Spectral Modulation of MIMO Channels for Multimode Fiber Communications

S.B. Colak (1), A. Alonso (2)

(1) Philips Research Labs, 5656 AA Eindhoven, The Netherlands
(2) Technical University of Eindhoven, 5600 MB Eindhoven, The Netherlands

The data carrying capacity of a multimode fiber can be improved by multiple-input multiple output (MIMO) techniques. We have recently proposed a spectral modulation method to improve the effectiveness of MIMO further by minimizing the correlation of communication channels. Here, we report on simulated results on the relative magnitude of the fluctuations in such communications channels by using a finite scatterer MIMO model in a simple rectangular waveguide with point scattering centers.

Introduction

It is envisaged that, in the future, our environments will have numerous wireless micro-devices, sensors and actuators to facilitate ambient intelligence applications. Multimode optical fibers can provide practical links to central gateway for such applications with the help of radio-over-fiber methods [1] for radio-frequency (RF) signal distribution. Due to modal dispersion, the data carrying capacity of step index multimode fibers are limited. This limitation can be avoided by grading the core index as in GI-POF [2], One may still, however prefer to improve the capacity of the step index fiber due to cost. An obvious possibility, then, is to use the modal structure of the fibers for multiplexing [3]. Recently, it was also shown that space-time encoding could be used to increase data rates by taking into account the mode dispersion and coupling [4]. In our previous work, we studied the experimental feasibility of this method further [5] and then proposed to tailor the space-time coding by spectrally modulated MIMO methods [6].

The spectral modulation can be used to decrease the correlation between the mode scattering events and to improve the effectiveness of MIMO leading to efficient space-time encoding. In this report, we provide results of simulations on the communication channel in a multimode waveguide, in order to evaluate the benefits of spectral modulation. Our simulations are done with a rectangular waveguide structure using a finite scatterer MIMO model [7] with point scatterers. The relative magnitude of the effects is then discussed using the matrix elements of a 2x2 channel MIMO model [8].

We should point out here already that, recently, there has been considerable interest in RF MIMO communications in waveguide geometries as well due to the similarity of RF propagation in hallways [9] and tunnels [10]. Such studies are also of interest to understand the limitations of MIMO in restricted geometries, such as keyholes, [11]. Furthermore, the basic principles of MIMO communications in diffuse media such as a disordered waveguide seem to attract considerable scientific interest [12]-[14].

Multimode Communication Channels in Disordered Waveguides

Our first set of studies [6] was done to explore experimentally the feasibility of observing RF beatings between the various spatial modes of a POF to explore using these for radio-over-fiber communications. Figure 1 shows an example experimental set done with 1m long POF samples with core diameters of 60 micron.
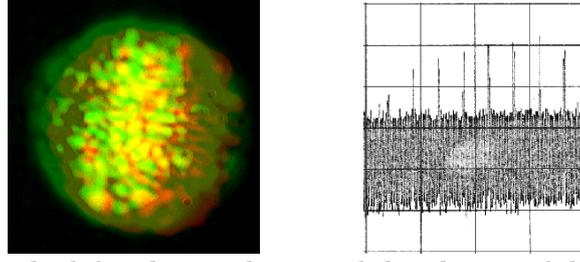
Figure 1. *The image on the left indicates the spatial distribution of the mode beating at the output of a POF exited with GaAlAs laser. An example RF beating spectra from such a pattern, taken with Ar laser excitation is on the right within a range between ~ 0.3 and ~1.5 GHz [6].*

As seen in Fig.1, the communications channels provided by the rich set of fiber modes and the RF beatings can be utilized for enhancing the data carrying capacity of multimode fibers with MIMO methods. Furthermore, since beating of different wavelength signals generates RF, the efficiency of MIMO application can be improved by changing these wavelengths by spectral modulation of the channel in the optical domain [7]. In order to illustrate the spectral modulation of MIMO for multimode fiber communications, we first consider the basic waveguide geometry in Figure 2.
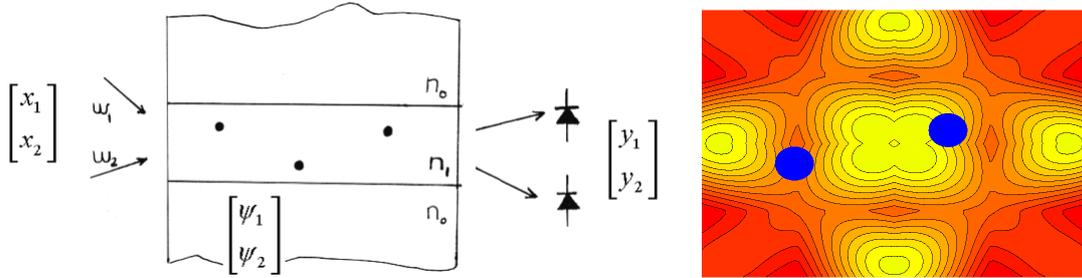

