the rf power measured at the input to the laser transmitter and P_{refl} is the reflected rf power measured at the same input. Results of reflection response measurements for the analog transmitter are the same for both fiber optic and FSO links over the frequency range 55 to 870 MHz, as shown in Fig. 10.

3.4 *Group Delay Measurements*

The group delay is a measure of the total delay a signal experiences when traversing a communications link, which thus gives rise to a phase shift in the signal. To guarantee that a communications channel does not introduce phase distortion, it is important to ensure that the group delay does not vary considerably with frequency. The group delay measurements for the fiber optic link, with and without the rf amplifier included, are illustrated in Fig. 11. Note that, without the rf amplifier, the group delay has an approximately constant average value of 84.70 ns. The rf amplifier introduces quite a bit of variation in the group delay below 125 MHz, but settles to an approximately constant average value of 93.62 ns above 125 MHz. Thus, without the rf amplifier, phase distortion is so small over the 55 to 870 MHz operating range of the fiber optic link as to be negligible. With the rf amplifier, operation should be bounded to an operating range of 125 to 870 MHz if phase distortion is to be reduced.

Results of group delay measurements for the FSO link are shown in Fig. 12. Clearly, without the rf amplifier, the group delay has a nearly constant average value of 79.66 ns. With the rf amplifier, the group delay has quite a bit of variation below 110 MHz, but settles to an approximately constant average value of 90.22 ns above 110 MHz. Similarly, without the rf amplifier, little phase distortion can be seen over the 55 to 870 MHz operating range of the FSO link. With the rf amplifier, operation should be limited to an operating range of 110 to 870 MHz if phase distortion is to be avoided. Obviously, the speed of light in free space is faster than that in the fiber, as shown in the measured values of the group delays in both links.

3.5 *CNR Measurements*

CNR is an important measure that quantifies the performance of communication channels relatively to the existing

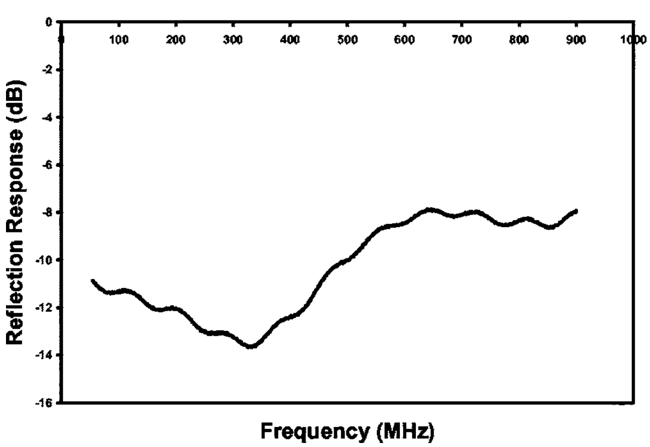

Fig. 10 Reflection response measurements.

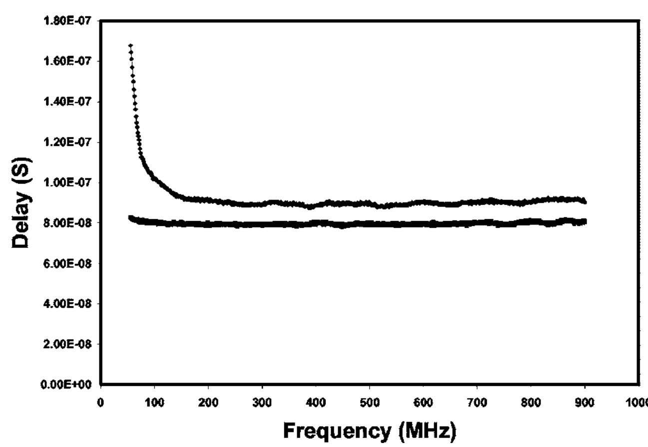

Fig. 12 Group delay measurements for FSO link.

noise. CNR plays an important role in determining the minimum average signal power that can provide error-free transmission through a communications channel.

