論 文 内 容 の 要 旨

Chapter 1: Introduction

Nowadays, the vast majority of worldwide data traffic is transported using optical fibers. The ever-growing data traffic in local area networks (LANs) has placed a bottleneck on system performance. Optical MIMO is dedicated to increasing link capacity by exploiting the space domain, which provides a new dimension in addition to conventional time division multiplexing (TDM), wavelength division multiplexing (WDM) and polarization division multiplexing (PDM). Optical MIMO has great potential for enhancing the capacity by using either brand new multicore fibers, defined as space division multiplexing (SDM), or multimode fibers, defined as mode division multiplexing (MDM). The large installed multimode fiber base is seeing an upgrading to newly developed multicore fibers, though, dedicated components such as connectors, amplifiers, etc. should also be developed correspondingly. Optical MIMO based on coherent detection needs local oscillators to interfere with incoming optical fields at the receiver end, in order to keep a linear down conversion process, therefore the complexity and cost are increased considerably, indicating that direct detection is a preferable choice. As far as MDM is concerned, conventional intensity modulation direct detection (IMDD) and subcarrier multiplexing (SCM) schemes show disability as optical fields of different channels spatially overlapped, which would result in detrimental cross terms upon square-law detection. In spite of aforementioned difficulties, the potential capacity brought by multimode fibers is certainly worth the effort.

In this dissertation, a direct detection implementation using SCM-SS scheme for optical MIMO transmission over multimode fiber links is proposed. Achievements of this research are summarized, and the promises and challenges of such systems are explored.

Chapter 2: SCM-SS scheme

The basic idea of SCM-SS scheme is to overcome intermodal coupling incurred impairment in direct detection regime. Transmitter of each channel consists of subcarrier multiplexing (SCM) and spread spectrum (SS) modulation, denoted as SCM-SS. The motivation of SCM is to produce a modulated single sideband with an optical carrier, which can be self-heterodyned through square-law detection, moreover it is able to relieve the impairment of chromatic dispersion. Spread spectrum modulation is to phase modulate the optical field created by SCM with a sequence of spectrum-spreading code, herein each channel is assigned a unique signature. Different modal power distributions are excited by different channels at the fiber input facet, each channel will experience a different propagation procedure, that is, carried by different set of modes with different fractions of power, until arriving at the receiver side. At the receiver side, every detector receives a collection of optical fields from different channels, attempts of decomposing channels in optical domain are not needed. Since each channel experienced a different propagation procedure, time delay was translated into a phase delay, we may take benefit from the multipath scattering environment provided by multimode fiber. The phase noise in optical carrier of each channel using individual laser behaves independently. Providing optical fields of different channels coupled together, upon square-law detection, the interaction of phase noises would also appear in RF band, along with the information-bearing RF signals. The impairment from laser phase noises may totally corrupt the transmission. By employing the spread spectrum technique, the phase noise induced impairment is spectrally broadened, so the power of phase noise containing terms in-band are dramatically suppressed. In the context of IMDD implementation, spatial overlap among fields of different channels should be reduced as much as possible in order to keep a linear relation with respect to optical intensity, otherwise with the advent of cross terms, it is unable to compensate for interferences among channels by MIMO signal processing. SS technique can be incorporated in IMDD to suppress cross terms, though, phase modulated constellations are not supported in the absence of subcarrier.

Transmitted symbols are recovered by MIMO signal processing. The real-valued bandpass signal is turned to complex lowpass equivalent through Hilbert transform. The sampled (at symbol rate) lowpass equivalent corresponding to each receiver can be expressed as a linear combination of transmitted symbols, and the input output relation can be represented in matrix form. The variation rate of multimode fiber channel is much smaller than the data rate, which is hence categorized into slow fading channel. The channel can be steadily tracked by sending training symbols, and is valid for the whole frame duration. All the

channels are frame synchronized, and each channel is allocated with a unique sequence of training symbols.

Impairments in optical MIMO transmission such as laser phase noise, thermal noise, modal noise, shot noise, etc., are analyzed.

Chapter 3: Numerical investigations

This chapter focuses on numerical investigations of SCM-SS scheme over nondispersive and dispersive channels.

Transmission over nondispersive channel. Numerical modeling is described. Power constraint is applied to each channel, that is, all the channels are allocated with equal power. Such a function is described by polarization beam splitter model. Simulation based on polarization beam splitter (PBS) model investigates the feasibility and performance of SCM-SS scheme. Condition number is introduced as a useful metric that determines the performance of MIMO communication systems. Degradation in performance is observed as different channels mixing more and more, noise enhancement mechanism is analyzed by singular value decomposition (SVD). Theoretical analysis on the generation of single sideband optical field through Mach-Zehnder modulator (MZM) is given.

