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# Focusing over Optical Fiber Using Time Reversal

Molly Piels, *Member, IEEE*, Edson Porto da Silva, *Student Member, IEEE*, Jose Estaran, *Student Member, IEEE*, Robert Borkowski, *Member, IEEE*, Idelfonso Tafur Monroy, *Senior Member, IEEE*, and Darko Zibar, *Member, IEEE*

**Abstract**—A time-reversal array in multimode fiber is proposed for lossless remotely controlled switching using passive optical splitters. The signal to be transmitted is digitally pre-distorted so that it is routed through the physical layer in order to arrive at only one receiver in an array. System performance in the presence of additive white gaussian noise, modal group delay, and timing error is investigated numerically for single-mode and 10-mode fiber. Focusing using a two-transmitter array and 44 km of single-mode fiber is demonstrated experimentally for 3 GBd QPSK signals with a bit error rate below the forward error correction limit.

**Index Terms**—Optical fiber communication, Access networks, Digital signal processing.

## I. INTRODUCTION

TRAFFIC over passive optical networks (PONs) is growing rapidly [1]. Methods to extend the reach, security, and capacity of PONs are therefore required, and techniques including wavelength division multiplexing, mode-division multiplexing, and multi-level and coherent modulation formats are under investigation [2]–[4]. A relatively simple way to extend reach and enhance security would be to use switches rather than traditional 1:N splitters. This would enhance reach by avoiding the loss incurred by splitters, and enhance security by ensuring that only the intended user receives that user’s data. In order to be compatible with future upgrades, such switches should be wavelength-independent and modulation-format-transparent, and in order to keep operating costs low, they should also be passive. Here, we expand the investigation of the use of time-reversal in multimode fiber based systems as a passive switching method for point-to-multipoint networks presented in [5]. By applying an appropriate digital filter at the optical line terminal (OLT), the data can be steered through the physical layer to a single user. This is compatible with any modulation format, has no wavelength dependence, and requires only components commonly used in coherent optical links.

Time-reversal arrays have been used in the past in underwater acoustics [6], radio transmission [7], and optics [8] to achieve spatio-temporal focusing over scattering but static channels. In this case, a multimode fiber serves as the scattering channel and the array consists of one coherent transmitter for each mode to be addressed, as shown in Fig. 1. In general, the performance of a time-reversal system depends on the

channel properties: the length of the impulse response and the power coupling between different transmitters and receivers. In optical fiber, time reversal is most useful when there is strong coupling between fiber modes, as would most likely be the case for extremely low modal group delay (MGD) few-mode fiber or within a single mode-group of multimode fiber. The transmitter array at the OLT and a single receiver at the optical network unit (ONU) are used to measure the channel impulse response and design digital filters that will focus the desired output at the desired receiver. Since the system is linear, the same transmitter array can be used to send different signals, potentially in different modulation formats, to each receiver simultaneously, and these signals can then be demodulated independently. We show through simulations that the system is capable of addressing any number of outputs, up to the number of modes supported by the fiber, independently and with low penalty. As a proof-of-concept, we show polarization-focused transmission of a 3.3 GBd QPSK signal over 44 km of standard single-mode fiber with better than 5 dB of crosstalk and BER below the FEC limit.

## II. OPERATING PRINCIPLE

Fig. 1 shows a diagram of a time-reversal array implemented in a coherent optical link. The data to be transmitted is passed through a digital filter bank and modulated onto a single optical carrier via an array of I-Q modulators at the central office. The modulator outputs are combined using a mode-selective splitter so that the output of each modulator is coupled to one element of a mutually orthogonal set of fiber modes. The signal is transmitted over a distance of fiber, and then a similar mode-selective splitter is used to distribute it to the users. Each user is equipped with a coherent receiver and recovers the signal using standard digital signal processing.

The focusing process consists of two steps: a channel estimation step and a transmission step. In the channel estimation step, the channel impulse response between all transmitters and the desired receiver is measured, in this case using a training sequence and symbol matrix inversion. For the transmission step, the channel impulse response is time-reversed and applied as a filter to the desired output. The filtered signal is then transmitted over the same channel and recovered with the same coherent receiver. Receiver-side signal processing is done independently on each channel, and typically consists of retiming, low-pass filtering, adaptive equalization, and carrier recovery [9], as shown in Fig. 1.

MIMO systems are usually described using a channel matrix  $\mathbf{H}$  of transmitter-receiver impulse responses:

$$\mathbf{r} = \mathbf{H}\mathbf{s} + \mathbf{n} \quad (1)$$

The authors are with DTU Fotonik, Department of Photonics Engineering, Technical University of Denmark, Kgs. Lyngby 2800, Denmark. e-mail: mopi@fotonik.dtu.dk.

