ON IMPLEMENTATION OF REMOTELY OPERATED UNMANNED TELEMETRY TRACKING SYSTEMS WITH FIBER OPTIC CABLE

WILLIAM C. TURNER
ELECTRO-MAGNETIC PROCESSES, INC.
CHATSWORTH, CALIFORNIA 91311

ABSTRACT

The high cost of real estate in countries with expanding populations, coupled with the long range capability of modern weapon systems has resulted in the need to expand test ranges to remote desert areas or areas over sea water. In order to preclude the cost of duplicating existing test centers, and the high cost of manually operating ground tracking stations, the requirement for unmanned remotely controlled telemetry tracking systems has emerged.

Until recently, implementation of such systems has been trivial because the microwave link had sufficient bandwidth. However, with the advent of multi-TM bands, encrypted T.V. video and dual-polarization diversity requirements, implementation of unmanned remote stations has become cumbersome, expensive and less reliable. For instance, a pair of dedicated computers are now required to remotely control as many as eight receivers and four diversity combiners.

This paper analyzes the advantages, limitations and feasibility of remotely controlling a wide-band antenna/pedestal with the restriction that all frequency downconverters, receivers, and combiners be located at the test center where they can be manually controlled and monitored, and more readily maintained. A comparison is made between the use of coaxial cable and fiber-optic cable as short-haul (0.25 to 25 kilometers) RF transmission media.

BACKGROUND

Until recently, dual polarization diversity telemetry tracking systems have been remotely operated by co-locating the data/tracking receivers with the antenna/pedestal. To accomplish this, the receivers, combiners, and associated test equipment were controlled via a GPIB bus from a remotely controlled local computer. Not only were the TM data and received signal strength transmitted to the control site, via narrow-band microwave links, but system operators demanded that the IF spectrum also be received for presentation on spectrum analyzers at the remote site.

Because of BAUD rate limitations, and overhead of the local and remote computers, the receiver control response time is slow, but acceptable. The response problem is compounded when two or more 100 MHZ telemetry bands and/or encrypted T.V. video from the instrumented vehicle must be accommodated by the tracking system. For this case, either a pair of receivers and a combiner are required for each band, or a dual-channel downconverter for each band, followed by a remotely controlled switching matrix and two or more receivers are required. For either solution, additional power, cooling, and rack space are required at the unmanned local site.

For multi-band telemetry tracking systems, it is preferred by operators and maintenance personnel to have the receivers and optional downconverters located at the manned remote site where patch panels and decrypting equipment are available, and where the environment is well controlled. In addition to the economies gained in reduced maintenance costs for the receiving and environmental control equipment, this approach provides the operator with immediate response of monitored parameters and eliminates the links and associated computers required for receiver control and spectrum display.

COAX VS. FIBER CABLES

The luxury of having the receivers at the manned remote site requires that the wide-band RF (1.4 to 2.4 GHz) be transmitted from the local site to the remote site. Since microwave links are currently limited to two 30 MHZ bandwidths by the receiver/transmitters, only two methods are currently known for meeting this requirement, either coaxial cable or fiber-optic cable.

It is neither cost effective nor practical to link an antenna/pedestal with a remote controller, via a hard-wire cable, longer than 200 meters. But, what are the cost effective and practical limits of using coaxial cable to link the antenna with the remote receivers?

The cost of driving a long length of coaxial cable becomes excessive when cable attenuation exceeds 40 dB. One-half inch diameter foam-dielectric coax is limited to 350 meters in length and costs $5,400 per pair including connectors.[1] Five-eighths inch diameter foam cable is limited to 550 meters in length, and costs $22,700 per pair. One and one-fourth inch diameter cable is the largest diameter cable that supports 2.4 GHz and is limited to 800 meters in length. The cost of a pair of 800 meter long high-quality 1 ¼-inch foam flex cables exceeds $54,000. Currently, at nine known existing installations, four dual-channel frequency downconverters are employed at the pedestal to drive eight one-half inch diameter coaxial cable runs 650 meters in length at a cost of $72,500. The cost of the latter two alternatives far exceeds that of a high-quality dual-channel fiber-optic link, which would remote the data/tracking receivers at a distance exceeding 15 kilometers.

