A Review of Coherent Optical Communication

Gerd E. Keiser, Donald H. Rice, and Stephanie White Quinn

Communication Systems Division
GTE Government Systems Corporation
77 "A" Street, Needham Heights, MA 02194-9123

ABSTRACT

Coherent optical communications for fiber transmission media are being seriously considered for both commercial and military applications. A variety of modulation schemes have been examined both in the laboratory and in field trials to verify the feasibility of this transmission technique using optical fibers. This paper will review coherent transmission techniques including optical heterodyne receiver concepts, implementation considerations, and device requirements. Some generic applications of these techniques to military communication systems will then be discussed.

INTRODUCTION

A great deal of research effort on optical fiber technology has been expended in the past ten years by all branches of the Armed Forces. Fiber optic links are used in a wide variety of military systems including aircraft, ships, base communications, and sensor systems, and further applications are emerging rapidly. Recent interest in this area has included examining different techniques of superimposing information onto the optical carrier in order to increase both the information capacity and the repeaterless transmission distance of an optical link. This can be achieved with coherent optical communications whereby information is transmitted through variations in either the amplitude, frequency, or phase of an optical carrier. Coherent fiber optic communications are considered the fifth generation of fiber optic communication systems. Figure 1 shows the capabilities of each generation of fiber optic systems in terms of repeater spacing and bit-error-rate.

SYSTEM COMPARISON

Figure 2 shows a typical intensity-modulated/direct-detection (IM/DD) fiber optic system. In intensity-modulation, the output optical power of the source is proportional to the input signal voltage. The information is placed on the carrier by varying the input signal voltage, which in turn varies the output optical power of the source. The source optical carrier itself consists of many optical waves which are unrelated in phase and frequency to each other and to the modulation. In direct-detection, the optical signal is detected at the receiver and directly converted into an electrical signal. The electrical signal is then amplified. No frequency conversion or sophisticated signal processing at lower frequencies is required. Intensity-modulated/direct-detection fiber optic systems are simple and less costly to implement.

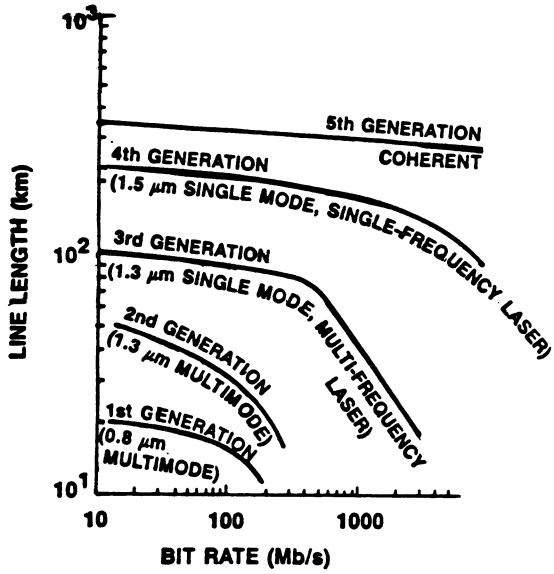

Figure 1. Five Generations of Fiber Optic Systems

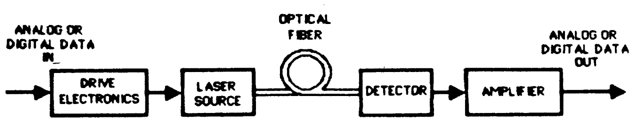

Figure 2. An Intensity-Modulated/Direct-Detection Fiber Optic System

Coherent fiber optic transmission techniques are similar to those used in microwave systems.

CH85CH2202-0/85/0000-0065 $1.00 © IEEE

At the transmitter, the information is placed on the carrier wave by altering the source's amplitude, frequency, or phase. The signal is then carried over the medium. At the receiver, a local oscillator locks with the incoming transmitted signal's phase. Both signals are mixed in a nonlinear device, filtered, and the information is then recovered.

