◆一般論文◆

1 Tbps光送受信技術

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Detection of a 1Tbps Superchannel with a Single Optical Receiver

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要　旨

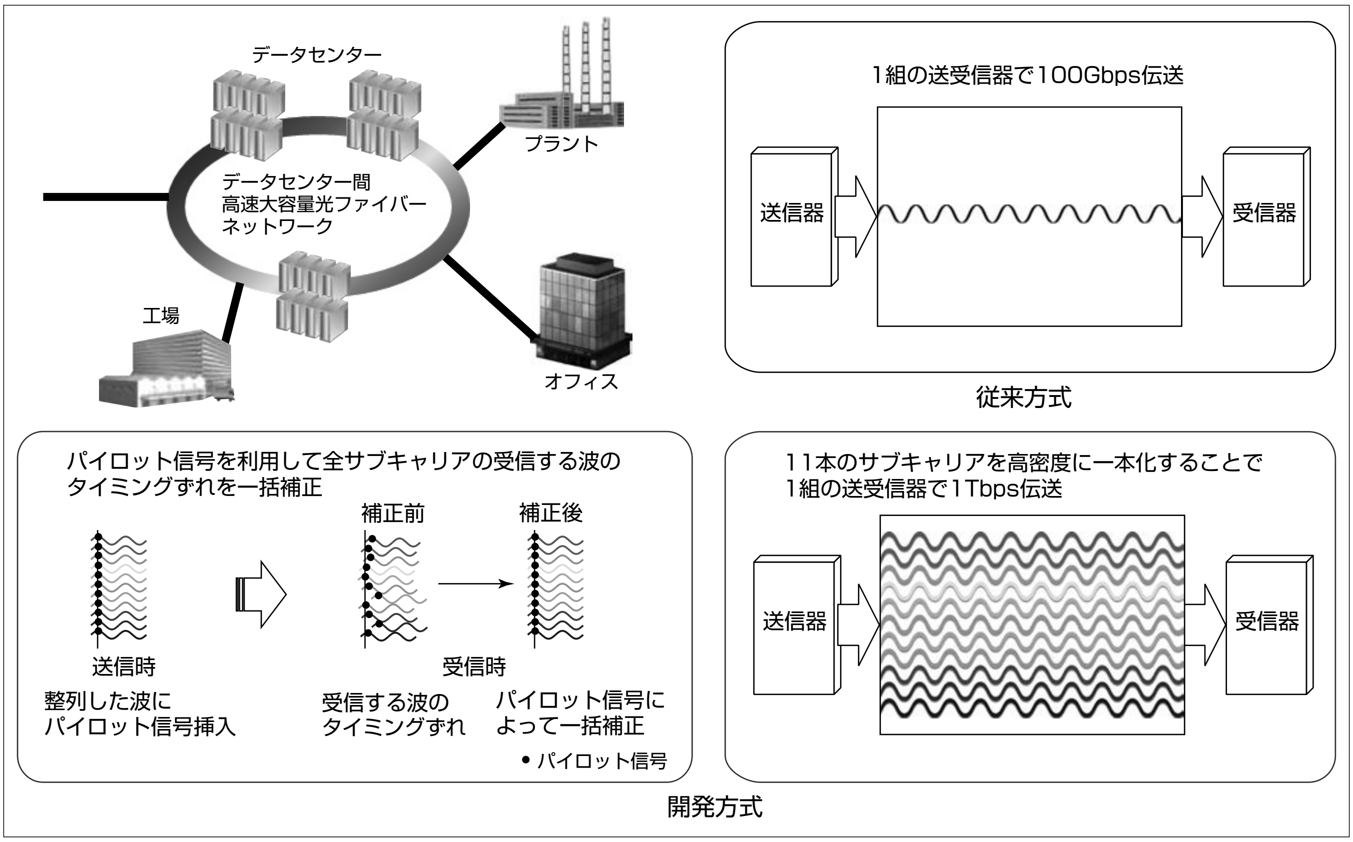
インターネットやスマートフォンの普及に加え，IoT(Internet of Things)時代にはあらゆるモノとモノがネットワークを介して接続されるため，それに伴った通信量の爆発的な増大が予想されている。一方，使用した通信量に応じた課金の不要なOTT(Over The Top：SNS(Social Networking Service)や動画配信サービスなど)が多様なサービスを提供しており，通信量が増大してもそれに応じた課金収入増加が見込めなくなりつつある。今後は，データ通信の大容量化とともに高いコストパフォーマンスが問われるため，敷設済みの光ファイバー網を活用した容量拡大技術が重要となる。