In order to maintain a low system noise temperature and drive a long coaxial cable, the RF low-noise preamplifier (LNA) not only must have a net gain of 63 dB, but must have a tapered frequency response to compensate for the 8 dB differential attenuation between 1.4 and 2.4 GHz in the coaxial cable. The same 63 dB LNA, but with a flat frequency response, will drive a single-mode analog fiber-optic transmission line 6 kilometers in length and provide virtually the same noise performance, and almost the same dynamic range. Since the frequency response of the fiber-optic transmission system is flat to within 0.5 dB over the band of interest, no leveling vs. frequency is required.

ADVANTAGES OF FIBER-OPTIC CABLE

Besides being more rugged and flexible than foam-dielectric coaxial cable, the four principal advantages of using fiber-optics over coaxial cable are EMI, security, moisture immunity, and cost.

Since the medium of transmission (glass) in optical fiber is totally non-electrical, the signal in the fiber will not be disturbed by the presence of external EMI, EMP or moisture. Also, since the medium is a dielectric, the signal cannot be tapped using current probes. The only way to tap the signal, short of breaking the connection, is to strip away the cable jacket and bend the bare fiber tightly enough so that some of the light is transmitted through the cladding. Either way, the loss in light power is immediately detectable at the photodiode receiver.

For cable runs longer than 550 meters, the most compelling reason for using an analog fiber-optic RF transmission system is cost: For a dual-diversity (two-

---

[1]Foam-dielectric cable was selected because it does not require pressurization with dry air and therefore the cost comparison with fiber cable is more equitable. 40 dB of cable attenuation limits its length without a repeater amplifier.

channel) TM ground station, the cost of two 800 meter long 1 ¼-inch diameter foam-dielectric cables having low VSWR is $54,000. Installing the cables in a secure conduit will incur additional costs. The cost of two pair of laser transmitters and photodiode receiver modules, and an 800 meter long bundle of four single-mode fibers is $33,000. The cost of installing the fiber cable is modest because it can be blown through existing conduit. The cost of installing the fiber-optic laser transmitter modules in the pedestal, and the fiber-optic receiver modules in the control console requires an additional $3,000 yielding a total cost of $36,000. (Note that the laser transmitter modules are designed for a severe environment and do not require an environmentally-controlled housing.) It is concluded that a savings of at least $18,000 is realized by utilizing a secure, EMI-proof fiber-optic transmission line system.

LIMITATION OF FIBER-OPTICS

The only limitation of a fiber-optic link, though not insurmountable, is dynamic range. The dynamic range is defined as the signal level range (in dB) between noise floor and LNA compression where the AM tracking error signal drops to one-half its nominal peak-to-peak level.

Telemetry receivers typically amplitude-limit at a -10 dBm input and have a noise figure of 10 dB. Assuming a 40 dB coaxial cable loss, the final stage of the power amplifier driving the transmission line must not limit below an output of +30 dBm, or have a 1 dB compression point of less than +30 dBm. The combined gain of the LNA and power amplifier driving the line must be 63 dB to overcome the cable loss and minimize the receiver noise contribution to the system noise temperature. This transmission system typically provides a dynamic range of 85 dB and a system noise temperature of 200 Kelvins. (Note that for each additional dB of cable loss, one must not only increase the amplifier gain and compression point by 1 dB but also increase the output power capability by 1 dBm.)