Figure 3 shows a typical coherent fiber optic communication system. The highly-stable laser source emits a very narrow band of optical frequencies. The optical wave of the laser source is temporally and spatially coherent. This means that at a given time at a given point in space, the laser's field will be in phase. By using the coherence properties of the laser's optical carrier wave, information may be placed on the carrier wave by modulating its amplitude, frequency, or phase. This is called coherent modulation. The optical signal is then transmitted along singlemode optical fiber.

At the receiver, the incoming carrier wave is optically mixed with a local oscillator wave emitted by a highly-stable coherent laser. The non-linear, square-law detector detects the mixed optical signals as a single optical wave, and converts it into an electrical signal. The resulting output electrical current contains the square, sum, and difference frequencies of the transmitted and local oscillator signals. Since the difference frequency is the lowest and contains the desired information, it is more easily processed than the square and sum frequencies which are filtered out. If the local oscillator and transmitted signal frequencies are equal, then the difference frequency will be zero and the information will be recovered at baseband. This process is called homodyne detection. However, if the local oscillator and transmitted signal frequencies are different, then the information must be recovered from the difference frequency (or intermediate frequency) electrically. This process is called heterodyne detection.

A coherent fiber optic system does not necessarily imply that coherent demodulation is performed in the receiver. Rather, the term "coherent" as applied to fiber optic systems generally refers to any fiber optic system that uses a laser source with a spectral linewidth considerably narrower than the linewidth of the laser sources used in traditional intensity-modulated/direct-detection fiber optic systems.

OPERATIONAL ADVANTAGES

In addition to the advantages fiber optic communications have over wire or microwave communications such as increased security, wide bandwidth, lightweight, immunity to electromagnetic interference, and freedom from electromagnetic pulse effects, coherent fiber optic communication systems have additional advantages over intensity-modulated/direct-detection fiber optic systems. Probably the most written-about advantage is increased receiver sensitivity. Since the detector sees the combined local oscillator and transmitted signal waves as a single wave, the signal detected at the receiver may be greatly increased by raising the local oscillator power. This means that only a very small amount of transmitted signal power has to reach the receiver in order for the information to be retrieved. If the local oscillator power is much greater than the transmitted signal power, shot-noise limited detection will be achieved.

In a coherent fiber optic communication system, the receiver sensitivity may increase by 10 to 19 dB over an IM/DD systsem depending upon the modulation format. In theory, any modulation format used in radio can be used in coherent fiber optic systems. As shown in Figure 4, a 10 to 25 dB improvement in receiver sensitivity is expected when amplitude-shift-keying (ASK) modulation/demodulation with heterodyne detection is used. The best performance is predicted for phase-shift-keying (PSK) modulation/demodulation with homodyne detection. The expected receiver sensitivity is 19 to 34 dB better than for an IM/DD system. Figure 5 shows the minimum detectable power required to achieve a BER of 10^{-9} versus the data rate for various coherent fiber optic systems.

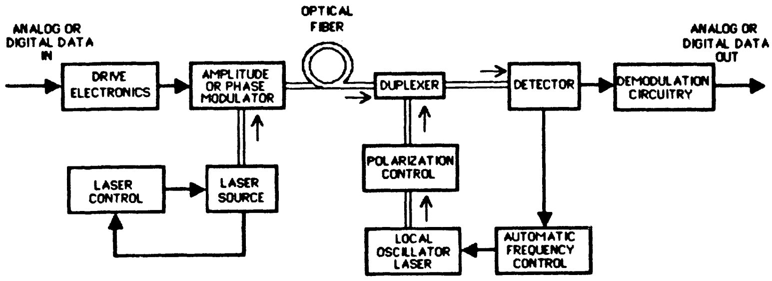

Figure 3. A Coherent Fiber Optic Communication System

3.2.2

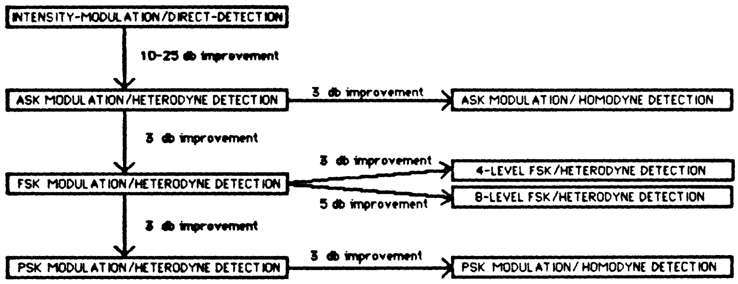

Figure 4. Improvements in the Receiver Sensitivity for Various Coherent Modulation/Detection Schemes

