Field Demonstration of X-Band Photonic Antenna Remoting in the Deep Space Network

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We designed a photonic link for antenna remoting based on our integrated system analysis. With this 12-km link, we successfully demonstrated photonic antenna-remoting capability at X-band (8.4 GHz) at one of NASA's Deep Space Stations while tracking the Magellan spacecraft.

I. Introduction

Photonic antenna remoting has become increasingly important in high-stability microwave and millimeter-wave communications systems. In an antenna remoting system, a photonic link is generally inserted between the low-noise amplifier (LNA), at the antenna front-end, and the downconverter, as shown in Fig. 1. One of the major advantages of such a link is that the downconverter and related equipment may be moved out of the antenna area to a remote command and signal processing center to substantially reduce the amount of equipment located at the antenna area. In systems with multiple and widely separated antennas, this new configuration will lower hardware and operating costs and increase system performance, flexibility, and reliability. In addition, this approach offers the capability to coherently array widely separated antennas at RF frequencies to increase receiving sensitivity.

For systems with high-frequency and high-dynamic ranges, externally modulated photonic links generally are preferred over the directly modulated links [1,2]. The performance of such links previously has been analyzed [3-6] and demonstrated in the laboratory environment [1,2,7]. However, most of the previous analyses were performed by considering the photonics link as an isolated entity rather than as a segment of the antenna-receiver system. In addition, in none of the previous studies was account taken of the influence of the laser's relaxation oscillation noise on the system performance, an effect that is critical in a number of antenna remoting applications.

In the present work, we present results of a study [8] to quantitatively determine the influence of a photonic link on the entire system and to explicitly account for the influence of the laser's relaxation oscillation noise on the system performance. From the analysis, we deduce the requirement for each component of the link, according to system specifications. Finally, we report on the successful demonstration of a photonic link capable of directly transmitting X-band (8.4-GHz) microwave signals from an antenna site to a remote signal processing facility located 12 km away in NASA's Venus Deep Space Station (DSS) 13. This demonstration is critical for implementing photonic antenna remoting throughout NASA's Deep Space Network [2,6].

The externally modulated photonic link essentially consists of a diode-pumped YAG laser, a high-speed $LiNbO_3$ modulator, an RF preamplifier, and a high-speed optical receiver. For ultimate performance in the antenna remoting applications, the insertion of the link between the low-noise amplifier and the receiver downconverter should be transparent to the rest of the system, and thus leave the system's noise temperature, dynamic range, and gain profile unaltered. This requirement forms the basis of our analysis of the link performance.

II. The Preamplifier Requirements

The RF insertion loss G_{op} (or gain) of a photonic link without a preamplifier is given by [5,8]

$$G_{op} = \pi^2 \frac{I_{ph}^2 R_L}{V_\pi^2 / R_m} \tag{1}$$

where I_{ph} is the photocurrent across the load resistor R_L of the receiver, R_m is the input impedance of the modulator, and V_π is the half-wave voltage of the modulator. In Eq. (1), the numerator is the electrical power generated by the photocurrent in the receiver, and the denominator is the input electrical power to the modulator with a modulation voltage of V_π. We, therefore, arrive at the requirement for a preamplifier with a gain of $G_{pr} = 1/G_{op}$ in order to compensate for any loss resulting from the insertion of the photonic link.

The input third-order intercept of the modulator IP_m can be expressed as [5,8,9]

$$IP_m = 10P_m^{1\mathrm{dB}} = \frac{4}{\pi^2} \frac{V_\pi^2}{R_m} \tag{2}$$

where $P_m^{1\mathrm{dB}}$ is the input 1-dB compression of the modulator. To ensure that the preamplifier does not limit the dynamic range of the link, the output third-order intercept IP_{pr} of the preamplifier must be much larger than IP_m, thus leading to the condition that

$$IP_{pr} >> \frac{4}{\pi^2} \frac{V_\pi^2}{R_m} \tag{3}$$

III. Impact of the Laser's Relaxation Oscillation Peak

Any diode-pumped YAG laser has a relaxation oscillation noise peak around a few hundred kHz [10]. However, this low frequency relative intensity noise (RIN) peak can be multiplied up to the modulation frequency by the modulator, as shown in Fig. 2. In systems where the frequency of the signal of interest is less than a few hundred kHz from the carrier frequency, these multiplied noise peaks interfere with the signal and may cause serious difficulties. To avoid this, the amplitude of the multiplied RIN should be kept sufficiently below the noise floor of the system. We found [8] that to keep the multiplied noise peaks 10 dB below the noise floor of the system,

$$RIN(f_{RLX}) \leq \frac{0.4}{D_{sys}} \tag{4}$$

is required. In Eq. (4), $R(f_{RLX})$ is the RIN at the relaxation oscillation frequency f_{RLX} and D_{sys} is the compression dynamic range (Hz) of the system.