The typical laser transmitter of a fiber-optic link begins to amplitude-limit at an input level of + 1 5 dBm. The noise figure of the fiber link can be held to 46 dB for a fiber length ranging from 0.25 to 15 kilometers. The corresponding power gain (loss) of the fiber link ranges from -32 to -37 dB. To achieve a system noise temperature of 200 Kelvins, the gain of the amplifier driving the fiber link again must be 63 dB. However, the laser transmitter goes into compression before the telemetry receiver by a power level ranging from 10 to 12 dBm. Thus, the dynamic range of the receiving system is reduced 7 to 12 dB depending on the length of the fiber-link. However, the dynamic range of 85 dB can be retained simply by automatically controlling the gain of the drive amplifier, bypassing the final stages of the amplifier or switching to a low-gain antenna once the received signal strength exceeds 60 dB above noise floor.

EXPERIMENTAL COMPARISON

A direct comparison of analog fiber with coaxial RF transmission line was made at Edwards Air Force Base, CA., using an 8-foot diameter tracking system at S-band. The 400-foot long LHCP channel coaxial cable was replaced by a fiber link and compared with the unmodified RHCP channel using one-half inch foam coaxial cable. A common Microdyne 1200MR receiver with an IF bandwidth of 1.5 MHZ was used to compare RF channels.

The two RF sources employed for the test were the solar disc and a boresight tower using a vertically polarized antenna located seven (7) miles distant. The gain of a second RF amplifier preceding a low cost laser transmitter module, located at the base of the pedestal, was adjusted to equalize the noise level of the two channels.

The solar disc was acquired and tracked using each channel. The RHCP (coax) channel showed a Y-factor (ratio of solar disc noise power to cold-sky noise power) of about 0.5 dB better than the LHCP (fiber) channel. The vertically polarized source was autotracked by the RHCP channel when the signal-plus-noise was equal to twice the noise. The signal level had to be raised approximately 3 dB before autotracking, via the LHCP (fiber) channel, performed equally well. (A bias in the tracking loop prevented stable autotracking of either channel on a lower signal level.)

The signal level of the RHCP (coax) channel had to be raised 30 dB above system noise floor before the bit error rate (BER) was less than one per 10^6 bits. The signal level in the LHCP channel had to be raised an additional 1.5 dB to achieve equal performance. The signal level was then raised 60 dB above system noise floor near laser saturation. No bit drop-outs were observed on either channel. Autotrack snap-on tests of either channel using both the high-gain antenna, and the low-gain acquisition aid antenna showed only a ten percent overshoot and no variation in the tracked angle. (The lack of a higher level RF test signal precluded measuring the full dynamic range of the fiber link.)

SYSTEM NOISE TEMPERATURE CALCULATION

Once the noise figure and power gain (loss) of the RF fiber-link in the TM frequency band are known, the system noise temperature can be determined using Friis' formula. The three sources that contribute to the noise temperature of the fiber link are laser noise, photodiode receiver thermal noise, and photodiode shot noise, (see Reference 1). The latter two sources are functions of system optical losses and become worthy of consideration when cable lengths exceed 1 kilometer where the optical loss due to fiber and connectors exceed 1.4 dB. The power gain (loss) of the link is a function of the laser to fiber coupling, the photodiode output impedance matching device and fiber attenuation. For longer cable lengths, photodiode thermal noise coupled with high power loss eventually limits link performance. Once the required cable length and quality are determined, the vendor will provide the Equivalent Input Noise power (EIN) for the link, and the link power gain (loss). The system noise figure can then be calculated.

