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ABSTRACT

M-ary pulse position modulation (*M*-ary PPM) is an alternative to on-off-keying (OOK) that transmits multiple bits as a single symbol occupying a frame of *M* slots. PPM does not require thresholding as in OOK signaling, instead performing a comparison test among all slots in a frame to make the slot decision. Combining PPM with optical code division multiple access (PPM/O-CDMA) adds the benefit of supporting multiple concurrent, asynchronous bursty PPM users. While the advantages of PPM/O-CDMA are well known, implementing a receiver that performs the comparison test can be difficult. This paper describes the design of a novel array receiver for *M*-ary PPM/O-CDMA ($M = 4$) where the received signal is mapped onto an *xy*-plane whose quadrants define the PPM slot decision by means of an associated control law. The receiver does not require buffering or nonlinear operations. In this paper we describe a planar lightwave circuit (PLCs) implementation of the receiver. We give detailed numerical simulations that test the concept and investigate the effects of multi-access interference (MAI) and optical beat interference (OBI) on the slot decisions. These simulations provide guidelines for subsequent experimental measurements that will be described.

Keywords: Pulse position modulation; optical CDMA; optical communications; quadrant receivers

1. INTRODUCTION

Optical code division multiple access (O-CDMA) is a possible technique for implementing rapidly configurable optical access networks[1]. In O-CDMA, users encode their data transmissions, and the coding allows multiple transmissions to occupy the same bandwidth while minimally interfering. On the receiving end, each user tunes its decoder to the code of the desired transmission, producing an autocorrelation that can be thresholded and separated from the crosscorrelation, or multi-access interference (MAI), of other transmissions. In a truly rapidly configurable network, active optimization of the thresholding levels would be required, as a change in the number of network users would cause a fluctuation in MAI levels. Although many O-CDMA schemes exist, the majority of schemes encode optical pulses, and these pulses are on-off-keyed (OOK) with binary data[2]. Due to its use of pulsed signaling, pulse position modulation (PPM) lends itself nicely as an alternative to OOK in O-CDMA[3-8]. In PPM, data symbols are represented as pulses that occupy one of *M* possible slots within a frame. A PPM receiver does not utilize thesholding, as a comparison test is instead performed between the slots, making a slot decision based on the presence of a pulse. The primary advantage of PPM is its ability to perform *M*-ary signaling, allowing for higher data throughputs than OOK. However, difficulty in implementing the comparison test has thus far limited PPM/O-CDMA to mostly theoretical studies[3-8]. In fact, the few existing implementations of PPM/O-CDMA avoid the comparison test altogether and continue to rely on thresholding[9]. In this paper, we propose a novel receiver module design for *M*-ary PPM/OCDMA (M=4) that preserves the comparison test. The module is called a virtual quadrant receiver due to its similarity to detectors used in laser spot tracking[10]; however, it does not require a physical array of quadrant detectors. Rather, a differential receiver array is used for detection, and its output is mapped using a control law onto an *xy*-plane whose quadrants determine the slot decision.

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Detailed numerical simulations of the receiver explore the effect of multi-access interference (MAI) and optical beat interference (OBI) on the slot decisions, driving the control law to declare incorrect quadrant coordinates.

2. RECEIVER DESIGN

The design of the virtual quadrant receiver is shown in Fig. 1, as applied to a PPM/O-CDMA network. Various asynchronous users data modulate their signal using PPM and encode them with O-CDMA. These PPM/O-CDMA signals transmit through the O-CDMA network (often in a star configuration) where they are summed. On the receiver end, the combined signals are first O-CDMA decoded and then processed for PPM slot decision. The processing implements the following control law or algorithm, which defines an estimate for the symbol slot position of any given frame:

$$\textit{Control Law}: \quad (x,y) = \big((slot_3 + slot_2) - (slot_1 + slot_0), (slot_3 + slot_0) - (slot_2 + slot_1)\big). \tag{1}$$

$slot_n$ is a copy of the O-CDMA decoded signal with an applied relative delay of n slot times. Slot addition is performed optically using combiners, while subtraction of slot sums is performed using differential detection. The outputs of the differential detectors sample the control law at the frame rate. The control law gives the xy-coordinates of the symbol slot position decision, where each quadrant of the coordinate plane represents one of the four possible slots. Although physical implementation of the control law requires the O-CDMA decoded signal to be divided into eight equal parts (one for each slot), loss within the virtual quadrant receiver can be minimized using a PLC-based lossless splitter[11]. The lossless splitter includes an in-line erbium-doped waveguide amplifier (EDWA) that compensates for splitting loss. With the incorporation of integrated delay lines, it is conceivable that all components of the virtual quadrant receiver prior to the differential receivers could be implemented into a single, monolithic PLC.