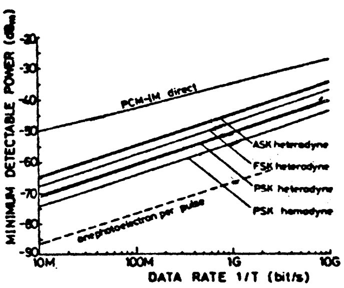

Figure 5. Minimum Detectable Power Required to Achieve a BER of 10^{-9} versus data rate.

As a result of the potential improvement in receiver sensitivity, the transmission distance between repeaters can be significantly increased while transmitting at higher data rates. This is especially true at long wavelengths (1550 nm) where fiber loss is lowest.

Another potential advantage is that optical amplifiers may be easier to implement in coherent fiber optic systems. A repeater could consist of a simple optical amplifier such as a laser diode with optical fiber pigtails.

For short distance links, the increased receiver sensitivity can be used to increase the dynamic range of the system. A greater margin of loss can be allowed to a given link. For example, in local-area-network applications, more splices and terminals are possible.

Another advantage of coherent fiber optic systems is higher channel capacity. Due to the very narrow optical bandwidth of the laser sources and the wide bandwidth of the optical fiber itself, more channels could be transmitted on carriers that are closely spaced in frequency. A thousand-fold increase in channel capacity has been predicted when optical frequency-division-multiplexing (FDM) is used.

SYSTEM IMPLEMENTATION

However, coherent fiber optic systems are more expensive and complex to design and build than intensity-modulated/direct-detection systems. Most of the additional cost and complexity is due to the components used in the systems. For example, the lasers used as the transmitter source and the local oscillator must be spectrally pure. Not only must the lasers emit optical power over an extremely narrow band of optical frequencies, they must maintain their optical frequency stability for long periods of time and over a wide range of temperature. At the receiver, the local oscillator must lock with the incoming transmitted signal. The polarizations of the two wave fronts must match very closely in order for the system to work properly. Polarization-matching of the two waves can be difficult. The detector itself must have a wide bandwidth and high quantum efficiency for converting the low levels of received light into an electrical signal. In addition, practical techniques for performing ASK, FSK, and PSK modulation need to be developed.

The transmitter and local oscillator sources used in coherent fiber optic communication systems must have a high degree of spectral purity and optical frequency stability. A spectrally pure laser emits optical power over a very narrow band of wavelengths. This band of wavelengths is called the spectral linewidth. In intensity-modulated/direct-detection systems, the laser's emission spectrum contains several frequencies spaced approximately 1 nm apart. Each frequency may have a spectral linewidth of around 0.1 nm. In a coherent fiber optic system, the laser must be forced to emit at a single optical frequency. In addition, the natural linewidth of the laser must be reduced. Phase noise due to spontaneous emissions in the laser cavity may cause the natural linewidth to broaden. This is particularly unsuitable for systems using frequency or phase modulation. Thus, in order to use coherent modulation techniques, the unmodulated laser's spectral linewidth must be less than the data bandwidth. The laser's optical frequency must remain very stable over long periods and wide temperature ranges while the laser is modulated. In order to achieve an optical frequency stability of 200 kHz for a 1500 nm wavelength laser, a fractional stability of 1 in 10^9 is needed.

In order for a coherent fiber optic communication system to work properly, the polarization states of the transmitted and local oscillator signals must be nearly identical. If the two signals are not matched, destructive interference will occur due to the different polarization states. Excessive bit errors and receiver fading may result.

There are two approaches to the polarization-matching problem. In the first approach, polarization-matching is achieved by using a polarization-insensitive receiver or a polarization-tracking receiver. Standard singlemode fiber is used as the transmission medium.