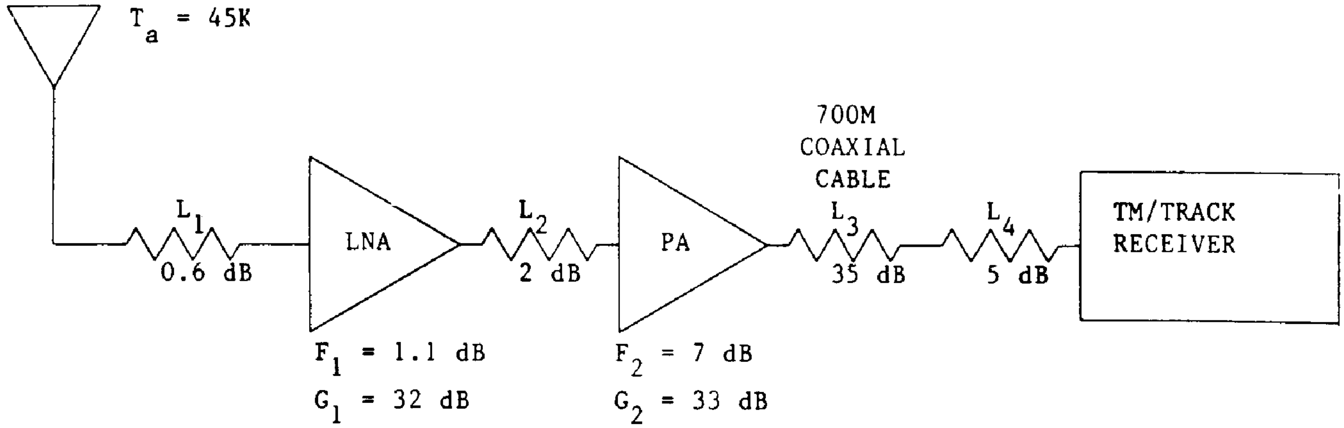
By definition, the Noise Figure (F) of a device is a figure of merit determined by the ratio of the noise power generated by the device, to the noise power generated by an ideal device, which is 4×10^{-18} milliwatts/Hz at 290K or -174 dBm/Hz when terminated in a passive load. When the equivalent input noise power of the link (EIN) is given in dBm/Hz, the noise figure for the link (in dB) is found by subtracting -174 dBm/Hz from EIN. Thus, for an EIN of -128 dBm/Hz, the noise figure (F) is -128-(-174) = 46 dB. The noise temperature (Te) of the device is $\log^{-1}$- [F/10)-1] times the operating temperature of the device. The typical laser is peltier cooled and operates at 296K ambient or 24.7 dBK. Since F is typically 4×10^{4} dB an adequate approximation for Te is $F_{(dB)}$ + $24.7_{(dBk)}$.

The noise temperature contributed by the fiber link can be washed out by selecting a low noise RF preamplifier that provides a net gain 22 dB higher than the link's effective noise temperature. Typically, the gain will compensate for the fiber-link power gain (loss) and wash out the noise temperature contributed by the TM receiver being driven by the link. To achieve maximum dynamic range, the amplifier gain should be selected to cause its final RF stage to go into compression after the laser transmitter starts to limit (+ 15 dBm typically).

Instead of employing a single high-gain amplifier, it is best to use two RF amplifiers in cascade with provision for automatically bypassing the final driver amplifier in order to extend the dynamic range.

Figures 1 A and 1 B are the noise temperature block diagrams for a coaxial cable link system and an optical fiber link system. In both systems an LNA is employed at the tracking antenna feed, and a power amplifier is employed at the base of the pedestal to drive the RF cable or laser transmitter. A foam dielectric cable 700 meters in length is compared to a 700 meter long fiber cable. The coaxial cable has an insertion loss of 35 dB, while the fiber cable and connectors has an electrical loss of 2.5 dB or twice the optical loss of 1.25 dB. A

