Temporal Multiplexing of Complex Modulation Formats Facilitated by their Coherent Optical Superposition

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Abstract *We experimentally study passive coherent optical addition of complex modulation formats using delay line interferometers to increase their bits per symbol and, thus, their spectral efficiency. Two possible applications are demonstrated as examples.*

Introduction

Next-generation communication systems will rely on complex modulation formats, wavelength and modulation format agile transponders, as well as dense photonic integration, to deliver sufficient capacity and flexibility to meet user requirements. An evolution in modulation formats being deployed has already been observed, from on-off keying (OOK) in legacy systems, through to differential binary phase shift keying (D-BPSK), and more recently polarization-multiplexed quadrature phase shift keying (QPSK). The complex phase encoded formats allow for higher spectral efficiencies (SEs), but are associated with more stringent optical signal to noise ratio (OSNR) requirements, meaning that the link budgets must be carefully designed. One proposal for future networks is to ensure that they are optically transparent, and as such optical techniques for signal manipulation may find increasing prominence.

The staggered nature of the system upgrades to these complex format transponders means that optical links are becoming increasingly hybrid in nature – a mix of optical formats can be found on a single optical fiber, and coherent transponders now offer the dynamic capability of switching between modulation formats.

An important component in such a transparent network is the optical modulation format converter. Format conversion can be performed using a number of techniques mainly exploiting nonlinear effects[1,2]. However, the linear approach of passively multiplexing single-carrier signals relying on a conventional delay line interferometer (DLI) to coherently superpose information-carrying symbols in time[3-5], provides a simpler solution. Nevertheless, if directly deployed in this fashion, information redundancy, caused by the presence of both the original symbol and its delayed replica, prevents an overall increase in SE.

In this paper, we experimentally demonstrate a system based on passive superposition[6-8] where the redundancy has been eliminated through optical gating of the format-converted signal, thus leading to an overall improvement in SE.

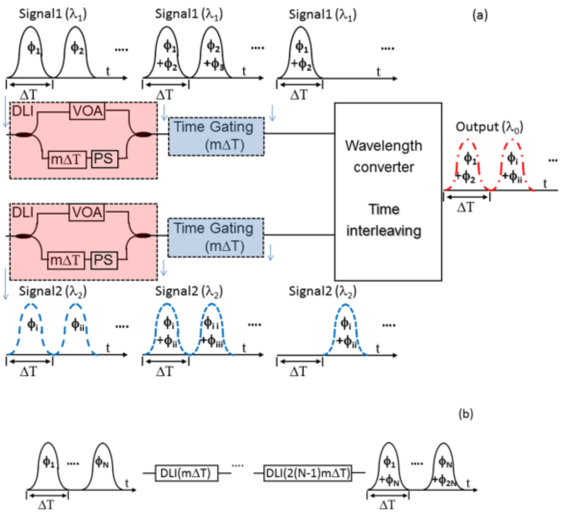

Fig. 1: a) Passive coherent optical superposition operation principle. b) Extension to higher spectral efficiencies and more complex modulation formats.

We consider two different application examples and experimentally demonstrate passive format conversion to (a) increase the SE of a 50 GHz channel by a factor of 4 and (b) temporally compress in time a 128-symbol BPSK (QPSK) packet, causing it to occupy only half of its original duration.

Operation Principle and Experimental set-up

Figure 1 (a) shows the operation principle of the passive coherent optical superposition scheme. A phase and/or amplitude encoded signal sequence at repetition rate $1/\Delta T$ is launched into a DLI, with a fixed delay line of $m\,\Delta T$, where m is an integer number. A phase shifter (PS) and a variable optical attenuator (VOA) are also included in the DLI. The signal is split into two paths; one copy is delayed by $m\,\Delta T$ (the value m depending on the specific application), suitably phase shifted and attenuated depending on the initial complex modulation format and coherently added to the second copy at the DLI output. Table 1 shows some examples of phase shift and attenuation values required to achieve various format conversions. (Note that the operation of format conversion will necessitate