Figure 2. *This cross section sketch on the left shows the waveguide structure of our MIMO model with input/output beams and point scattering centers. An example output intensity mode pattern from such a channel waveguide is shown on the right with the position of the detectors.*

We assume that the inputs and outputs to the guide, shown in Figure 2, are two beams, which consist of a combination of two frequencies, w_1 and w_2. These are optical frequencies and they can generate RF beatings either between themselves or by direct modulation of their respective sources. These two input beams, defining the input vector x, are assumed to couple to different modes, Ψ_m with mode index m, of the guide. These modes get redistributed during propagation due to scattering by disorder in the guide. The output, y, is then monitored by two photodiodes at the exit of the guide. The original information can be extracted from the output by signal processing techniques as done in the theory for wireless communication channels with antenna arrays [15,16].

The received signal vector, y, is obtained from the transmitted signal vector, x, using the relationship below, where H is the normalized communication channel matrix, in our case, of the multimode guide.

$$\begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} H_{11}(w_1, w_2) & H_{12}(w_1, w_2) \\ H_{21}(w_1, w_2) & H_{22}(w_1, w_2) \end{bmatrix} * \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

Although, we have explicitly indicated the frequency dependence of the channel matrix elements, these also depend on the spatial positions of the scatterers as well, as in the

case of microwave wireless communications resulting in correlations [8]. These matrix elements can be calculated from waveguide mode analysis and transfer-matrix techniques coupling the modes of the guide due to scattering centers.

Modal analysis of waveguide channels with point scatterers

Our waveguide channel simulations are done with a rectangular waveguide structure with a longitudinal cross section as shown in Figure 2 (left). The dimensions of this rectangle are (a,b). The guide index, n_1, is assumed to be much larger than the clad index, n_0. With these assumptions the modes are defined by (mπ/a) and (mπ/b), where m is the mode index, similar to the hallway MIMO problem [9]. A variety of modes gets excited by the RF modulated optical transmitters at the entrance of the guide. We take into account the scattering from the point centers with a form ($\Psi_{m2}=D_{m2, m1}\Psi_{m1}$), where Ψ indicates a mode and D is the scattering cross section. We also take into account the wave-number dependence of D with Exp[-α($k_{z,m1}$-$k_{z,m2}$)^2], where $k_{z,m}$ is the propagation constant and α defines the width of the Gaussian. The intensity profile at the output of the waveguide has the form ($\Psi_{m1}\Psi_{m2}$)Exp[- j (Δwt+ΔkL)], where Δw=(w_{m1}-$w_{,m2}$) is the beat frequency, and Δk_z =($k_{z,m1}$-$k_{z,m2}$) is the phase mismatch. These are all defined at the end of the guide with length L. An example of output mode pattern is shown in Figure 2 (right) for a waveguide with dimensions of (a,b)=(10,7)λ and length L=$10^{+7}\lambda$ by taking into account the first 5 of the lowest order modes. The two circular dots in this figure indicate the two omni-directional detectors placed directly on the output face.

The sensitivity of the channel matrix to spectral modulation is calculated using the simulations described above by changing the wavelength, λ, of the optical inputs. For these simulations, the wavelength is assumed to vary in small steps with increments of $10^{-6} \lambda$. For a wavelength of 1 micron, this corresponds to about 100MHz in the frequency domain. For each new wavelength, a new mode propagation structure was computed and the channel matrix for a 2x2 system was found. As expected the results show fluctuations due to the phase relationship between the modes and their scattered components. A set of examples, taking only the first two lowest order modes and three scatterers, are shown in Figure 3. We assumed that each scatterer couples only one mode to another one for the sake of simplicity.

It is seen from Figure 3 that the relative fluctuations in the matrix elements are considerable. This shows that the MIMO channel capacity of the multimode waveguide can be varied considerably by spectral modulation. This can be seen directly from the capacity expression of a 2x2 case [8]

$$C = \log_2 \det\left(I + \frac{S\ H(w)H(w)^*}{N\ n} \right) \approx \log_2\left(1 + \frac{S}{N} + \left[1 - r^2(w)\right]\times\left(\frac{S}{2N}\right)^2 \right) \frac{bit\ /\ s}{Hz}$$