In the second approach, specially-fabricated singlemode fibers such as polarization-maintaining singlemode fibers or absolutely single-polarization singlemode fibers are used as the transmission medium. Polarization-maintaining singlemode fibers preserve the polarization state of the signal as it travels through the fiber. Absolutely single-polarization singlemode fibers force the optical signal to travel in only one polarization state.

HETERODYNE/HOMODYNE DETECTION

Heterodyne or homodyne detection techniques are used in coherent fiber optic communication systems. The main advantage of heterodyne/homodyne detection is that the receiver amplifier noise and photodetector dark current noise are effectively eliminated by optically mixing the transmitted signal with a large local oscillator signal. At 1300-nm and 1500-nm wavelengths, heterodyne or homodyne detection are the only methods by which shot-noise-limited detection can be achieved.

In heterodyne detection, the optical frequencies of the transmitted and local oscillator signals are different. Figure 6 shows a block diagram of a receiver using heterodyne detection. The local-oscillator optical signal is combined with the incoming optical signal in a duplexer and detected. The resulting electrical output signal contains the square, sum, and difference (or IF) frequencies between the two signals. Since the IF frequency is lowest and contains the desired information, the square and sum frequencies are filtered out. Part of the filter's output signal may be sent back to the local oscillator to stabilize the laser. The rest of the filter's output is demodulated and sent to the decision circuitry.

In heterodyne detection schemes, the carrier-to-noise density increases as the local oscillator power increases. However, a low-noise front-end amplifier and a high-power local oscillator with minimized AM quantum noise is necessary in order to achieve an optimum carrier-to-noise ratio.

Receiver sensitivity using heterodyne detection is at least 10 to 15 dB better than in intensity-modulated/direct-detection systems. As shown in Table 1, PSK/heterodyne detection is the most sensitive of the heterodyne detection schemes with only 18 photons theoretically required to achieve a BER better than 10^{-9}.

Another advantage of heterodyne detection techniques over IM/DD techniques is that a better BER can be achieved for a given signal-to-noise ratio.

Table 1. Minimum Detectable Peak Power Level in Photons Per Bit for a 10-9 Error Rate

MODULATION \ RECEIVER	HETERODYNE	HOMODYNE	DIRECT DETECTION
INTENSITY MODULATION	-------	-------	21
AMPLITUDE-SHIFT-KEYING	72	36	-------
FREQUENCY-SHIFT-KEYING	36	-------	-------
PHASE-SHIFT-KEYING	18	9	-------

In homodyne detection, the optical frequencies of the transmitted and local oscillator signals are the same. Figure 7 shows a block diagram of a receiver using homodyne detection. The local oscillator optical signal is combined with the incoming optical signal in a duplexer and detected. The resulting IF frequency is zero, and the electrical signal is recovered at baseband. The electrical output of the baseband amplifier filter provides phase and frequency control of the local oscillator laser.

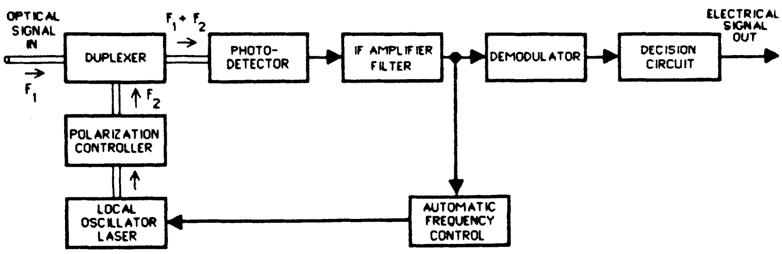

Figure 6. Optical Heterodyne Receiver

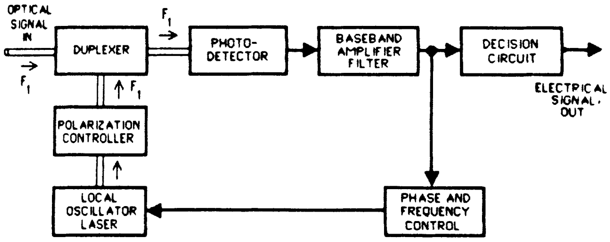

Figure 7. Optical Homodyne Receiver

Receiver sensitivity using homodyne detection is 3 dB better than in heterodyne detection for the same modulation format. As shown in Table 1, PSK/homodyne detection is the most sensitive detection technique with only 9 photons theoretically required to achieve a BER better than 10^{-9}. Homodyne detection also has twice the data rate capability of a heterodyne detection receiver for the same receiver bandwidth.

