Multi-user asynchronous coherent OCDMA system

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Abstract: Key techniques enabling asynchronous coherent OCDMA are discussed: to lower the interference level by ultra-long superstructured FBG encoder/decoder, optical thrtesholder and multi-port encoder/decoder; to enhance noise tolerance of system by forward-error-correction and differential-phase-shift-keying with balanced detection.

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Introduction Optical code division multiple access (OCDMA) is one promising technique other than TDMA, SCMA and WDMA for next-generation broadband multiple access network attributing to *full asynchronous transmission*, *low latency access* as well as *soft capacity on demand*. The encoding/decoding can be done incoherently based on optical power or coherently based on the phase and amplitude of optical field [1]. Recently, coherent OCDMA using ultra-short optical pulse is receiving increasing attention with the progress of reliable and compact encoder/decoder (E/D) devices, such as spatial light phase modulator (SLPM) [2-4], micro ring resonator [5], planar lightwave circuit (PLC) [6], superstructured fiber Bragg grating (SSFBG) [7-8] and arrayed waveguide grating (AWG) multi-port device [9-11].

A multi-user coherent OCDMA system could suffer from severe signal-interference (SI) beat noise if the signal and interferences overlap each other. If the receiver is fast enough to perform the chip-rate detection, the SI beat noise will be the dominant noise source and eventually limits the maximum number of active users that can be supported [1]. However, in a practical multi-user coherent OCDMA system, data-rate detection in the receiver is essential. In this case, another major noise source is the multiple access interference (MAI) noise, which refers to the incoherent interferences [12]. The MAI could be suppressed by employing time gating [3, 6] or optical thresholding techniques [2-6]. But the SI beat noise could not be suppressed effectively as it accompanies with the recovered signal pulse. Therefore, either slot-level or chip-level timing coordination has been applied in previous experiments [2-6] to enable multi-user transmission. Both of them are synchronous approaches that sacrifice the most desired feature of OCDMA: "asynchronism".

In an asynchronous OCDMA network with K active users, the received signal of target user could overlap with the K-1 interferences from undesired users asynchronously as illustrated in Fig.1. Therefore, the challenge is to enable multi-user asynchronous OCDMA in the presence of SI beat noise as well as MAI with data-rate detection.

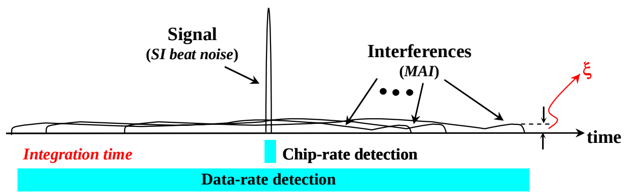

Fig.1. Received signal and interferences in asynchronous OCDMA

Noise suppression techniques

a. Ultra-long OC generation/recognition with SSFBG

One effective approach to suppress the noise level is employing ultra-long optical code (OC) with uniform cross-correlations to lower the interference level ξ. Theoretical analysis has predicted that to support up to K=10 error free ($BER<10^{-9}$) transmission with chip-rate detection, ξ should be lower than -28 dB [1]. Phase-shifted SSFBG E/D is one desired candidate that has the capability to process OC as long as 511-chip with chip-rate as high as 640 Gchip/s [8]. An SSFBG is defined as an FBG with a slowly varying refractive-index modulation profile imposed along its length [7]. The full complex refractive-index modulation profile can be realized in an SSFBG by inserting phase shifts between different segments. This sort of phase-shifted SSFBG can be fabricated with a single short phase mask by continuous grating writing [7] or holographic techniques [8] to provide high flexibility in producing different

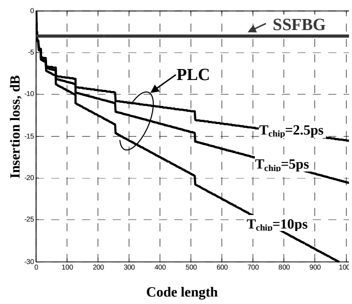

Fig.2. Comparison of insertion loss between PLC and SSFBG

ultra-long optical code. High-precision phase control can be achieved as well for BPSK, QPSK or even more multiple phase level OC.