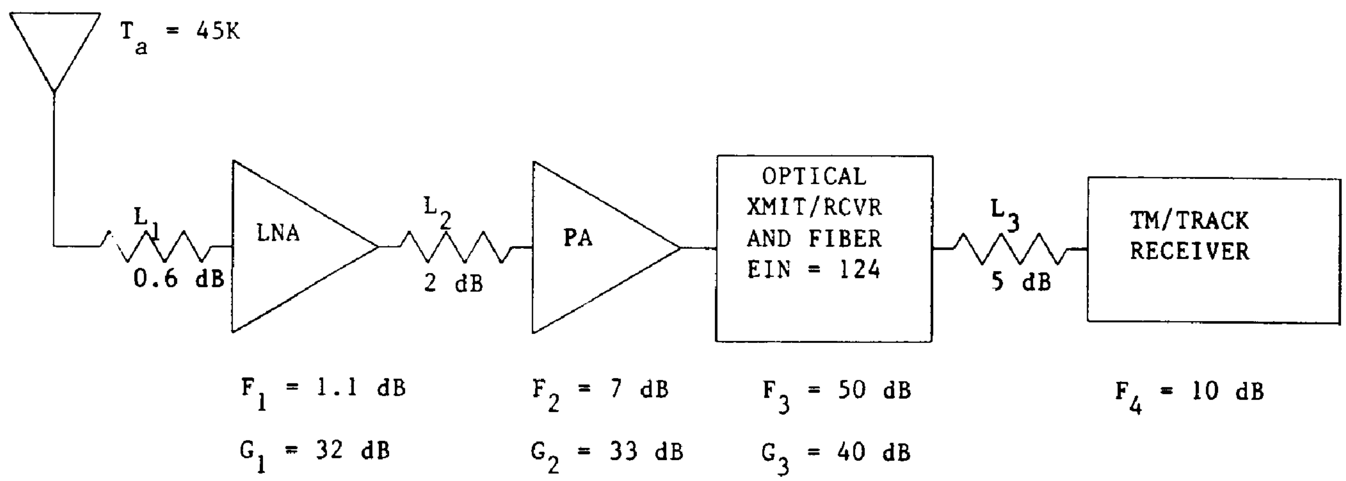
FIGURE 1 A COAXIAL CABLE LINK SYSTEM



$$T_s = T_a + (L_1 - 1)\, T_o + L_1\, (F_R - 1)\, T \qquad T_o = 300K,\ T = 240K$$

$$F_R = F_1 + \frac{L_2F_2 + 1)}{G_1} + \frac{L_2\,(L_3L_4F_3 - 1)}{G_1\,G_2}$$

FIGURE 1 B FIBER-OPTIC LINK SYSTEM



$$T_s = T_a + (L_1 - 1)\, T_o + L_1\, (F_R - 1) \qquad T_o = 300^{o}K,\ T = 290K$$

$$F_R = F_1 + \frac{L_2F_2 - 1}{G_1} + \frac{L_2(F_3 - 1)}{G_1G_2} + \frac{L_1G_3(L_3F_4 - 1)}{G_1\,G_2}$$

5 dB loss is assumed for the RF distribution network and patch panel. (Note that a 800 meter long cable could be used if an active multicoupler replaces the RF distribution network.) In Figure 1 B, the coaxial cable is replaced by the optical fiber link having a 50 dB noise figure (EIN = - 124) with power gain of -40 dB.

Using Friis' formula, the system noise temperature, referenced at the antenna, for the coax system of Figure 1 A is calculated in the usual manner where the 0.6 dB of antenna feed loss is used in each downstream calculation. The 63 dB net gain upstream of the 700 meter long cable compensates for the 40 dB of cable attenuation, leaving an excess of 22 dB to reduce the noise contribution of the data/tracking receiver. The resulting noise temperature is 202.1 K.

The system noise calculation for the RF fiber optic link of Figure 1 B is accomplished in the same manner. The net gain of 63 dB upstream of the laser transmitter adequately reduces the noise temperature contribution of the laser, but is 6 dB short of fully compensating for the downstream noise sources. The calculated system noise temperature is 253.2K. Were it not for the dynamic range problem, one could increase the gain of the power amplifier an additional 6 dB. An alternative method is to use a distributed feedback laser with an optical isolator to reduce link noise. With this improvement, noise figure of the fiber link is 44.5 dB (EIN = -129.5 dBm/Hz), the power gain loss is only -35.5 dB, and the resulting system noise temperature is 208.2K. (The same noise temperature can be attained by a fiber 6 kilometers long by using fiber in lieu of an optical attenuator that protects the photodiode.)