IV. Dynamic Range Degradation

The output intercept IP_{op} of the optical link is simply the product of the RF gain G_{op} and input intercept IP_m of the link: $IP_{op} = G_{op} IP_m$. Using Eqs. (1) and (2), we obtain

$$IP_{op} = 10P_{op}^{1\mathrm{dB}} = 4I_{op}^2 R_L \tag{5}$$

where $P_{op}^{1\mathrm{dB}}$ is the output 1-dB compression of the optical link. It is important to note that the output intercept of the link is determined solely by the photoelectric power in the photoreceiver and is, therefore, independent of the modulator characteristics. It is also evident that the higher the photocurrent, the larger IP_{op} will be.

From our analysis, the degradation $\Delta(SFD_{sys})$ of the spur-free dynamic range of the system caused by the insertion of the optical link can be expressed as [8]

$$\Delta(SFD_{sys}) \approx 6.7 \log \left(1 + \frac{G_{LNA} IP_{sys}}{IP'_{op}}\right) \tag{6}$$

where G_{LNA} is the gain of the low-noise amplifier of the antenna, IP_{sys} is the input third-order intercept of the system, and IP'_{op} is both the input and the output (because of the unity gain) third-order intercept of the loss-compensated link. One may express IP'_{op} as

$$\frac{1}{IP'_{op}} = \frac{1}{G_{op} IP_{pr}} + \frac{1}{IP_{op}} \tag{7}$$

If Eq. (3) is satisfied, $IP'_{op} \approx IP_{op} = 4I_{ph}^2 R_L$, and from Eq. (7), the dynamic range of the system is solely limited by the photoelectric power. On the other hand, if

$IP_{op} >> G_{op}IP_{pr}$, then the preamplifier limits the system's dynamic range.

V. Noise Factor Degradation

The noise factor increase ΔF_{op} of the system, caused by the optical link, can be written as [8]

$$\Delta F_{op} \approx \frac{T_{op}F_{pr} + 1160I_{ph} + 116I_{ph}^2}{T_{LNA}G_{LNA}} + \frac{1}{4}SNR_{sys}RIN(f - f_m) \quad (8)$$

where T_{op} and T_{LNA} are the temperatures of the link and the low-noise amplifier, respectively; F_{pr} is the noise factor of the preamplifier; I_{ph} is expressed in mA; and SNR_{sys} is the signal-to-noise ratio (in a 1-Hz bandwidth) at the input of the low-noise amplifier. In Eq. (8), the first term is the noise factor contribution from the preamplifier; the second term is from the shot noise of the optical link (assuming $R_L = 50\ \Omega$); the third term is from the baseband RIN of the laser (assuming a baseband RIN of −165 dB/Hz); and the last term is due to the multiplied relaxation oscillation noise. This last term is frequency dependent and peaks at $f = f_m \pm f_{RLX}$.

At low modulation levels, the contribution to the noise factor from the multiplied RIN is small. However, at high modulation levels, the contribution from the multiplied RIN peaks becomes more important around $f = f_m \pm f_{RLX}$. Because the largest signal-to-noise ratio of the system is set by the dynamic range D_{sys}, the maximum ΔF_{op} is obtained by replacing SNR_{sys} with D_{sys} in Eq. (8).

VI. Link Design

As mentioned above, the ultimate aim of the study was to design a photonic link for the Venus station of the NASA Deep Space Network at Goldstone, California. Thus, the parameters of the system in the Venus station were used to determine the appropriate parameters of the photonic link. In the Venus station, the gain of the antenna's low-noise amplifier was $G_{LNA} = 36$ dB, and the input noise temperature was $T_{LNA} = 36.8$ K. The temperature at the input of the optical link was $T_{op} = 290$ K. The input third-order intercept point and 1-dB compression of the system before inserting the optical link were $IP_{sys} = -47$ dBm and $P_{sys}^{1dB} = -53$ dBm, respectively, and were limited by the system's X-band downconverter. The corresponding compression dynamic range of the system was $D_{sys} =$ 131 dB-Hz, and the bandwidth and the total noise temperature of the system were 500 MHz and 40.4 K, respectively.