There are three key statistically independent sources of noise in rf photonic links:

1. Thermal noise caused by the thermally induced electron movement in conductors. The mean-squared current of the thermal noise is expressed by

$$\langle i^2_{\text{thermal noise}}\rangle = \frac{4kTB}{R}, \tag{4}$$

where k is Boltzmann's constant, T is the absolute temperature in degrees Kelvin, B is the noise bandwidth in hertz, and R is the resistance producing the noise in ohms.

2. Shot noise generated by the photodiode, which produces an electrical current proportional to the optical signal at the input. When an external laser modulator is used, the shot noise is the dominant noise source. The mean-squared current due to shot noise is expressed by

$$\langle i^2_{\text{shot noise}}\rangle = 2e\langle I_d\rangle B, \tag{5}$$

where e is the electron charge, I_d is the dark leakage current in amps, and B is the noise bandwidth in hertz.

3. Relative intensity noise (RIN) caused by spontaneous emission in the laser source. These variations of laser intensity at the laser transmitter output can have impact at the photodiode output after being converted to electrical current. The mean-squared noise current is expressed by

$$\langle i^2_{\text{RIN}}\rangle = \frac{\langle I_d\rangle^2}{2} 10^{\text{RIN}/10} B, \tag{6}$$

where RIN is the optical noise power, I_d is the dark leakage current, and B is the noise bandwidth. When a directly modulated laser transmitter is used, the RIN is dominant over all other noise sources throughout the rf photonic link.

For this investigation, CNR measurements were performed for both fiber optic and FSO links, with and without the rf amplifier, over a frequency range of 55 to 870 MHz. The rf output power from the signal generator was 0 dBm for all measurements. The results of the CNR measurements for fiber optic link are shown in Fig. 13. Without the rf amplifier, the CNR varied between 40.75 and 58.13 dB over the frequency range 55 to 850 MHz, while CNR with the rf amplifier varied between 58.54 and 73.15 dB over the same frequency range. These values compare favorably with results from CNR measurements on other analog fiber optic links reported in Refs. 3 and 10.

The results of CNR measurements for the FSO link are shown in Fig. 14. Without the rf amplifier, the CNR starts at minimum value of 17.52 dB at 55 MHz and trends upward with increasing frequency to a maximum value of 46.55 dB at 850 MHz. With the rf amplifier, the CNR starts out at a minimum value of 43.52 dB at 55 MHz and trends upward with increasing frequency to a maximum value at 63.3 dB at 850 MHz. These values compare favorably with results of CNR measurements of the previous fiber optic link. Therefore, FSO can be a viable replacement for fiber optics in short distance implementations.

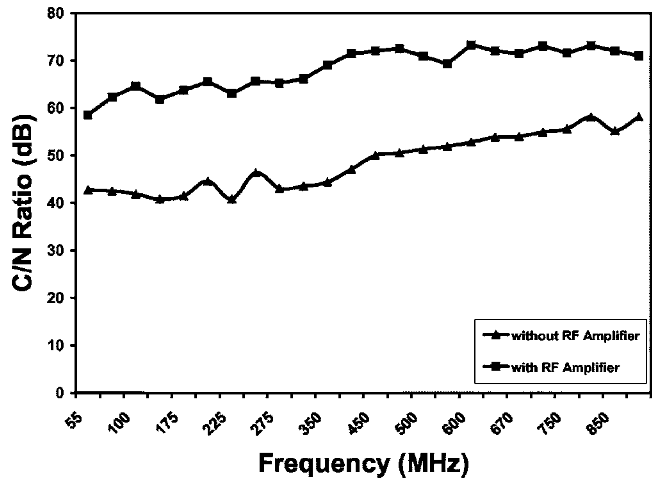

Fig. 13 CNR measurements for fiber optic link.