For fiber links greater than 15 kilometers in length, the noise contributed by the photodiode receiver becomes the critical factor. Here again, performance of the standard optical receiver module can be improved by utilizing active or reactive, rather than a resistive impedance matching devices at the diode output. Using a close-coupled active RF amplifier having a 5 dB noise figure and a gain of 12 dB, the fiber link noise figure of 44 dB is achieved and the power gain is reduced to -36.5 dB for a 15 kilometer link. Further, the added amplifier helps to wash out the noise contribution of the RF distribution network and receiver, but does not reduce the dynamic range of the system. The resulting noise temperatures for a 15, 20, and 25 kilometer link are 192.9K, 198.7K and 218.6K, respectively.

Once the lower, limit of EIN is reached, one has no alternative but to increase the gain of the power amplifier and to adopt measures to achieve the desired system dynamic range. For example, a gain increase of 2 dB lowers the system noise temperature of the 25 kilometer link from 218.6K to 203.1 K, but compresses the system dynamic range by an additional 2 dB. The RF gain will have to be increased approximately 0.6 dB for each additional kilometer of high quality single mode fiber cable to compensate for both the increased noise and power gain loss.

REMOTE CONTROL OF THE ANTENNA/PEDESTAL

Hard-wire cabling from the antenna control unit at the control console to the antenna/ pedestal is limited to 200 meters in length. Besides being bulky, heavy and expensive, it is susceptible to EMI, lightning, and is not secure.

Antenna/pedestals have been successfully “remoted” using full duplex telephone lines at a 4800 BAUD rate, and via full duplex microwave links at 9600 BAUD rates. For both cases, a modem, a multiplexer and a microprocessor-based control unit, were employed at each end of the transmission line. At these BAUD rates, a refresh rate of at least 10 times per second is achieved. The time division multiplexer/demultiplexer allows one to address three or more different devices, such as a Wake-Up Device, T.V. Camera, Antenna Control Unit and/or a computer.

Using two inexpensive optical fibers and replacing each modem with an inexpensive optical transmitter/receiver pair, the same technique used by microwave commutation links may be employed. Now, the wide bandwidth available with a fiber cable allows extremely high data transmission rates. The logical candidate for a high-speed interface is MIL-STD-1553B which accommodates data rates to 2.5 megabytes/sec and eliminates the need for a multiplexer and a microprocessor-based control unit at the pedestal.

This design employs a MIL-STD-1553B Manchester II encoded digital interface coupled to a fiber-optic transducer to relay data and commands between the antenna control unit and the antenna pedestal. The link is transparent to the EMP Model ACU-6 Controller which will continue to close the autotracking loop (digitally) via a pair of angle error demodulators. The details of this design will be presented in a subsequent paper.

CONCLUSIONS

The recent development of semi-conductor lasers and photodiodes have made practical the transmission of wide-band amplitude-modulated radio frequency signals as well as television video over single mode optical fiber transmission lines. This new technology coupled with the highly developed digital communication fiber-link technology, make practical, and cost effective, the remote control of an unmanned autotracking antenna pedestal. Telemetry tracking data receivers and an antenna control unit can now be located at the operator's control console up to 15 miles away, in a controlled environment without use of repeater amplifiers. A high speed full duplex data link allows the autotracking loops to be closed (digitally) via a microprocessor based antenna control unit, and the simultaneous control of remote T.V. camera and zoom lens. These high speed wide-band links make control and response virtually instantaneous to the operator.

REFERENCES

1) RF Microwave Fiber Optic Link Design Guide, Ortel Corporation.

ACKNOWLEDGMENTS

R.A. Potter, C.W. Chandler, Electro Magnetic Processes, Inc. (EMP), for editing and constructive comments.

W.G. Grimes, Ortel, Corporation, for loan of optical fiber equipment and assisting in experiments.

E.J. McAvoy, AML, for loan of calibrated power amplifier.