According to Eq. (4), a laser with noise $RIN(f_{RLX}) \leq -135$ dB/Hz is required in order to obtain a D_{sys} of 131 dB-Hz. The $RIN(f_{RLX})$ of a diode-pumped YAG laser without noise reduction circuitry is typically as high as −100 dB/Hz and cannot meet this stringent requirement. We selected a diode-pumped YAG ring laser with a built-in noise reduction circuit [10] that has a noise peak $RIN(f_{FLX})$ just low enough (−135 dB/Hz) to meet the requirement of Eq. (4). This is the lowest noise laser that is currently commercially available. For systems with a higher dynamic range, additional external noise reduction schemes [11] must be deployed. The output power of the laser used in our link was 50 mW.

We used a $Ti{:}LiNbO_3$ Mach–Zehnder modulator with a frequency response of 18 GHz. The stability of this modulator is excellent, but the optical insertion loss is high (10 dB). The receiver we chose has a frequency response from 0.1 to 12 GHz and a load resistance of 50 Ω. With 12 km of single-mode fiber between the modulator and receiver, the photocurrent in the load resistor of the optical receiver was $I_{ph} = 0.25$ mA. The frequency response of the link without the preamplifier was very flat from 130 MHz to 10 GHz.

Due to the high V_π (about 30 V) of the modulator used in the link and the low photocurrent of the optical receiver, the RF insertion loss G_{op} was high at about −60 dB. The preamplifier used to compensate for the loss consisted of two cascaded amplifiers and had a gain of 60 dB, a noise factor of $F_{pr} = 2$, and an output intercept $IP_{pr} = 36$ dBm. Because of the high V_π, IP_{pr} could not meet the requirement of Eq. (3), and the dynamic range of the system was limited by both the preamplifier and the photoelectric power. From Eqs. (8) and (9), the expected degradation $\Delta(SFD_{sys})$ of the system's spur-free dynamic range is calculated to be 9.6 dB. This degradation can easily be reduced to less than 1 dB, as will be shown below.

With the system parameters given above, the maximum noise factor contribution from the multiplied RIN peaks is calculated to be 0.1 at $f = f_m \pm f_{RLX}$, and the noise temperature degradation caused by the first three terms in Eq. (8) is 0.75 percent. Such a small degradation is not expected to be measurable in our experiment.

VII. System Evaluation

As a first step, we evaluated the performance of the photonic link in the laboratory. With the preamplifier described above, the frequency response of the link was very flat (±1 dB) in the frequency range of interest (from 8 to 9 GHz). The phase noise [12] of the laboratory-based photonic link with 10 m of fiber was measured to be less than −110 dBc-Hz at 1 Hz from the carrier frequency of 8.4 GHz, as shown in Fig. 3. This measurement value was limited by the noise floor of the measurement system. The phase noise at this level is consistent with the previously reported results [2] and is 56 dB below the local oscillator phase-noise specification of the Deep Space Network.

As a next step, we evaluated our optical link at S-band (2.295 GHz) in a test facility (CTA-21) that simulated the operating conditions of a real antenna receiving system in the Deep Space Network. A telemetry signal of 7.2 kbit/sec was first sent to the receiving system and was attenuated to be slightly above the noise floor of the system. The noise figure of the system was calculated from the received bit-error rate. Using this method, we measured the system noise figures with and without the optical link inserted between the low-noise amplifier and the downconverter. We found that the insertion of the 12-km fiber-optic link added no measurable degradation to the receiving system.

Finally, we evaluated the 12-km photonic link at the Venus Deep Space Station (DSS 13) while the Magellan spacecraft was being tracked. As shown in Fig. 1, the optical link was inserted between the low-noise amplifier and the X-band downconverter, both of which were located at the pedestal room of the antenna. When the fiber-optic link was inserted, no changes in the level and the quality of the received spacecraft signal at 8.426 GHz were observed. We also measured the noise temperature of the system before and after the insertion of the optical link and found no observable difference. This is consistent with the result of Eq. (8).