However, there have been indications that the linewidth requirements for the laser source used in homodyne systems are much more stringent than for laser sources used in heterodyne systems.

In addition, actual synchronization of the local oscillator wave with the transmitted signal wave is difficult to achieve, particularly at low received-signal power levels.

APPLICATIONS

Coherent fiber communication techniques are the only methods which can exploit the potential long-distance and wide-bandwidth capabilities of optical fibers. At the present time, the longest unrepeatered transmission distance can be achieved at 1550-nm wavelength. The theoretical bandwidth of singlemode fiber for wavelengths of 1550 nm to 1700 nm is 24,000 GHz.

Very long-distance underwater and terrestrial repeaterless links are possible using coherent fiber optic communication systems. The number of repeaters required for a transoceanic link can be substantially reduced by increasing the transmission distance of each section of the link.

Fiber optic cables less than 300 km long can be used in underwater communication links connecting either two on-shore locations or an on-shore location with a platform located at sea. In such a configuration, no repeaters are required--only the terminal equipment at the on-shore or platform locations are needed. To upgrade to a higher data rate system, the terminal equipment is simply changed.

Long-distance ground links 100 to 300 km long are another possible application of coherent fiber optic systems. In a fixed installation or in the field, this additional 15 to 24 dB link margin could be used to extend the lifetime of a fiber optic system. Thus the system would be allowed a wider margin to degrade before failure.

In a nuclear environment using a survivable fiber optic communication system, a coherent fiber optic communication system is expected to recover more quickly than an intensity-modulated/direct-detection system. After a nuclear burst, the fiber attenuation suddenly increases and then gradually decreases to a point where enough detectable power reaches the photodetector. Since the receiver in a coherent fiber optic system requires less detectable power than a IM/DD system, the coherent fiber optic system will resume operation sooner.

Coherent fiber optic communication systems are also suitable for short-distance applications. By using the wideband potential of this technology, city-wide or local networks that provide CATV, interactive viewphone, or teleconferencing facilities to many users in homes and offices is possible. More channels can be distributed to more customers.

Because of the laser launch powers and receiver sensitivities of coherent fiber optic systems, optical insertion losses of 40 dB or more can be tolerated. This feature can be used to increase the optical switching and branching capabilities of local area networks.

Coherent fiber optic techniques are also suitable for short-distance military systems requiring very high signal-to-noise ratios. In the tactical environment, 1-km lengths of connectorized fiber optic cables are required. By using coherent fiber optic techniques, the total length of a link could be extended by 15 to 24 km.

Coherent fiber optic techniques make possible true optical frequency division multiplexing (FDM). Large numbers of channels can be frequency-multiplexed over a singlemode fiber. A possible military application is an overlay-type system where different kinds of signals are transmitted. Such a system might include a 20 Mb/s digital channel for backbone communications, a video channel, and a 200 Mb/s digital channel for the computers in a local-area network.

A multi-level-security (MLS) communication system is another potential government application that utilizes the optical FDM capability of coherent fiber optic systems. In a MLS system, one band of frequencies would be dedicated to top-secret communications, another band of frequencies to secret communications, and a third band would be used for unclassified communications.

CONCLUSION

Coherent fiber optic communication is certainly a challenging technology that still requires more research and investigation. Data from experimental systems indicate that theoretical system performances can be achieved, and the government has already shown interest in these systems. As the trend toward higher data rates continues, coherent fiber optic techniques are the only methods which can fully exploit the long-distance and wide bandwidth potential of fiber optic systems.