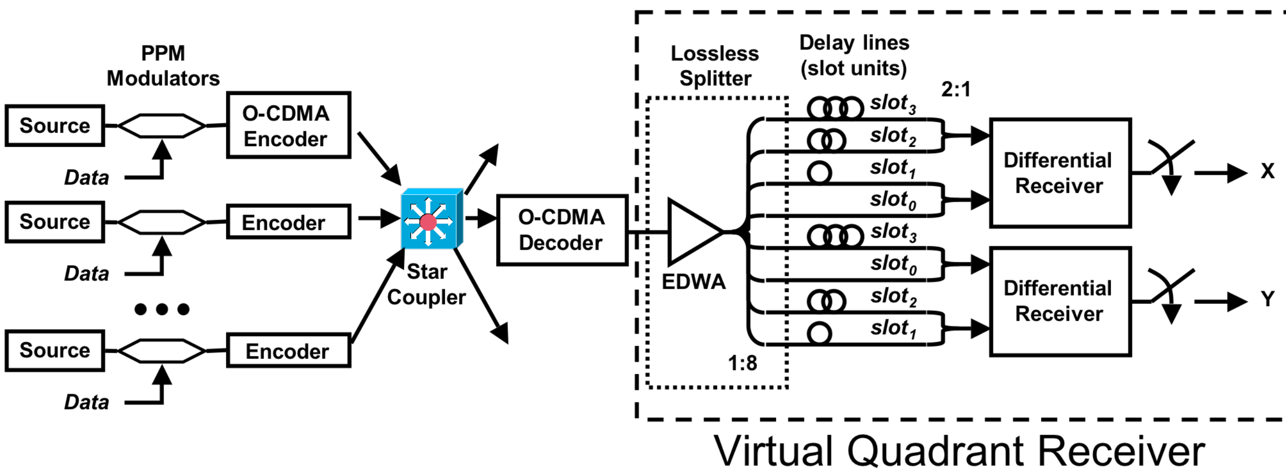

Fig. 1. PPM/O-CDMA Network and 4-ary Virtual Quadrant Receiver

3. SIMULATION DESCRIPTION

In order to assess the performance of the virtual quadrant receiver, a 4-ary PPM/O-CDMA system is simulated using RSoft's OptSim. The system uses time/wavelength-coded O-CDMA[12], whereby each encoded signal is represented as a sequence of multi-wavelength pulses. We specifically use a time/wavelength code set derived from folded optimum Golomb rulers[13] and base the simulator architecture on an actual technology demonstrator[14]. Fig. 2 shows the resulting topology. Pulses are first generated by on-off-keying a multi-wavelength laser containing eight wavelengths, as specified by the code set. The transmitter pulse position modulates 4-ary symbols on to this stream. The single modulated stream distributes to several encoders, each representing a user. Fixed time delays added into each path bit shift the stream between users, decorrelating the data between different paths. This simulates different users that transmit different data. In each encoder module, an AWG wavelength demultiplexes the incoming data stream, forwarding each wavelength to a delay line that applies time shifts. Four of these wavelengths combine to produce an encoded signal. A feature of the codes allows the remaining four wavelengths to constitute a second encoded signal, and thus each encoder module produces two codes. All the encoded signals combine through a network of combiners that represent the star coupler of a network, and the output is sent to a single decoder. The decoder is implemented similarly to the encoder, but with the inverse delay lines. The output of the decoder proceeds to the virtual quadrant receiver. For simplicity, we assume a worst-case scenario where all signals are aligned to the same polarization, maximizing OBI. The simulation assumes that the system performance is limited by MAI and OBI, rather than other noises sources (often a realistic assumption). Thus, enough initial power is provided to the system to ensure that all erbium-doped amplifiers (EDFAs) operate in saturation, minimizing ASE. Additionally, strategic placement of the EDFAs ensures that each user has enough power to exceed the receiver noise levels of the differential detectors within the virtual quadrant receiver.