Because of time and equipment constraints, the dynamic range degradation of the system, expected to be 9.6 dB, was not measured. However, this degradation can be greatly reduced by simply replacing the modulator with a state-of-the-art unit that has a V_π less than 10 V and an optical insertion loss less than 4 dB. With the 6-dB improvement in the optical insertion loss, the photocurrent I_{ph} would be increased to 1 mA. With such a modulator in the link, the required gain of the preamplifier would be reduced to 36 dB, and the minimum required output third-order intercept point would be reduced to 29 dBm. Commercial amplifiers are currently available to meet these requirements and, thus, will not limit the system's dynamic range. From Eq. (7), it can be seen that the total degradation in the spur-free dynamic range of the system would be 1 dB. We are currently exploring alternative options [13] for improving the photonic link for systems requiring higher dynamic range.

VIII. Summary and Conclusions

In summary, we have presented analytical results for predicting the noise temperature and the dynamic range degradation of the antenna receiving system caused by the insertion of a photonic link. We have specified design parameters for each component of the link according to the system requirements. In this study, special attention was paid to the effect of the relaxation oscillation noise peak of the laser, resulting in the important conclusion that the maximum allowed noise amplitude is inversely proportional to the dynamic range of the system. We also found that a high level of photoelectric power is critical for a system with a high dynamic range.

Based on the analytical results, we designed and fabricated a photonic link. With this link, we successfully demonstrated photonic antenna remoting capability at X-band in an operating antenna receiving system in NASA's Deep Space Network and concluded that the link added no observable degradation to the 40.4-K noise temperature of the system. We also determined that a modulator with an optical insertion loss of less than 4 dB and a half-wave voltage of less than 10 V may be used in the future to reduce the degradation of the system's dynamic range to less than 1 dB.

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References

[1] G. E. Betts, L. M. Johnson, C. H. Cox III, and S. D. Lowney, "High-Performance Optical Analog Link Using External Modulator," *IEEE Photonics Technology Letters*, vol. 1, no. 11, pp. 404–406, November 1989.

[2] R. T. Logan and G. F. Lutes, "High Stability Microwave Fiber Optic Systems: Demonstration and Applications," *Proceedings of the 46th Annual Symposium on Frequency Control*, Hershey, Pennsylvania, pp. 310–316, May 27–29, 1992.

[3] W. E. Stephens and T. R. Joseph, "System Characteristics of Direct Modulated and Externally Modulated RF Fiber-Optic Links," *Journal of Lightwave Technology*, vol. LT-5, no. 3, pp. 380–387, March 1987.

[4] W. L. Glomb, "Fiber Optic Links for Antenna Remoting," *SPIE Proceedings*, vol. 1703, pp. 523–527, 1992.

[5] W. L. Glomb, J. D. Farina, and S. W. Merritt, "Minimum Noise Figure Microwave Transmission System," *SPIE Proceedings*, vol. 1703, pp. 528–534, 1992.

[6] R. T. Logan, G. F. Lutes, and L. Maleki, "Microwave Analog Fiber Optic Link for Use in the NASA/JPL Deep Space Network," *The Telecommunications and Data Acquisition Progress Report 42-100, vol. September–December 1989*, Jet Propulsion Laboratory, Pasadena, California, pp. 21–33, February 15, 1990.

[7] G. E. Betts, C. H. Cox III, and K. G. Ray, "20 GHz Optical Analog Link Using an External Modulator," *IEEE Photonics Technology Letters*, vol. 2, no. 12, pp. 923–925, December 1990.

[8] X. S. Yao and L. Maleki, "Influence of an Externally Modulated Photonic Link on a Microwave Communications System," *The Telecommunications and Data Acquisition Progress Report 42-117, vol. January–March 1994*, Jet Propulsion Laboratory, Pasadena, California, pp. 16–28, May 15, 1994.

[9] B. H. Kolner and D. W. Dolfi, "Intermodulation Distortion and Compression in an Integrated Electrooptic Modulator," *Applied Optics*, vol. 26, no. 17, pp. 3676–3680, September 1987.

[10] T. J. Kane, "Intensity Noise in Diode-Pumped Single-Frequency Nd:YAG Lasers and Its Control by Electronic Feedback," *IEEE Photonics Technology Letters*, vol. 2, no. 4, pp. 244–245, April 1990.