従来の敷設済みの光ファイバー網では，１組の送受信器での伝送速度が100～200Gbpsであったが，今回その５～10倍となるデータ伝送速度１Tbpsを実現する技術の基本方式を確立した。開発方式は次の特長を持つ。

(1) 11本のサブキャリアを高密度に一本化して送受信するマルチサブキャリア光送受信技術によって，既設の光ファイバーを用いて１組の送受信器で伝送速度１Tbpsを実現した。

(2) 送信器側で各サブキャリアにパイロット信号(送受信間で定められた信号パターン)を定期的に挿入し，受信器で全サブキャリアが受信するタイミングを一括補正することで受信性能を向上した。

(3) パイロット信号に加え，高度なエラー訂正符号によって高い周波数利用効率を実現した。



光通信ネットワークの大容量化技術

データセンター間のコアネットワークは光ファイバーによる高速大容量通信で接続されている。敷設済みの光ファイバー網を置き換えるためには膨大なコストが必要となるが，開発技術を用いることによって敷設済みの光ファイバー網をそのまま用いて更なる大容量化が可能となる。今後実用化に向けた研究開発を進めていく。

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1. Introduction

Optical fibers carry much of the world's data traffic, and the capacity requirements continue to grow at more than 20% annually to support connectivity among people and machines. The Cisco Visual Networking Index forecasts that annual global IP traffic will surpass[1][2]. 1 zettabyte(10^{21}bytes or 1 million million Gigabytes) for the first time in 2016, with the highest growth rates being for mobile and machine-to-machine(M2M) applications with 74% and 71% growth per year respectively.

One important factor restricting capacity is the data rate for each optical receiver, which is currently limited to 100-200Gbps for commercial systems. In this article, we describe recent work at MERL (Mitsubishi Electric Research Laboratories, USA) in which we experimentally achieved a capacity of 1Tbps (1,000Gbps) using a single optical receiver : a 5-10× improvement over current commercial systems[3]. The technology is suitable for use with existing fiber plants allowing for a smooth upgrade path.

Obtaining the ultra-high capacity achieved in this work required innovation in the coherent optical transmitter and receiver, new pilot-aided digital signal processing algorithms[4], and advanced error correction codes. We were able to transmit a gross bit rate of 1.32Tbps, which after removing overhead for coding and pilot symbols resulted in 1.01Tbps user data rate, with an estimated bit error rate (BER) of below 10^{-15}, the standard BER requirement for deployed optical systems. The experiment also achieved a spectral efficiency of 9.2bps/Hz, which as of January 2016, was the highest in the world in a 1Tbps transmission using a single optical receiver suitable for existing fiber.

The experimental portion of this work was performed in collaboration with the Optical Networks Group at University College London, UK.

2. Experimental Setup

A traditional coherent optical transmitter uses one laser and a single modulator that is used to impart the data information onto the light wave. To increase the transmitted data rate requires a corresponding increase in speed of optical and electrical devices to avoid distortion, which is becoming increasingly difficult to achieve in practical systems. Instead, in this work, we used a multi-subcarrier approach, where a single laser output was applied to an optical comb generator which creates 11 sub-carriers with equally spaced frequency separation, allowing lower speed optical and electrical devices to be used to obtain the desired data rate[5]. Using an optical comb rather than separate lasers ensured that the subcarriers were very highly matched in terms of frequency and phase. This had two significant advantages. Firstly, it allowed the subcarriers to be very densely packed without causing interference between them and, in turn, increased capacity. Secondly, we were able to exploit the high degree of matching between the subcarriers at the receiver to improve the performance of the decoding process.

A traditional coherent optical receiver uses one laser per channel or subcarrier to convert the modulated light to electrical signals, each with an individual 4-channel analog-to-digital converter. However, recent advances in optical receiver devices and analog-to-digital converters used in this work enabled the conversion of the entire multi-subcarrier signal to be performed in a single step using a single laser at the receiver and a single high speed analog-to-digital converter. This ensured that the highly matched nature of the transmit signals from the optical comb was also maintained at the receiver.