where, C is the capacity in [(bits/s)/Hz], I is identity matrix, S/N is signal to noise ratio (dB), and n is the equal number of transmitters/receivers. The capacity gain is a function of the matrix components, which in turn are dependent on the correlation, r(w), between the different channels of the medium. Spectral modulation of the laser frequencies is used to decrease the correlations between the matrix elements. Therefore, w_1 and w_2 in our case is used to minimize r(w) giving the result as close to C=2.$\log_2$(1+(S/2N)) as possible.
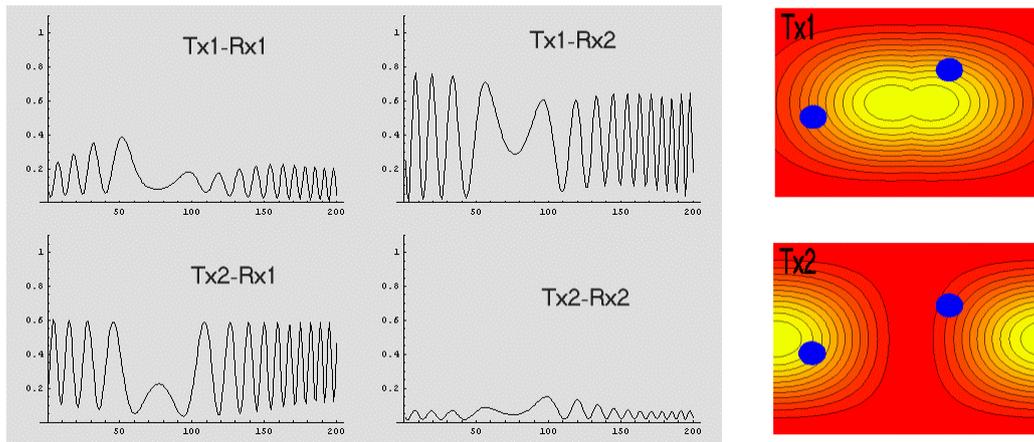
Figure 3. *The figure on the left gives the real values of the MIMO channel matrix elements of the simulated waveguide as a function of wavelength (200 steps of 10^{-6} λ each). The dimensions of the waveguide are the same as in fig.2, that is $(a,b)=(10,7)\lambda$ and $L=10^{+7}\lambda$. The output intensity mode patterns for transmitter 1 (Tx1) and 2 (Tx2) are shown in the right.*

Although the channel matrix elements in Figure 3 have large relative amplitude fluctuations, they seem to be too rapid in frequency scale. In some sections, the period of the fluctuations is about a few hundred MHz. It is questionable whether the light sources, such as standard semiconductor lasers, can be stabilized to within such a small frequency range to optimize the MIMO channel capacity at an acceptable system cost.

Conclusions

In this report, we have shown by simulations that spectral modulation of MIMO channels in multimode fiber communications can result in substantial gains in communication capacity. Spectral modulation of the optical inputs gives the freedom to tailor signal propagation by choosing spectral components, which minimize correlation between the MIMO channels.

References

[1] A.J. Seeds, in IEEE MTT-S Digest, pp. 23-25, 1997.

[2] T. Ishigure, Y.Koike, J.W.Fleming, IEEE J. Lightwave Tech., vol. 18, pp. 178-184 , 2000.

[3] M.Saffman, D.Z.Anderson, Opt. Lett., vol. 16, pp. 300-302, 1991.

[4] H.R. Stuart, Science., vol. 289, pp. 281-283 , 2000.

[5] A.Alonso, S.B.Colak, in Proc. 6th Ann. Symp. IEEE/LEOS Benelux, pp. 129-132, 2001.

[6] A.Alonso, S.B.Colak, LAT Conf, Moscow 2002, paper in Proc. SPIE, vol. 5135, pp. 1-4, 2003.

[7] A.G.Burr, IEEE J. Sel. Areas Comm., vol. 21, pp.812-818, 2003.

[8] S.L. Loyka, Electronics Lett., vol. 35, pp.1421-1422, 1999.

[9] D.Porrat, P.Kyritsi, D.C.Coxin Proc. IEEE Global Telecom. Conf., vol. 2, pp. 1930-1934, 2002.

[10] M.Lienard, P.Degauque, J.Baudet, D.Degardin, IEEE J.Sel. Areas Comm., vol.21, pp.332-339, 2003.

[11] D.Chizhik, G.J.Fochini, M.J.Gans, R.A.Valenzuela, IEEE Tr. Wireless Com., vol.1, pp.361, 2002.

[12] A.L.Moustakas, H.U.Baranger,L.Balents,A.M.Sengupta, S.H.Simon, Science, vol.287, pp.287, 2000.

[13] S.E. Skipetrov, Phys. Rev. E, vol. 67, pp. 036621-(1-11), 2003.

[14] A.Derode, A.Tourin, J.de Rosny, M.Tanter,S.Yon, M.Fink, Phys.Rev.Lett., vol.90, pp.014301, 2003.

[15] A.J.Paulraj, C.B.Papadias, IEEE Signal Proc. Mag., pp. 49-83 , November 1997.

[16] A.F.Naguib, N.Seshadri, A.R.Calderbank, IEEE Signal Proc. Mag., pp. 76-92, May 2000.