Tutorial

Coherent transmission systems

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Abstract

Coherent optical communications were studied extensively in the 1980s; however, their R&D activities have been interrupted for almost 20 years behind the rapid progress in high-capacity WDM systems using EDFAs. In 2005, the demonstration of the digital coherent receiver stimulated a widespread interest in coherent optical communications again. This is because such receiver enables us to employ a variety of spectrally-efficient multi-level modulation formats. In addition, we can realize post-processing functions such as compensation for GVD and PMD in the digital domain.

In this lecture, after talking about the history, we discuss state-of-the-art coherent technologies and challenges for the future.

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Kazuro Kikuchi was born in Miyagi Prefecture, Japan, on March 6, 1952. He received his Ph.D. degree in electronic engineering from the University of Tokyo in 1979. Since 2008, he has been a professor at the Department of Electrical Engineering and Information Systems, University of Tokyo, and since 2002, a board member of Alnair Laboratories Corporation, Japan.

His work has been on the optical communication system. He is especially interested in coherent optical communication systems that realize multi-level modulation formats with high spectral efficiency.

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Extended Abstract

The coherent optical receiver down-converts the whole optical signal linearly to an electrical signal by means of heterodyne or homodyne detection. The shot-noise limited receiver sensitivity can be achieved with a sufficient local oscillator (LO) power. In addition, the ability of phase detection can further improve the receiver sensitivity compared with the IMDD system.

Using high receiver sensitivity achieved by the coherent receiver, a number of research groups challenged unrepeated long-distance optical transmission experiments in the 1980s. However, the invention of EDFAs made the shot-noise limited receiver sensitivity of the coherent receiver less significant. This is because the signal-to-noise ratio (SNR) of the signal transmitted through the amplifier chain is determined from the accumulated amplified spontaneous emission (ASE) rather than the shot noise. Technical difficulties inherent in coherent receivers could not also be disregarded. The heterodyne receiver requires an intermediate frequency (IF), which should be much higher than the signal bit rate. The homodyne receiver is essentially a baseband receiver; however, the complexity in stable locking of the carrier phase drift has prevented its practical applications. From these reasons, further R&D activities in coherent optical communications have almost been interrupted for twenty years. On the other hand, rapid progress in EDFA technologies entirely changed the direction of R&D in optical communications. The EDFA-based system started to take benefit from WDM techniques to increase the transmission capacity of a single fiber, and brought forth 1,000 times increase in the transmission capacity during the 1990s.

With the transmission-capacity increase in WDM systems, coherent technologies have restarted to attract a large interest over the recent years. The motivation lies in finding methods of meeting the ever-increasing bandwidth demand with multi-level modulation formats based on coherent technologies. The new stage has opened up with high-speed digital signal processing. The recent development of high-speed digital circuits has offered the possibility of treating the electrical signal in a digital signal processing (DSP) core and retrieving the IQ components of the complex amplitude of the optical carrier in a very stable manner. Using the phase-diversity homodyne receiver and the succeeding DSP, the author has demonstrated demodulation of the 20-Gbit/s QPSK signal. While an optical phase-locked loop (PLL) that locks the LO phase to the signal phase is still difficult to achieve, DSP circuits are becoming increasingly faster and provide us with simple and efficient means for estimating the carrier-phase drift.

Any kind of multi-level modulation formats can be demodulated by the coherent receiver. While the spectral efficiency of binary modulation formats is limited to 1 bit/s/Hz/polarization, modulation formats with bits of information per symbol can achieve up to the spectral efficiency of bit/s/Hz/polarization. QPSK (M=2), 8PSK (M=3) and 16QAM (M=4) formats are examined at >10 Gsymbol/s.

The polarization sensitivity of the coherent receiver was one of the most serious disadvantages of the conventional coherent receiver. However, this problem has been overcome by introducing polarization diversity into the digital coherent receiver, where polarization alignment can be done in the digital domain. Moreover, electrical demultiplexing of the polarization-division multiplexed signal has also been demonstrated to increase the transmission capacity twice.

Another advantage of the digital coherent receiver is the post signal-processing function. The demodulation process by the coherent receiver is entirely linear; therefore, all the information on the complex amplitude of the transmitted optical signal including the state of polarization (SOP) is preserved after detection. We can thus perform signal processing such as chromatic-dispersion compensation and polarization-mode dispersion (PMD) compensation at the electrical stage. It should be stressed that although PMD is time varying, the digital coherent receiver can equalize it in an adaptive manner.

Real-time operation of the coherent receiver at 11.5 Gsymbol/s, recently reported by the Nortel group, is really a milestone in the development of the modern coherent optical communication. By using the QPSK modulation format and polarization multiplexing, 46-Gbit/s transmission capacity has been obtained in the real-time mode of operation.

The combination of coherent detection and DSP provides new capabilities that were not possible without detection of the phase of the optical signal. We believe that the born-again coherent optical communication system will innovate on the existing optical communication system in the near future.