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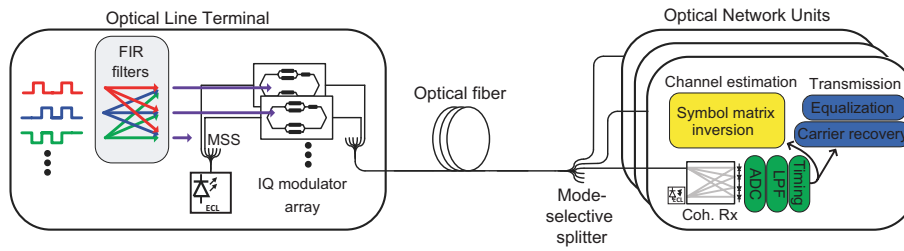


Fig. 1. A time-reversal-based routing system. Digital processing (DSP) at the optical line terminal (OLT) is used in conjunction with mode-selective splitters so that each ONU receives independent data. Here, three distinct data streams and receivers are shown, but the concept can be scaled up to the number of modes (spatial and polarization) supported by the fiber.

where  $\mathbf{r}$  represents the vector of received signals,  $\mathbf{s}$  represents the vector of transmitted signals, and  $\mathbf{n}$  is noise. For multimode fiber with very weak mode coupling, the channel matrix is similar to the identity matrix, though the temporal locations of the impulse response peaks are shifted due to MGD. In this case, because intermodal coupling is low, switching can be achieved without transmitter-side predistortion as in [3]. If there is strong mode coupling but no MGD,  $\mathbf{H}$  will be an  $N \times N$  symmetric unitary matrix [10], [11]. This is likely to be the case for any subgroup of degenerate modes (e.g.  $LP_{11a}$  and  $LP_{11b}$ ) over the 20-80 km distances common in PONs, for the same reasons it is the case for the two polarization modes supported by single-mode fiber. Measurements of deployed fiber over this distance have not been carried out to the best of our knowledge, but experiments on fiber spools have been consistent with the theory [12]. Time reversal is most necessary and useful in these cases, as it is equivalent to finding the inverse of the channel matrix.

For very strong mode coupling and large MGD, time reversal will not produce the exact inverse of the channel. This is also the case in wireless and in underwater communications, and different techniques are preferred in these two areas due to differing channel characteristics. Singular value decomposition-based techniques are effective in multipath radio environments [13], but do not achieve spatial focusing on the physical layer. This approach is not practical in underwater acoustics, where the statistical properties of the channel are different, and combinations of time reversal and adaptive equalization are typically preferred [14] even though they do not allow for operation at the theoretical channel capacity. For the application envisioned here, remote switching over a passive optical network, only MIMO techniques that achieve focusing can be used. The remaining task is to quantify the penalty associated with using this sub-optimal method

over multimode fiber in particular. Given that the alternative is the large loss incurred by 1:N splitters, it would not be surprising if there were some regimes of operation in which time reversal provided a competitive advantage. The penalty will be determined by the correlation properties of the channel impulse response [15], [16]. For the signal to be perfectly reconstructed after time-reversal, the autocorrelation of the impulse response must be a delta function and the cross-correlations must be zero everywhere; this is not expected to be the case for multimode fiber. To estimate the magnitude of this penalty, we used the random matrix model of [10], [11], which assumes strong mode coupling and no mode-dependent loss. Using this model, and assigning one receiver to each orthogonal mode, the complex impulse response from transmitter  $n$  to receiver  $m$  can be written as

$$h_{nm}(t) = \sum_{i=0}^{N-1} \mathbf{P}_{i,m} (\mathbf{H}\mathbf{P})_{i,n} \delta(t - \tau_i) \quad (2)$$

where  $\tau_i$  is the group delay associated with principal mode  $i$  of the fiber,  $\mathbf{P}_{i,m}$  is the  $m$ th element of  $\mathbf{P}_i$ , a column vector representing a principal mode (as described in [17]; these are linear combinations of the optical modes supported by the fiber), and  $\mathbf{H}$  is a symmetric unitary matrix describing mode mixing in the fiber. The signal at receiver  $m$  is composed of two parts: (1) the intended received signal, which is filtered by the autocorrelation of the channel impulse response and highlighted in black in Fig. 2; and (2) signals intended for other users, which are filtered by the cross-correlations of the channel impulse responses and highlighted in red in Fig. 2.