Using these innovative transmitter and receiver architectures we successfully created an 11×10Gbaud dual-polarization 64-ary quadrature amplitude modulation(DP-64QAM) multi-subcarrier transmit signal with a very dense spacing of 10.01GHz and detected the transmitted data using 70GHz bandwidth photodiodes and a 160G Sample/sec 4-channel analog-to-digital converter with 63GHz of bandwidth. The block diagram for the experimental setup is shown in **Fig. 1**, and a photograph of the transmitter equipment is shown in **Fig. 2**.

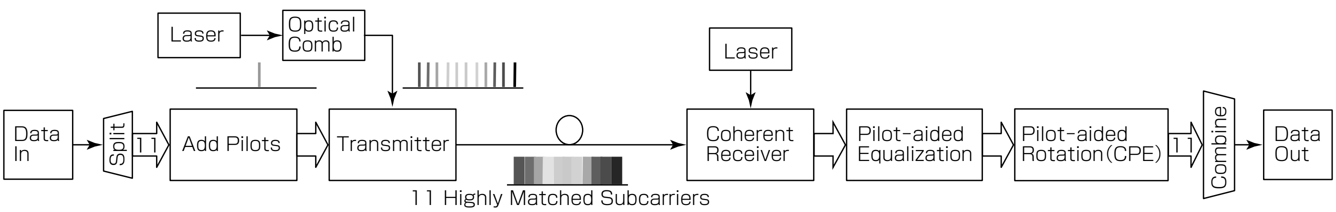

Fig. 1 Transmitter/Receiver Block Diagram

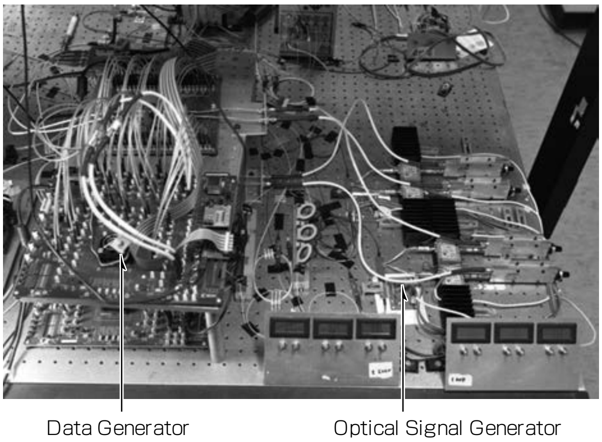

Fig. 2　Transmitter equipment

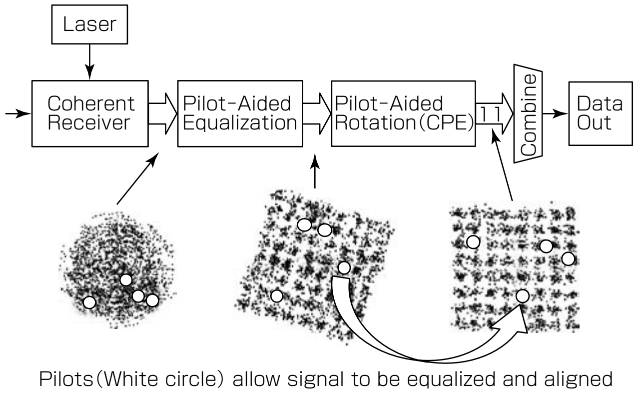

Fig. 3　Pilot-aided DSP for a single subcarrier

3. Digital Signal Processing Algorithms

Once the received optical signal is converted to the electrical domain and then captured to digital samples, a series of digital signal processing algorithms is used offline to compensate for numerous degradation factors caused by the imperfect optical and electrical components and propagation in the optical fiber. In this work, the most important algorithms are the equalizer, which compensates for the non-flat frequency response of the optical and electrical devices, and the carrier phase estimator (CPE), which compensates for the frequency offset and linewidth (random phase fluctuations) between the transmit and receive lasers(6).

In most coherent optical transmission systems, so-called "blind" equalization and CPE algorithms are used, which make limited assumptions about the signal characteristics in the adaption processes(7). The algorithms are simple to implement and are suitable for QPSK modulation. However, in this work we utilized 64QAM to increase data rate, and for these multi-level formats, blind algorithms suffer from very poor performance when there are significant symbol errors. Instead, we utilized an initial training mode where known data symbols are transmitted continuously, allowing the adaptive algorithms to converge accurately, followed by a pilot-aided mode where known data symbols are inserted into the random information data stream at a low rate (1%), allowing the adaptive algorithms to accurately track temporal variations.