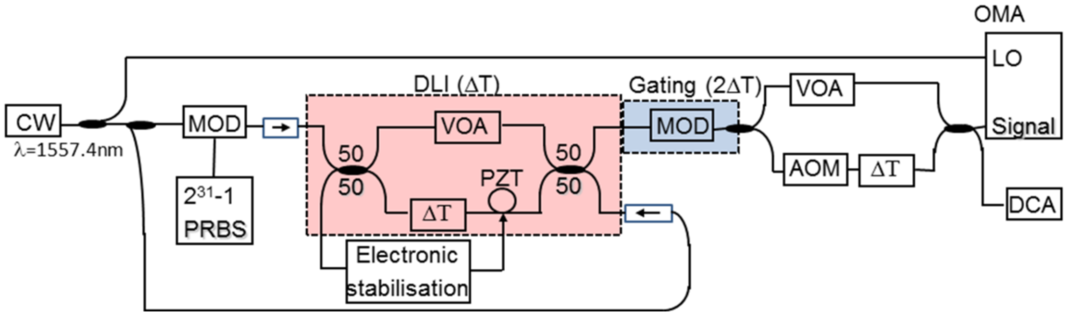

Fig. 2: Experimental set-up. MOD: Electro-optic amplitude modulator, VOA: variable optical attenuation, PZT: piezoelectric transducer, AOM: acousto-optic modulator, LO: local oscillator.

Tab. 1: Phase shift and attenuation values for various complex modulation formats.

Initial signal	Final signal	Phase shift [rad]	Attenuation [dB]
BPSK	QPSK	$(2n+1)\pi/2$	0
QPSK	16QAM	$n\ \pi/2$	6dB
16QAM	256QAM	$n\ \pi/2$	6dB

the use of data pre-coding.) The coherent addition of the electric fields allows compressor of the information carried by the original signal by doubling the bits per symbol, without broadening the spectral content of the signal. However, as the same signal is added to its delayed copy, redundant information is also created, which needs to be removed to fully take advantage of this compression function and this can be done using a time-gating switch. The new signal has the same information content as the original one, but occupies half of its space in time. This empty space could be filled in by a different signal, properly time-interleaved and wavelength shifted to a common carrier to effectively increase the SE and, thus, the overall transmission capacity.

Furthermore, if multiple DLIs with appropriately adjusted delays are used in series, followed by a single time-gating switch, the original signal can scale to even higher SE factors and more complex modulation formats, as shown in Fig.1(b). Once more, the empty spaces can be easily filled in by different signals to fully reach the maximum SE.

According to the specific delay used in the DLI, different applications of this temporal compressor can be envisaged. Use of a few bits delay leads to symbol-by-symbol recoding of the signal, while if a delay comparable to hundreds of bits is set, a packet compression scheme (through format conversion) can be implemented. Both examples are discussed in detail in the following sections.

The experimental set-up of the passive coherent optical superposition scheme is shown in Fig.2. A 10 Gbaud non-return-to-zero BPSK (or QPSK) $2^{31}-1$ pseudorandom bit sequence (PRBS) was modulated on a narrow-linewidth continuous wave (CW) laser at the central wavelength of 1557.4nm. The signal was then launched into the DLI to temporally multiplex the signal and achieve a QPSK (or 16QAM) signal. For the format conversion experiment a free-space 400ps DLI was used (4 bits at 10 Gbaud). For the packet compression experiment a fiberized DLI was used incorporating a few meters of single mode fiber to achieve 12.8 ns (128 symbols at 10 Gbaud) delay between the two arms. An electronic feedback control was implemented to stabilize the system from perturbations induced mainly by thermal drifts. The feedback circuit we built, comprised part of the original CW signal propagating in an opposite direction in the DLI to the modulated signal, an optical detector and a proportional integral (PI) controller to control the piezo-electric transducer (PZT) based fiber stretcher inside the DLI. A synchronously driven amplitude modulator was used as the time gate and to emulate the effect of a second independent signal, the multiplexed and gated signal was split in two, with one of the two copies having its carrier frequency shifted by 30MHz (using an acousto-optic modulator) to decorrelate it from the other one and then recombined together. The signals were characterized using a digital communication analyzer and a homodyne optical modulation analyzer.

Format Conversion

Figure 3 shows the eye and constellation diagrams at various points of the format converter scheme when the input signals were BPSK (Fig.3 (a), (b) and (c)) and QPSK (Fig.3 (d), (e) and (f)). The original BPSK (QPSK) signal had an error vector magnitude (EVM) of 6.9% root mean square (rms) (6.9%rms). After temporal multiplexing to QPSK and time gating

