The Impact of Errors on Differential Optical Processing

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Abstract: Nonlinear optical processing can reduce noise by combining time-shifted signals, creating a differential translation. Sender and receiver compensations are compared and shown to affect repeated use of noise reduction and amplify errors in different ways.
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1. Introduction

Recent nonlinear optical signal processing combines time-shifted signals and their derivations to cancel noise while preserving signal information [1,2]. These techniques leverage the difference in how fast encoded data *vs*. noise components of an optical signal vary. When the data varies much faster than the noise, noise can be cancelled by creating a time-shifted differential translation of the input signal.

Consider an input signal (*I*) encoded over a sequence of time intervals. *I[t]* is distinct from *I[t−1]* because the information encoded at these intervals differs. When that signal propagates, either through active or passive devices, noise (*N*) is introduced. This noise typically varies at a much lower frequency than the input signal, so that *N[t]* is very similar to *N[t−1]*. New approaches to optical noise reduction rely in this property, using nonlinear devices such as periodically-poled lithium niobate devices (PPLNs) to translate an input signal (*I*) into its differential (*D*). Because the input signal includes noise components by the time it is processed, this equation becomes $D[t]=(I[t]+N[t]-(I[t-1]+N[t-1])$. When the noise varies over much larger timescales than the data, $N[t] \sim N[t-1]$, and this equation becomes $D[t]=(I[t]+N[t])-(I[t-1]+N[t])$, which reduces to $D[t]=I[t]-I[t-1]$. The noise component can thus be cancelled out. In nonlinear devices, this noise cancellation in phase encoded signals involves deriving the conjugate of the time-delayed signal, such that their conjugates add destructively (Fig. 1).

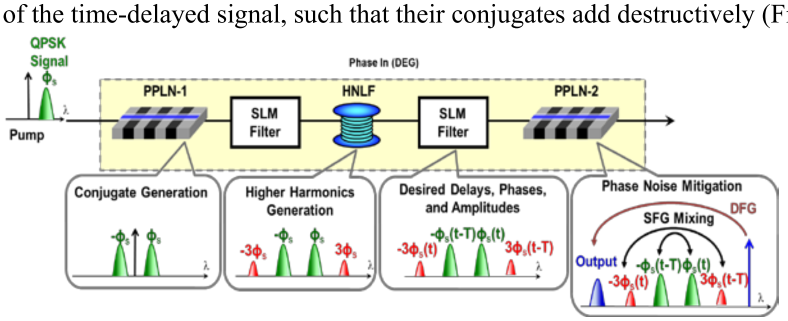

Fig. 1 Noise reduction using differential processing [1].

Differential processing provides an efficient, simple method to cancel long-timescale effects while preserving short-timescale properties; in this case, cancelling noise while preserving data. The difference in the timescales needs to be at or higher than the BER of the system, because when the long-timescale assumptions are incorrect, the assumption that $N[t] \sim N[t-1]$ is not true, and the subtraction of the two values amplify noise instead. In the systems our team examined, 10 Gbaud data transmissions exhibited noise in the 0.1-100 Baud range, *e.g.*, a ratio of 1E8.

Unfortunately, differential processing has an impact on overall optical system design. Conversion of the original source encoding requires compensation by preprocessing or postprocessing. Differential processing also impacts error propagation, and the effect is different for errors that occur before processing *vs*. after processing. Finally, these devices cannot be silently inserted as noise cancellers in transmission systems, because each translation changes the preprocessing or postprocessing requirements.

2. Electronic processing requirements

Differential processing changes the encoding of transmitted data. This might be convenient if receiver expected a differential encoding of the sent data, but it also violates a fundamental communication property – 'data received is not the data sent'. We therefore assume that such a system needs to compensate for this differential translation. However, there is no known optical processing method that can invert the operation of differentiation. Signals converted by differential optical processing can be compensated only at an electronic origin or at an electronic destination. Consider transmitting a source sequence; in non-differential encoding, the transmitter emits a symbol sequence: A,B,C,D,E and the receiver decodes those symbols. In differential encoding, the transmitter sends the differences: $A–B,B–C,C–D,D–E$, but typically only if that is the sequence the receiver is intended to accept. In differential processing, the original source is converted to the sequence of differences. If the receiver needs to recover the original, non-differential source, either the sender, the receiver, or an intermediate device needs to invert the signal to “undo” the translation. This inversion can occur before or after differential translation, which we call (respectively) preprocessing and postprocessing.