Besides the unique capability of generating ultra-long OC with ultra-high chip-rate, SSFBG E/D also has other advantages such as polarization independent performance, low and code-length independent insertion loss, which is also essential for ultra-long OC generation compared to PLC type E/D as shown in Fig. 2, inherent compatibility with fiber-optic system, high compactness as well as potential low cost for mass producing. Truly asynchronous multi-user OCDMA experiment has been demonstrated using ultra-long SSFBG E/D [8].

b. Multi-port E/D with high PCR

AWG-based multi-port OCDMA E/D has the unique capability of simultaneously processing multiple time-spreading OCs with one device [9], which makes it a potential cost-effective device to be used in the central office of OCDMA network to reduce the number of E/Ds [10-11]. Another attractive feature of the AWG E/D is that it has very high power contrast ratio (PCR) between auto- and cross-correlation signals compared to other coding devices as shown in Fig. 3. The AWG E/D can reach 15~20 dB PCR in most of the cases, while the PCR of the SSFBG is around 1 dB and SLPM is 0 dB. That means the ξ value could be significantly reduced (up to 20 dB) using the AWG decoder with the same length of code [10]. Therefore, this device has the potential to tolerate more active users at a high data rate. Moreover, flexibility of the OCDMA network can be improved by hybrid using different type of the E/D in a network [11].

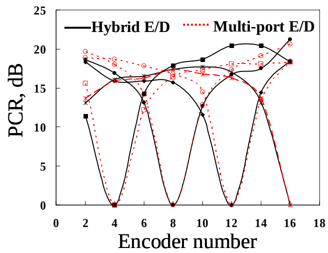

Fig. 3 PCR of multi-port E/D and hybrid E/D

c. Optical thresholding In the coherent OCDMA with ultra-short optical pulse, the properly decoded signal is rather narrow (in a chip time) compared with the bit duration. In a practical system that employs "data-rate" instead of "chip-rate" detection, the MAI noise still remains to be a serious problem. Therefore, applying optical thresholding (OT) technique to remove the MAI noise is crucial to enable data-rate detection for achieving a practical asynchronous OCDMA system [12]. Several optical thresholding techniques have been applied by using nonlinear effect in periodically-poled lithium niobate (PPLN) and different optical fibers. Figure 4 shows an example of eye diagrams (left) and BER performances (right) of OCDMA signals with and w/o OT for different receiver bandwidth [12]. The using of OT is essential to enable data-rate detection.

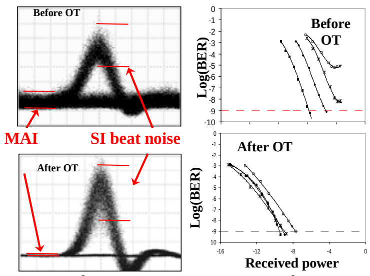

Fig. 4 Performance improvement of using OT

Noise tolerance enhancement

Another kind of approaches to improve the multi-user capability is to enhance the system noise tolerance by:

a. Forward-error-correction (FEC)

FEC is a powerful technique to enhance the system performance. The ITU-T G.709 has recommended the interface for optical transport network (OTN) that consists of RS(253,239) FEC, which can improve the BER with more than 6dB net coding gain. Therefore, including FEC to enhance the system noise tolerance can significantly improve the capacity, particularly the soft capacity of OCDMA system [10, 13]. Figure 5 shows the BER performance improvement of using FEC in a 10 Gbps multi-user OCDMA system [10].

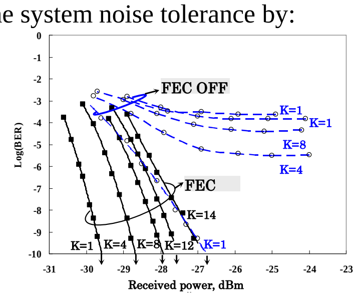

Fig.5. FEC improved BER in OCDMA system

b. Differential-phase-shift-keying (DPSK) with balanced detection

Previously, most OCDMA system used on-off-keying (OOK) modulation for payload data followed by power detection. The OOK-OCDMA has poor multi-user capability, and requires complex real-time K evaluation and dynamic threshold level setting [14]. On the contrary, coherent OCDMA with DPSK modulation format and balanced detection (DPSK-OCDMA) offers the advantages of improved receiver sensitivity, better tolerance to beat noise and MAI noise without OT, and no need for dynamic threshold level setting [11,14]. Figure 6 shows the theoretical and experimental comparison of K vs. ξ for OOK- and DPSK-OCDMA with BER=6×10^{-5}. Theoretical analysis predicts that

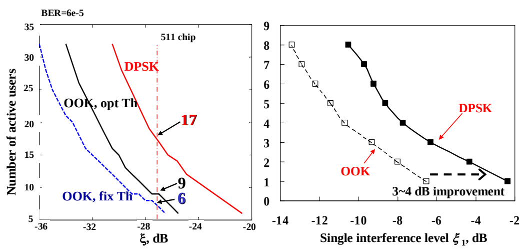

Fig.6. Theoretical (left) and experimental (right) comparison between OOK-OCDMA and DPSK-OCDMA

for a given K, DPSK-OCDMA can tolerate about 4 dB higher ξ comparing to OOK-DPSK with optimal threshold, and this was verified in the experiment with 3~4 dB noise tolerance improvement. Therefore, DPSK-OCDMA is superior to OOK-OCDMA for multi-user coherent OCDMA system.