[11] D. M. Dagenais, K. P. Koo, and D. Dandridge, "Demonstration of Low-Frequency Intensity Noise Reduction for Fiber Sensors Powered by Diode-Pumped Nd-YAG Lasers," *IEEE Photonics Technology Letters*, vol. 4, no. 5, pp. 518–520, May 1992.

[12] R. T. Logan, L. Primas, G. F. Lutes, and L. Maleki, "Design of a Fiber-Optic Transmitter for Microwave Analog Transmission With High Phase Stability," *The Telecommunications and Data Acquisition Progress Report 42-102, vol. April–June 1990*, Jet Propulsion Laboratory, Pasadena, California, pp. 27–33, August 15, 1990.

[13] C. H. Cox III, G. Getts, and L. M. Johnson, "An Analytic and Experimental Comparison of Direct and External Modulation in Analog Fiber-Optic Links," *IEEE Transactions on Microwave Technology and Techniques*, vol. 38, no. 5, pp. 501–508, May 1990.

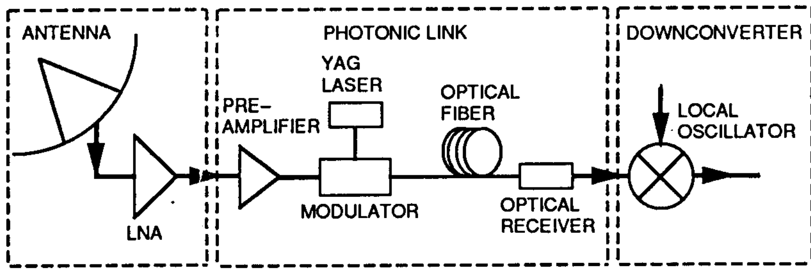

Fig. 1. An illustration of photonic remoting. The downconverter and local oscillator are ordinarily directly connected to the LNA at the antenna. The photonic link permits them to be moved out of the antenna to a remote signal processing center.

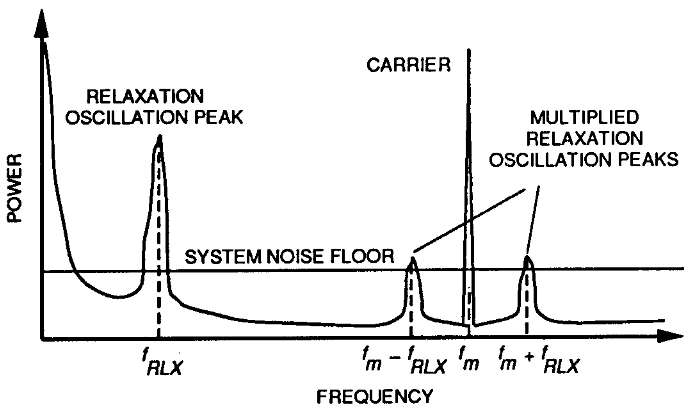

Fig. 2. The laser relaxation peak is multiplied up by the modulation signal. The multiplied peaks may be mistaken for the signal when they are above the system floor noise.

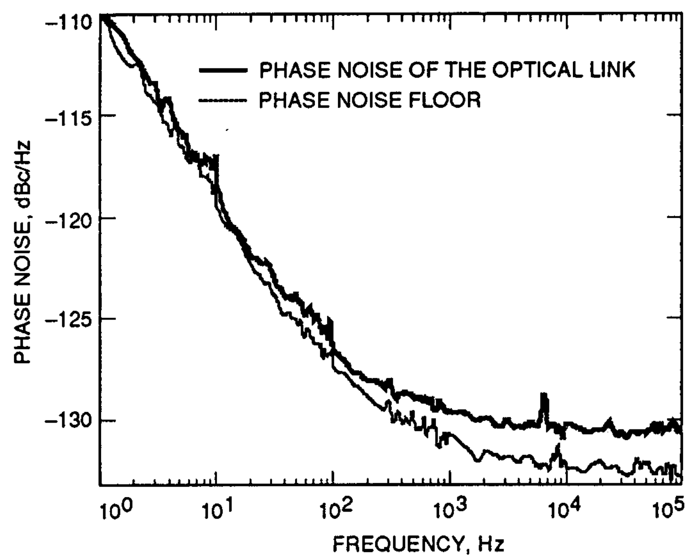

Fig. 3. Close-in phase noise measurement of the photonic link. The noise floor is set by the X-band microwave amplifier used in the measurement. A fiber length of about 10 m was used between the modulator and receiver.