Imperfect autocorrelation results in low-pass filtering of the signal that can be at least partially compensated by adaptive equalization, but non-zero cross-correlation cannot be compensated and can limit system performance. If the messages intended for other receivers are unknown to the receiver, the cross-correlation terms add noise at that receiver. This noise contribution has a fixed power and is band-limited; numerical simulations indicate that within its bandwidth (and for this fiber model) the noise is nearly white. The effect of increasing (decreasing) the MGD is to decrease (increase) the bandwidth the interference noise occupies. Thus as the MGD increases beyond the symbol period, the in-band noise power from the cross-correlation terms increases as well. For fiber supporting more modes, the magnitude of this noise is greater because there are more users. The effect of cross-correlation interference is similar to the situation in code-division multiple access

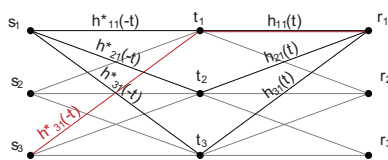


Fig. 2. Butterfly diagram of system while focusing. Messages are at left, transmitters are in the center, and receivers are on the right. All paths taken by signal 1 to receiver 1 are shown in black. One path from signal 3 to receiver 1 is also shown, in red. Signal transmission over this path will degrade receiver performance.

systems, where multi-user interference noise (MUI) dominates system performance for large numbers of simultaneous users.

### III. NUMERICAL SIMULATIONS

To evaluate the performance of time-reversal based communication systems over multimode fiber, we simulated transmission for 28 GBd QPSK over fiber supporting 20 total (10 spatial) modes. For the simulation, the fiber impulse response was modeled as in Equation 2, both the transmitter laser and local oscillator had linewidths of 100 kHz, and no other impairments were included. Fig. 3 shows the BER of the time-reversal array when there is no MGD and when there is a mean MGD of 635 ps. The mean MGD here is defined as the length of the MGD vector as defined in [10]; the maximum delay spread was 105 ps (about three symbol periods). When there is no MGD and the array is used to transmit different data to all receivers simultaneously (orange squares), there is very little penalty (0.8 dB at the FEC limit of  $3.8 \cdot 10^{-3}$ ) relative to theoretical system performance. For the same system configuration with MGD (blue triangles), the penalty becomes larger because the power of the in-band cross-correlation noise increases. However, it is still less than the 13 dB penalty incurred by 1:20 splitting loss. When the system is used to transmit data to only one receiver, there is again very little penalty even in presence of MGD. This is promising for PON applications, where it is often the case that not all receivers operate simultaneously.

In addition to the fundamental limitations on focus quality imposed by the characteristics of the channel, a real time-reversal based system will suffer from impairments due to synchronization errors. Focusing is only effective during the part of the symbol period when each element of the array is transmitting the same symbol, and synchronization errors decrease the percentage of time that this is the case. Fig. 4 shows the simulated OSNR required to reach a BER of  $3.8 \cdot 10^{-3}$  for focused systems over two-mode (SSMF) and twenty-mode fiber for 28 GBd QPSK. The OSNR required for a 2x2 system in a standard configuration is also shown as a reference. For both two-mode and twenty-mode fiber, the penalty (relative to the standard system) increases with the jitter. This is due to the propagation of error from the channel estimation to the transmission step. At realistic levels of jitter,

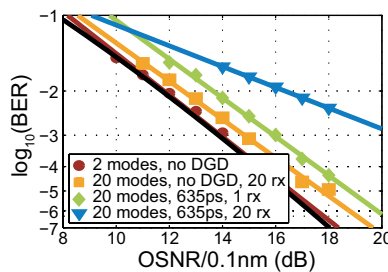


Fig. 3. Simulated BER as a function of OSNR for a focused system over single-mode and 20-mode fiber with zero and 635 ps mean MGD (see text for definition of mean DGD). For single-mode fiber, the simulated result of a 2x2 system is shown while for 20-mode fiber, results for both 20x20 and 20x1 systems are shown. The lines shown are fits to the simulated points. A theoretical reference curve is shown in black.

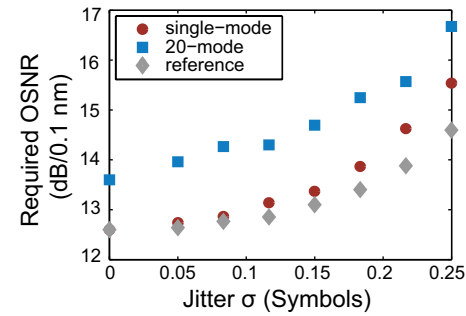


Fig. 4. Minimum OSNR required to reach a BER below the FEC limit of  $3.8 \cdot 10^{-3}$  for time-reversal arrays in single-mode and 20-mode fiber as a function of random jitter RMS magnitude. The reference is simulated performance of a standard system in single-mode fiber with receiver-side polarization demultiplexing.

there is very little difference between a time-reversal array and a standard system.