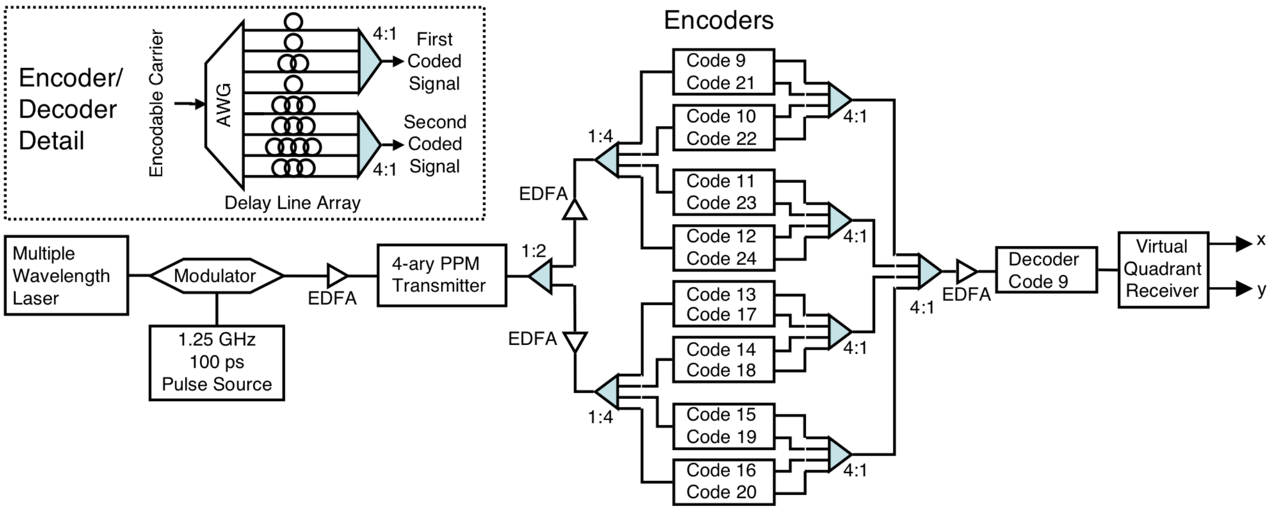

Fig. 2. O-CDMA Technology Demonstrator architecture for 2D codes

3. RESULTS & DISCUSSION

The quadrant receiver produces coordinates *x* and *y* for each sampled symbol, and Fig. 3 plots example *xy*-coordinates for 1 to 12 concurrent users for a particular set of transmission delays between different users. (Different delays will produce varying results). Results are normalized such that coordinates (±1,±1) are the single user starting point for each slot (1-user case, Fig. 3a) and variations from these points represent the change due to the MAI and OBI as users are added. The result resembles a constellation plot, as in other communication signaling schemes. Errors occur when the *xy*-coordinate strays beyond its initial (single user) quadrant. For the four-user case (Fig. 3b), interference with the desired signal causes some points to deviate from the starting point, but all remain within their respective quadrants, indicating that no incorrect slot decisions have been made. However, at eight users (Fig. 3c), two points (out of 64 symbols) cross over to an adjacent quadrant causing a slot decision error. These two points have been marked. At twelve users (Fig. 3d), 19 errors occur, some of which occur outside of the plot area.

To alleviate MAI, we can apply phase modulation to the desired transmission by placing a phase modulator in the path of Code 9. With 16.5 GHz modulation applied, we can compare the resulting constellation plots shown in Fig. 4 to the previous result. Now, noticeably less variance occurs within the constellations. In fact, for the eight user case (Fig. 4c), phase modulation causes the overlapping coordinates to return to their proper quadrant, and the system can now operate beyond eight users. Again, the effectiveness of phase modulation will vary depending on the relative delay between asynchronous users' transmissions. Out of 16 possible delay combinations tested, all cases showed that errors would occur at 12 users, with and without phase modulation. Keeping in mind that the simulation has assumed that all users are aligned in polarization, improved results could be obtained with polarization diversification of each user. A more effective reduction of errors can be obtained (hence more asynchronous, concurrent users supported) by combining this simple, hardware-implementable virtual quadrant receiver with other PPM (software) decision schemes that retain and compare the sampled values of all slots in the frame.