Multi-user asynchronous OCDMA experiments

In a general asynchronous OCDMA system, the signals from different users should have equal power, random transit delay, random data patterns, random bit phases, and random polarization states. The experimental setup of our multi-user asynchronous OCDMA system is shown in Fig. 7 [8, 10-11]. Fixed fiber delay lines with different lengths were used to randomly set the transit delays and de-correlate the signals from different OCDMA users. Tunable optical delay lines (TODL) were used to investigate the impact of different phases of signal-interference overlapping. Variable optical attenuators were employed to balance the optical power of signals from different users and optical switches were placed to adjust the number of active users. Polarization controllers (PC) were placed as well for investigating the system performance in different scenario. To guarantee that the system can operate in a truly-asynchronous environment, we tested the performances in the worst scenario by adjusting the PCs and TODLs. Here, we'd like to emphasis the difference between *asynchronous* and *synchronous* experiments: in asynchronous OCDMA experiments, TODLs are adjusted to obtain the worst performance of the system [8, 10-11], while in synchronous OCDMA experiments, TODLs are adjusted to obtain the best performance [2-6].

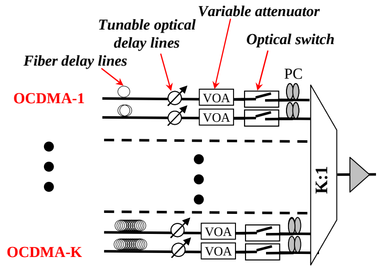

Fig.7. Experimental setup of multi-user asynchronous OCDMA

The first multi-user asynchronous coherent OCDMA experiment was 10-user, 1.25 Gbps/user using 511-chip, 640 Gchip/s SSFBG E/D and supercontinuum (SC)-based OT [8]. Figure 8 shows the average power penalty against K for BER=10^{-9} with and w/o OT. In the case of w/o OT, the experimental results agree with the theoretical predictions very well that up to 7 active users can be accommodated. In the case of with OT, there are deviations between experiment and theory. This is mainly due to the non-ideal performance of the SC-based OT. Further improvement of the OT will enable more active users.

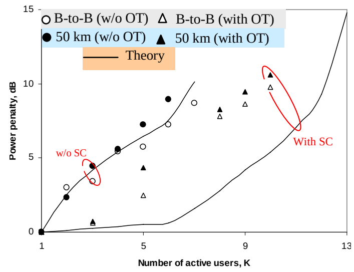

Fig.8. Experimental setup of multi-user asynchronous OCDMA

FEC assisted 12-user, 10.71 Gbps/user asynchronous OCDMA has been demonstrated to transmit ITU-T G.709 OTN frames using a pair of multi-port E/D [10]. The BER performance has been shown in Fig. 5. Combining a larger scale AWG E/D with FEC, high performance asynchronous OCDMA network could be envisioned with up to several tens active users transmitting at >10 Gbps data rate.

Field trial of asynchronous WDM/OCDMA was also demonstrated using hybrid multi-port encoder, tunable transversal-filter (TVF) type decoder, and DPSK data format. Truly-asynchronous signals of 3 wavelengths (400GHz spacing), 10-OCDMA users at 10.71Gbps/user has been successfully transmitted over 100 km installed fiber with BER<10^{-9} without using OT and FEC. For back-to-back transmission, the number of active users goes up to 12 with frequency efficiency of 0.32 bit/s/Hz. Figure 9 shows the BER performance comparison between DPSK- and OOK-OCDMA with and w/o FEC in this experiment. The BER performance has been significantly improved in DPSK-OCDMA.

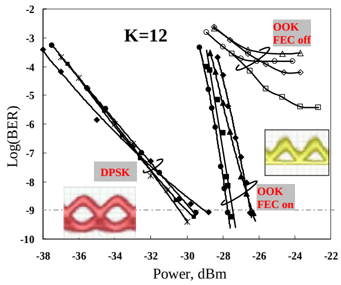

Fig.9. BER performance comparison

Summary We discussed several approaches to enable multi-user asynchronous OCDMA in the presence of SI beat noise as well as MAI with data-rate detection. Further interesting research topics could include high performance OT, OCDMA with advanced modulation formats, and the application of OCDM technique in secured communication.

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