### IV. EXPERIMENT AND RESULTS

As a proof-of-concept, we built a two-transmitter time-reversal array for polarization multiplexed (two-mode) transmission over 44 km of standard single-mode fiber (SSMF). It is worth noting that replacing a 1:N splitter with a polarization beam splitter and two 1:N/2 splitters (i.e. using the system demonstrated here) would yield a 3 dB improvement in required launch power for a branched network. At this distance, MGD (DGD) in SSMF is negligible and inter-modal crosstalk is large, so theoretically there should be very little penalty for using time-reversal, and active focusing would be required to make this substitution. The transmitter consisted of two synchronized arbitrary waveform generators at 3.33 GBd driving a dual-polarization IQ modulator with either QPSK (for training) or pre-distorted QPSK (for focusing) signals. It was not necessary to stabilize the fiber in the experiment in order to ensure a static channel. In a deployed fiber, the channel impulse response would need to be updated regularly to track the state of polarization (most likely hourly for buried single-mode fiber [18]) and modal cross-talk (the relevant timescales for this are not well-known).

To measure the quality of focusing, we transmitted data to the x-polarization only. The full system setup was similar to that shown in Fig. 1, with polarizing beam splitters in place of mode-selective splitters. We used a standard (EDFA and attenuator) noise loading stage. Fig. 5 shows the crosstalk, defined as the ratio of the optical power in the x polarization to the optical power in the y polarization, as measured at the output of the coherent receiver after digital low-pass filtering, as a function of channel optical signal to noise ratio (OSNR). The OSNR is specified during channel estimation; it was typically 1-2 dB lower during transmission because pre-distorting the signal results in a decrease in transmitter power without a corresponding reduction in noise from the EDFA used for noise loading. This behavior would also be expected for a time-reversal system implemented in a network. Constellation diagrams of the demodulated output in the x- and y-polarizations at 8 dB OSNR are shown as insets. For an ideal

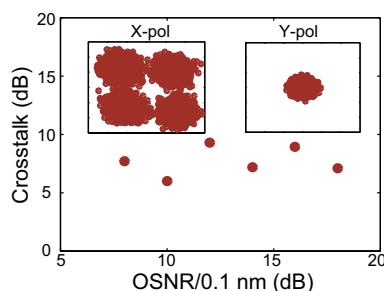


Fig. 5. Crosstalk as a function of optical signal to noise ratio. Inset: demodulated constellations for focused data at an OSNR of 8 dB. The two polarizations were demodulated separately and re-scaled to have the appropriate relative sizes in the figure.

transmitter, the polarization extinction ratio would increase with OSNR because the power in the y polarization would only come from amplified spontaneous emission. However, the transmitter used suffered from large timing errors (on the order of a full symbol period), and this limited the maximum achievable crosstalk to about 10 dB.

Time-reversal-based focusing can also be used to send different data to multiple users. Fig. 6 shows the bit error ratio measured when the system was used to send different data to both polarizations simultaneously. The signal can be successfully recovered when equalization and carrier recovery are applied to each polarization separately (orange squares), as is only possible for focused transmission. Using full 2x2 MIMO (red circles), as is required for standard polarization-multiplexed transmission, yields very little change in BER. This indicates that the system was focusing effectively. Fig. 6 also shows reference data generated by sending independent QPSK signals in both polarizations (i.e. using the link in the standard configuration). The penalty for focusing is primarily due to the poor synchronization between the two arbitrary waveform generators, which is consistent with the simulations shown in Fig. 4.

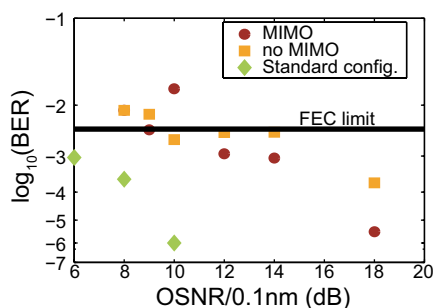


Fig. 6. BER as a function of OSNR for standard (green diamonds) and focused systems with (red circles) and without (orange squares) MIMO processing.

## V. CONCLUSION

We have shown that a time-reversal array can be used in conjunction with a passive splitter for lossless switching. For multimode fiber, simulations show that there is very little inherent penalty to switching this way in the absence of MGD.

In the presence of MGD, communication between the central office and a subset of available receivers simultaneously is feasible, but there is a penalty due to multiuser interference noise that scales with the number of users. Simulations were verified with proof-of-principle experiments over standard single mode fiber, and effective focusing was demonstrated.

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