4. CONCLUSION

We have described a novel 4-ary PPM/O-CDMA virtual quadrant receiver that eliminates the need for adaptive threshold adjustment in rapidly configurable access networks. Numerical simulations illustrate the behavior of the PPM/O-CDMA system as affected by MAI and OBI, as well as the improvement that could be gained by phase modulating the desired user. Severe MAI and/or OBI can lead to ambiguous or incorrect quadrant assignments in the slot decision process (see Figs 3(c) and 4(c)). (When these cases are anticipated, additional slot decision schemes must be incorporated to decode the correct slot position.) In order to validate the results of the numerical simulation, the virtual quadrant receiver shown in Fig. 1 will be implemented with an InPlane lossless splitter that was recently procured under the OIDA PTAP program. The virtual quadrant receiver will then be integrated with the O-CDMA Technology Demonstrator shown in Fig. 2. The analog voltages from the differential receivers (the *xy*-coordinates) will be recorded on an oscilloscope, sampled at the appropriate chip time, and plotted against each other as an initial method of duplicating the constellation plots shown in Figs. 3 and 4. The plots will demonstrate the combined effects of MAI and OBI. This will include measurements that incorporate phase modulation within the path of the Code 9 encoder to isolate the effects of MAI. These initial experiments will establish the threshold number of users that can be supported before additional decision schemes are required.

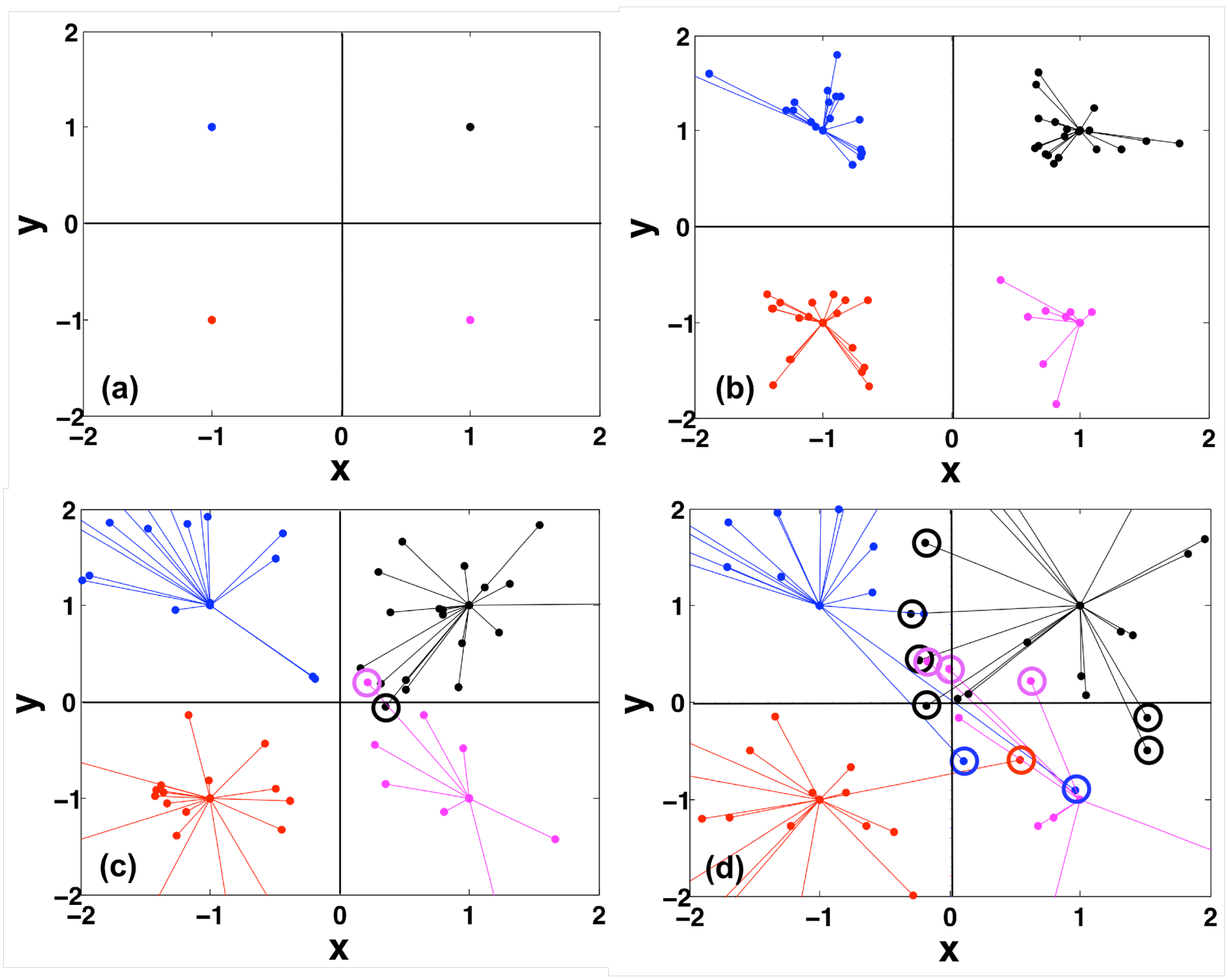

Fig 3. Constellation plots of the virtual quadrant receiver for various users: (a) one user, (b) four users, (c) eight users, (d) twelve users.