Corresponding experiments are conducted based on a pair of PBS. Optical fields of two channels are coupled to the two orthogonal optic axes of the first PBS, by adjusting polarization controller, the optical fields projected on the optic axes of the second PBS are coupled fields from the two channels. No differential path delay is introduced during propagation.

Transmission over dispersive channel. Multimode fiber dispersion model is deduced.

Physical characteristics of multimode fiber are more involved. Simulation of four-mode fiber link confirms the influence of modal dispersion. Parameter dependences such as driving voltage of phase modulator, laser phase noise are discussed.

Statistics such as probability density function (PDF), cumulative distribution function (CDF) based on four-mode fiber link model are investigated. Wideband channel is theoretically elaborated. Intra-channel differential mode delay (DMD) imposes negative influence on system performance because of multipath effect, though, inter-channel DMD induced ISI can be tackled by signal processing.

Four-mode fiber link model is experimentally realized based on translation stage. Beam splitter cubes and half mirrors are placed on the stage to form light paths with different lengths, which is a mimic of four-mode fiber. Beam splitter cube splits incident optical field to p-polarization and s-polarization, half mirror is used to combine optical fields from different channels. Numerical comparison between SCM-SS and SCM are conducted. Referred simulations are experimentally verified.

Chapter 4: Transmission over multimode fiber links

This chapter is dedicated to experimental transmission over multimode fiber links. The feasibility of this approach is verified experimentally by 2×2, 2×4 and 4×4 MIMO systems.

From a statistical viewpoint, 2×4 MIMO can achieve higher diversity gain than 2×2 MIMO, which is thought to improve communication reliability. A 1550nm DFB laser acts as the light source. Binary phase shift keyed (BPSK) data is moved to passband by RF subcarrier, the RF signal is then split to two orthogonal arms by a pi/2 hybrid coupler. A dual-drive MZM is biased at quadrature point, and the two arms of MZM are modulated by the two orthogonal electrical signals respectively. This optical field is then phase modulated by a sequence of spectrum-spreading code. SCM-SS optical signal is split into two channels, one of the channels is delayed by single mode fiber with the intention of decorrelating the two channels. The two channels carried by single mode fibers are coupled to the input ports of a fused multimode coupler through connectors, which will excite lower order modes of graded index multimode fiber (GI-MMF) link. Different link lengths are constituted by 500m and 1000m fiber reels, which are connected by optical connectors. When switching to different link lengths, fiber reels and connectors should be reorganized accordingly, though, stringent adjustments are not exercised, the requirements in alignment are shown to be loose. The output optical fields are directed to photo detectors by another fused multimode coupler. Each detector receives a mixing of signals from both channels. The electrical signals are sampled for off-line MIMO signal processing.

Up to 2000m transmissions have been achieved via SCM-SS scheme. To confirm the advantages of the proposed SCM-SS scheme further, the experiments of SCM scheme that using no spread spectrum technique and IMDD-SS scheme are also conducted. Quantitative comparisons among them are given. Superior performance of SCM-SS scheme compared with SCM and IMDD-SS schemes is exhibited. Strategies that optimize the performance over multimode fiber links are explored.

Chapter 5: Conclusions

Summary

SCM-SS scheme was proposed.

Transmission over nondispersive and dispersive channel has been investigated.

Condition number is introduced as a useful metric that determines the performance of MIMO communication systems.

Noise enhancement mechanism is analyzed by singular value decomposition (SVD).

Generation of single sideband optical field through Mach-Zehnder modulator (MZM) is given.

Satisfactory performance of optical MIMO using SCM-SS scheme is demonstrated in the presence of intermodal coupling, showing its applicability of capacity enhancement in multimode fiber links.

Outlooks

A host of open questions remain to be answered.

The group delay distribution are used to investigate differential mode delay (DMD) and EMBc.

Mitigation of intersymbol interferences in wideband systems where the group delay spread is comparable to the symbol period will be further studied.

Intramodal dispersion such as chromatic dispersion, may also induce impairments to the transmission, although not a main concerning in multimode fiber channel.

Compensation of these impairments leave us work to do.

To improve the data rate further, optical CDMA (OCDMA) is considered, to our knowledge, OCDMA using CW laser sources is encoded in electrical domain, optical domain implementation uses pulsed laser sources, the viability of incorporating in SCM-SS scheme remains to be convinced. To evaluate the performance further, the statistics of multimode fiber channel should also be taken into account. Transmission performance over other types of fibers, such as few mode fiber, plastic optical fiber, etc., leaves us work to do.