3.6 *Dynamic Range Measurements*

Dynamic range measurements indicate the range of the rf input power over which no distortion of the output signal occurs due to the effects of harmonic distortion. Nonlinear devices incorporated into the analog transmitters and receivers are the major causes of distortion in an optical link, particularly the analog modulators.[11] Distortion is a key link parameter in certain distribution systems that convey multiple carriers, such as CATV applications.[6] However, it has minor importance in distribution systems that carry one single frequency, such as radar applications.

Contrary to the noise, distortion is a deterministic phenomenon, which can be defined for any link that includes nonlinear devices. There are two principal methods used to measure the dynamic range:[2,11]

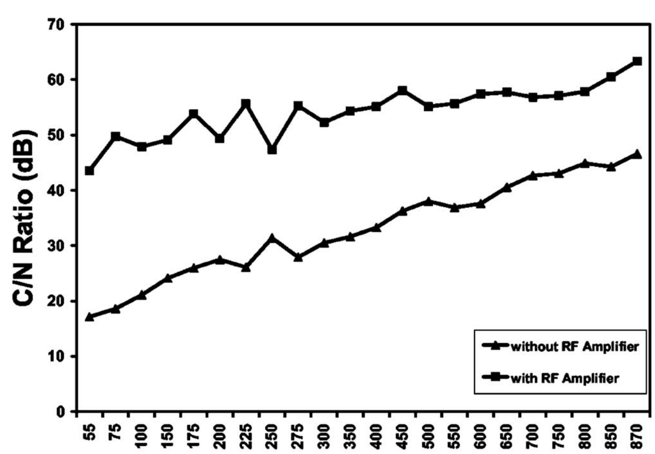

Fig. 14 CNR measurements for FSO link.

Table 1 Fiber optic link parameters.

Optical wavelength	λ	1552.524 nm
Optical output power	P_o	10 dBm
Laser noise	RIN	−159 dBm
Optical modulation index	MOI	8.8%/channel
Modulator impedance	R_m	75 Ω
Optical link loss	L_o	3.45 dB
Photodiode responsivity	η_p	0.85 A/W
Photodiode load	R_p	75 Ω
Noise bandwidth	BW	1 Hz

Table 2 FSO link parameters.

DFB	λ	1552.524 nm
Optical output power	P_o	10 dBm
Laser noise	RIN	−159 dBm
Optical modulation index	MOI	8.8%/channel
Modulator impedance	R_m	75 Ω
Optical link loss	L_o	13.70 dB
Photodiode responsivity	η_p	0.85 A/W
Photodiode load	R_p	75 Ω
Noise bandwidth	BW	1 Hz

1. Inject a single rf sinusoid signal f through the optical link and measure the resulting second- and third-order harmonic distortions at $2f$ and $3f$, respectively.
2. Inject two sinusoidal rf signals of equal amplitude and close in frequency spacing through the optical link and measure the second-order intermodulation distortion at f_2+f_1 or f_2-f_1 and the third-order intermodulation distortion at $2f_1-f_2$, $2f_2-f_1$, $2f_1+f_2$, or $2f_2+f_1$. Narrowband links allow the frequencies $2f_1-f_2$ and $2f_2-f_1$ to pass and eliminate the rest.

The second method is the more practical way of measuring the dynamic range and was used in this paper. The third-order intermodulation (3IM) power was measured to provide the 3IM free dynamic range. An rf multiplexer was used to multiplex two equal power rf signals at closely spaced frequencies of $f_1=499$ and $f_2=501$ MHz. Supplying the composite rf signal into the FSO channel, the 3IM signal power was measured at frequencies $2f_1-f_2=497$ and $2f_2-f_1=503$ MHz. Repeating the same measurements while increasing the input power for both frequencies enables the 3IM line to be plotted. Measuring the output power of the fundamental frequency $f=500$ MHz over the same range of input power allows the fundamental output line to be plotted, which intersects the 3IM line. In this study, a directly modulated, distributed feedback (DFB) laser diode was used as the transmitter, so RIN is the dominant noise source.