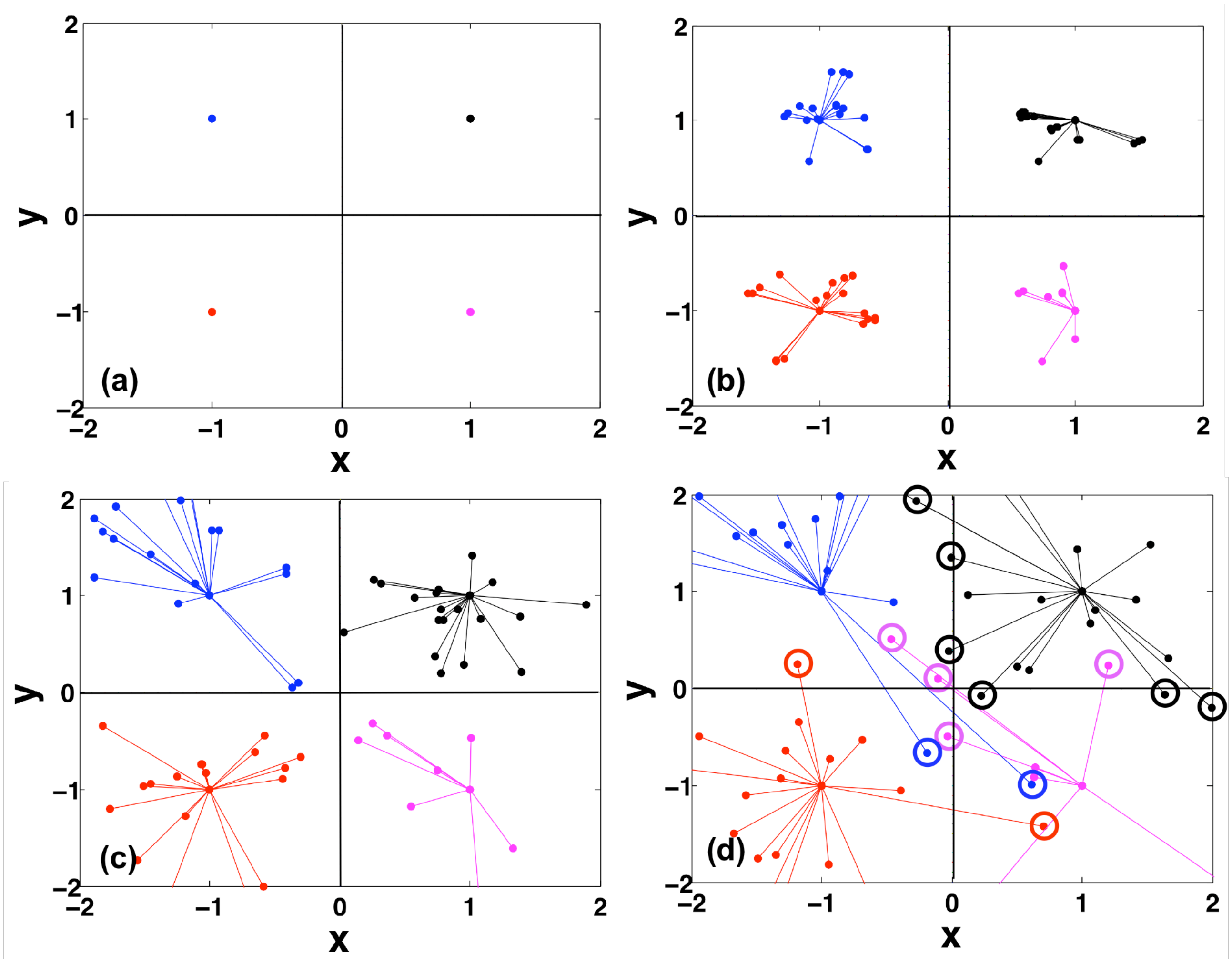

Fig 4. Constellation plots of the virtual quadrant receiver for various users with phase modulation applied to reduce optical beat interference: (a) one user, (b) four users, (c) eight users, (d) twelve users.

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