Training and pilot-aided operations are well known in wireless communications but are not typically utilized in optical communications systems, partly due to the overhead of the pilots, which reduces available user data. A key innovation in this work was to utilize the highly-matched nature of the subcarriers created by the optical comb at the transmitter (and maintained at the receiver through the simultaneous conversion of all subcarriers using a single coherent receiver) to allow carrier phase estimation to be performed jointly across all subcarriers rather than individually. This allowed the phase of subcarriers with very poor error rate (up to 14% errors) to still be tracked with the assistance of other subcarriers with lower error rate, while still achieving a post-error correction BER of $<10^{-15}$. This joint processing allowed the pilot insertion ratio to be kept very low (1%), with only a small impact on data rate, while still achieving excellent adaptive algorithm performance. The algorithm was designed to be simple enough to be efficiently implemented in a practical ASIC (Application-Specific Integrated Circuit, the custom chip used to implement the digital signal processing (DSP) and forward error correction (FEC) at the high data rates needed for optical transmission systems). In addition, the superior performance of the pilot-aided CPE compared to blind methods allowed the use of lasers with 100kHz linewidth at the transmitter and receiver. Such lasers are substantially cheaper and smaller than the ultra-low linewidth lasers typically used for DP-64QAM experiments with blind algorithms.

The operation of the pilot-aided equalization and CPE is illustrated in **Fig. 3** for a single subcarrier. The joint estimation process across subcarriers is not shown, for simplicity.

4. Forward Error Correction

The received symbols after the CPE still have significant levels of noise, which will introduce errors in the output data as shown in the right-hand constellation diagram in **Fig. 3**. In fact, the subcarrier shown has a relatively good error rate of

0.8%, allowing the 64 distinct constellation points to be seen, but the BER on other subcarriers was up to 14%, resulting in a constellation whose points cannot be distinguished visually. To correct the bit errors introduced by noise and other residual impairments requires strong forward error correction(FEC).

In this work, we used an optimized irregular low-density parity-check(LDPC) code[8] with rate 0.78 (meaning that for each 78 bits of information that is sent, 22bits of parity code is added for error correction), achieving a theoretical threshold within 0.07dB of the Shannon limit. The information bits are interleaved(spread) over all the subcarriers and polarizations, and a finite block of time, to ensure that the probability of a bit error is approximately constant, which improves code error correction performance and that no bursts of errors occur. After LDPC decoding with 60 iterations, no errors where seen for the duration of the experimental transmission. However, to guarantee a bit error rate of $<10^{-15}$, as required in a practical system, requires $>10^{17}$bits to be transmitted, which is not possible in an offline experiment, such as the one performed. Instead we added another(outer) code, using a 0.9922 rate BCH(Bose-Chaudhuri-Hocquenghem) code with a minimum Hamming distance of 33, for which we can theoretically calculate that the output BER will be $<10^{-15}$ if the input BER is $<5\times10^{-5}$. We transmitted sufficient bits without error(7.8million bits) to ensure such a threshold and so can state that the output error rate after the concatenated code would be below 10^{-15}, as needed.

The addition of pilots and code parity reduces the rate available for user information data compared to the gross data rate. The gross data rate for the experiment is determined from the use of 11 subcarriers, each with a symbol rate of 10 Gbaud, carrying DP-64QAM, which provides 12bits per symbol, and equals 1,320Gbps, or 1.32Tbps. The net data rate available for user data is reduced by the overhead introduced by the pilots(0.99, determined from the 1% pilot insertion ratio), the LDPC inner code rate(0.78), and the BCH outer code rate(0.9922), and equals 1.01Tbps. The experiment achieved a spectral efficiency(SE) of 9.2bps/Hz(1.01Tbps transmission within a bandwidth of 110.11GHz, determined from 11 subcarriers with 10.01GHz spacing), which as of January 2016, was the highest in the world in a 1Tbps transmission using a single optical receiver suitable for existing fiber.

5. Conclusion

This paper has presented the experimental demonstration of a 1Tbps optical transceiver using a single optical receiver and described the novel pilot-aided digital signal processing algorithms and error correction codes that enable such performance. The practical development of such high rate transceivers would greatly aid the capacity of fiber optic links, particularly useful for high growth applications such as mobile backhaul and machine-to-machine communications.

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