In preprocessing, the sender computes and transmits an inverse differential sequence: $\varnothing,–A,A–B,A–B–C,\ldots$; after differential processing, the receiver sees the desired sequence. In postprocessing, the receiver sees a given sequence and knows that given A it can compute: $A,A-(A–B)=B,B-(B\text{-}C)-C$, *etc.*. The receiver needs to know the start of the sequence ($\varnothing$), which is typically achieved using a known preamble. Preambles can be provided by sending a long (otherwise prohibited) symbol sequence, but preamble transmission represents lost capacity.

3. Error sensitivity

A system using differential processing is affected differently by input and output errors. Consider the original sequence as input to the differential processing, and the difference sequence as output. An error between the transmitter and the differential processor (the input to the processor) results in two erros, *e.g.*, $A,B,\underline{\mathbf{C}},D,E$ becomes $A–B,B–\underline{\mathbf{C}},\underline{\mathbf{C}}–D,D–E$, *i.e.*, the error in the symbol C affects both $B–C$ and $C–D$. This type of error amplification is independent of the use of pre- or post-processing; it is inherent in the differential processing itself.

Postprocessing presents an additional challenge. Consider a single error on the processor output side, *e.g.*, $A–B,\underline{\mathbf{B–C}},C–D,D–E$. Assuming the preamble is known, the receiver computes $A,B,\underline{\mathbf{C}},\underline{\mathbf{D}},\underline{\mathbf{E}}$. The error term remains in every value, thus a single output side error results in an infinite sequence of errors in the reconstituted inverse. This effect can be compensated by periodically retransmitting the preamble, resynchronizing to recover from such errors.

4. Impact on system design

Differential processing is not without cost to the system, its complexity, the implementation of the transmitter, or its susceptibility to errors. Error compensation devices are usually expected as “insertion devices”, *i.e.*, that they can be added along a path to compensate for error as needed. Differential processing devices change the data encoding, and either preprocessing or post requires knowledge of how many such devices are used on a path. Differential processing thus requires electronic preprocessing or postprocessing to be useful as a communications system.

When multiple differential processing occurs on a path, the source or receiver needs compensate accordingly by computing multiple integrations of the signal. Each integration requires one additional symbol of delay, *e.g.,* a two-hop preprocessor would calculate the sequence: $\varnothing,\varnothing,A,2A\text{-}B,3A\text{-}2B\text{-}C,4A\text{-}3B\text{-}2C\text{-}D$. Differential processing makes every input side error into two successive output side errors, and when that signal traverses subsequent differential devices another error is created for each device, *i.e.*, in the worst case, a sequence of N errors on the input of the first device becomes an adjacent sequence of $N+1$ errors after each device, *i.e.*, $N+d$ errors for d devices (Tab. 2).

Input	A	B	**C**	D	E
First differential	∅	A-B	B-**C**	**C**-D	D-E
Second differential	∅	∅	(A-B)-(B-**C**)=A-2B+**C**	(B-**C**)-(**C**-D) = B-2**C**+D	(**C**-D)-(D-E) = **C**-2D+F

Tab. 2 Propagation of input errors through successive differential processor translations

Preprocessing does not affect these errors or their propagation; it is chains information inside the preprocessor itself , thus limiting error amplification to the number of translations. Postprocessing propagates post-translation transmission errors infinitely until resynchronized, which both severely amplifies errors and requires periodic resynchronization using preambles, which are costly and comparably inefficient. Preprocessing is thus the preferable solution to compensating for the effects of differential processing.

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