Table 1 provides the component parameters for the fiber optic link under test. These parameters were taken from the specifications of the utilized components. The 3IM free dynamic range was found to be 101 dB Hz$^{2/3}$, as shown in Fig. 15. Previous studies have reported a typical 3IM free dynamic range of 116 dB Hz$^{2/3}$ for the CATV application over fiber-optic links.[3,4,11,12] Thus, the measured result is acceptable compared to the reported result. The reduction in the measured 3IM free dynamic range results from the built-in rf amplifier (a nonlinear device) at the output of the photodiode.

Table 2 provides the component parameters of the FSO link under test. The 3IM free dynamic range was found to be 101 dB Hz$^{2/3}$, as shown in Fig. 16. This value compares favorably with the previously mentioned measured value for the fiber optic link under test and indicates the absence

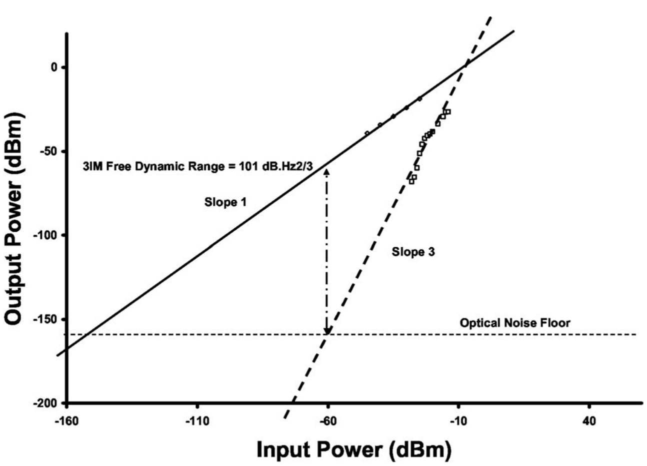

Fig. 15 Third-order intermodulation free-dynamic-range measurements for fiber optic link.

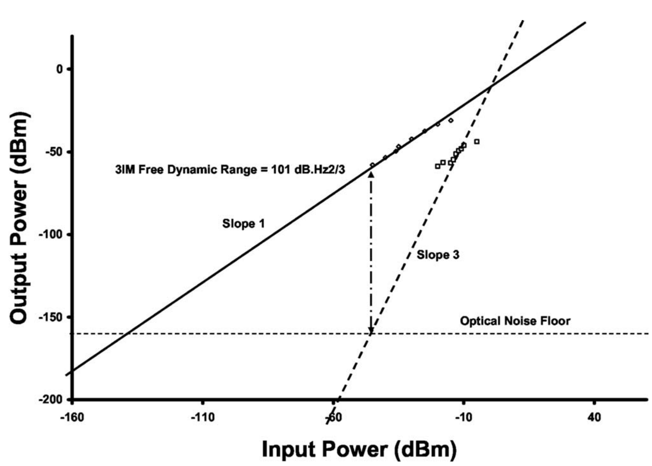

Fig. 16 Third-order intermodulation free-dynamic-range measurements for FSO link.

of any nonlinear devices. From a distortion point of view, both fiber-optic and FSO links behave similarly. However, the addition of an optical amplifier to the FSO link to increase span length would lead to increased distortion.

4 Conclusion

This paper presents a comparison of key performance measures for a FSO link versus a fiber optic link for the transport of analog rf signals. The authors are not aware of any reports of similar comparative studies in the literature. The comparative study consists of experimental data collected from optical power, transmission response, reflection response, group delay, CNR, and dynamic range measurements. The data indicate that FSO is suitable for rf transmissions and performs comparably with similar fiber optic links. When direct line-of-sight is available between two locations, FSO can offer an attractive substitute for fiber optic links to transport modulated rf analog signals over short distances.