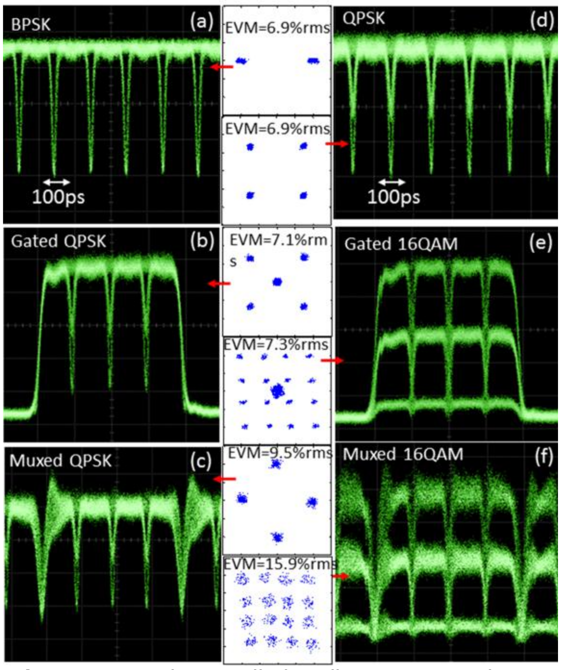

Fig. 3: Eye and constellation diagrams at various points of the format converter for BPSK and QPSK as input signals. Scale: 100ps/div.

the EVM became 7.1%rms (5%rms). It should be emphasized that even in the QPSK case, the signal was originally generated by a BPSK transmitter followed by a DLI-based format converter. It is worth pointing out that Fig.3 (a) and (b) (Fig.3 (d) and (e)) contain the same information, with Fig.3 (b) (Fig.3 (e)) occupying half of the time slot available. The zero level in the constellation diagram for the gated signals underlines that the redundant signal was properly cleared and a second signal could occupy this time window to double the SE. Fig.3 (c) shows the eye and constellation diagrams when a second signal at about the same carrier was temporally aligned and added to the empty slot. Clean and open eyes can be seen for both cases; the small beating that can be observed is due to the non-optimal temporal gating function used. Note that by cascading two DLIs, the second one with double the delay as compared to the first one, one can directly go from BPSK to 16QAM. In this case, the SE increases by a factor of 4.

Bit-error ratio (BER) measurements, not shown here, revealed a power penalty of about 3dB going from BPSK to QPSK and about 9dB from QPSK to 16QAM for BER=10^{-3}.

Packet Compression

Similar measurements to the previous case were taken for the packet compression scheme. Fig.4 (a) and (c) show the eye and constellation

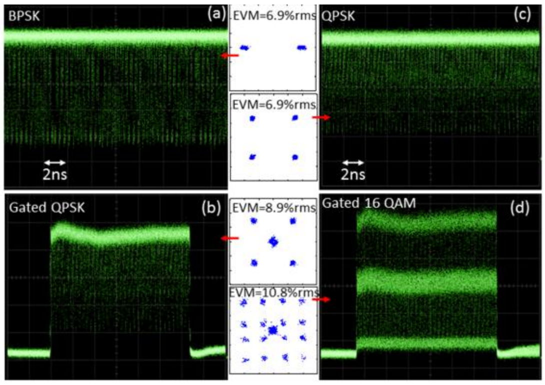

Fig. 4: Eye and constellation diagrams at various point of the packet compression for BPSK and QPSK as input signals. Scale: 2ns/div.

diagrams of the initial BPSK and QPSK signals, respectively. Fig.4 (b) and (d) show the newly generated and properly gated QPSK and 16QAM packets. Again, the same information is held in half of the available time slot. The slightly worse flat top of the gating switch as compared to the format converter scheme is reflected in a slightly worse performance (EVM of 8.9%rms and 10.8%rms for the QPSK and 16QAM, respectively).

Conclusions

We presented two experiments, in which passive coherent superposition of data bits was combined with time gating to eliminate redundant information and thus efficiently increase the overall spectral efficiency. The experiments demonstrated all-optical format conversion and packet compression respectively with up to four times SE improvement (by cascading two DLIs together). Note that various conversions can be envisaged at arbitrarily high symbol rates simply by adjusting the DLI parameters and higher SE can be achieved by adding DLIs to achieve higher order modulation formats.

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References

[1] K. Mishina et al. Optics Express, 15 (13), 8444-8453 (2007).
[2] G. W. Lu et al. J. Lightwave Technol. 29 (16), 2460-2466 (2011).
[3] J.Kakande, et al., ECOC, PD 3.3 (2010).
[4] H. Kishikawa, et al., Photonics Conference (PHO), 513 - 514 (2011).
[5] M. Sköld et al., ECOC PD Th.13.B.3 (2011).