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Hakki H. Refai received his BS degree in electrical engineering in 1992 from Aleppo University, Syria, and his MS degree in electrical and computer engineering in 2002 from the University of Oklahoma, where he is currently pursuing his PhD degree in electrical and computer engineering. His current research interests are the development of laser communications, fiber optics and free-space optics, high-performance analog optical links for avionics applications, and optical imaging technologies. He is a member of the IEEE, the SPIE, and the OSA.

James J. Sluss, Jr., is a professor of electrical and computer engineering in the Telecommunications Systems Program at the University of Oklahoma, Tulsa. He received his BS degree in physics in 1984 from Marshall University, and his MS and PhD degrees in electrical engineering in 1986 and 1989, respectively, from the University of Virginia. His current research and teaching interests are optical communications, photonics, and intelligent transportation systems. He was awarded seven U.S. patents, has authored or coauthored numerous journal and conference publications, and has been principal or coprincipal investigator for over $5M in sponsored research grants and contracts. He is currently assistant dean for research at the University of Oklahoma's Tulsa Graduate College and is a member of the IEEE, the IEEE Education Society, IEEE Communications Society, the OSA, the SPIE, and the ASEE. He is currently treasurer of the IEEE Education Society.

Hazem H. Refai received his MSEE and PhD degrees from the University of Oklahoma (OU) in 1993 and 1999, respectively. Since the fall of 2001, Dr. Refai has been an assistant professor at the school of Electrical and Computer Engineering (ECE) Telecommunication Program in Tulsa, Oklahoma. From 1996 to 2001 he was a research associate at OU with a joint appointment from the School of Electrical and Computer Engineering and the School of Petroleum and Geological Engineering (P&GE). With ECE, he played a key role in the development of hardware interfaces and software algorithms to integrate a global positioning system and its wide and local augmentation systems into an aircraft navigational system to flight test precision terminal instrument procedures. With P&GE, he conducted research to model the characteristics of fracturing fluids at the Well Construction Technology Center, where his work involved the development of a fiber optic vision system to real-time capture and process images of fluids flowing through the high pressure simulator. Since joining the Telecommunication Graduate Program at OU, Tulsa, Dr. Refai has been responsible for developing and teaching wireless communication and networks courses. He is involved in the development of a laser mobile communication system using free-space optics. He is also leading the effort to design a medium access control protocol for intervehicle communication. Dr. Refai is the IEEE ComSoc Tulsa Chapter Chair and the IEEE ComSoc Distinguished Lecturer Tour Coordinator for North America.

Mohammed Atiquzzaman earned his MSc and PhD degrees in electrical engineering and electronics from the University of Manchester Institute of Science and Technology, United Kingdom. He is currently a professor in the School of Computer Science at the University of Oklahoma. Dr. Atiquzzaman has over 140 publications in leading journals and conferences in the areas of communications and networking, parallel/distributed computing, and image processing. He has received funding from state and federal agencies such as National Aeronautics and Space Administration (NASA), National Science Foundation (NSF) and the United States Air Force. Atiquzzaman is the co-editor-in-chief of the *Computer Communications* journal, and serves on the editorial board of the *IEEE Communications Magazine*, the *Journal of Real-Time Imaging*, the *Telecommunication Systems* journal, and the international journal on *Wireless and Optical Communications*. He has guest edited many special issues in various journals including the *IEEE Communications Magazine*, the *Computer Communications* journal, the *Journal of Real Time Imaging*, the *International Journal of Computer Systems Science & Engineering*, *Parallel Computing*, and *Image and Vision Computing*. He was technical program cochair of the 2003 Workshop on High Performance Switching and Routing and the SPIE Quality of Service over Data Networks conference, and panels chair of IEEE INFOCOM, and has been involved in the program committees of many leading international conferences. He has been invited for seminars at various organizations and has served as panelist in conferences and funding organizations. He is a senior member of the IEEE.