BROADBAND MULTI-SERVICE IN-HOUSE NETWORKS USING MODE GROUP DIVERSITY MULTIPLEXING

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Abstract: Multiple broadband services are carried independently in a highly multimode polymer optical fibre network by selectively launching and detecting several mode groups, while counteracting mode-mixing by adaptive electrical signal processing. With cheap integrated signal processors, mode group diversity multiplexing can offer the same functionality as wavelength multiplexing at lower costs.

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1. Introduction
Optical fibre is an excellent medium for providing high bandwidth and service format transparency. It has brought tremendous data transport capabilities in core telecommunication networks, and it is now conquering the metropolitan area networks and subsequently it is moving into access networks. Coming closer to the end user and penetrating his residential area, however, the costs of installing and maintaining the fibre network become ever more important.

Polymer Optical Fibre (POF) offers distinct advantages regarding cost-effective installation and maintenance in in-building business and residential areas, as compared with the commonly used single-mode fibre. The POF’s large core considerably eases coupling and splicing, and its flexibility and ductility enables fast installation in often less accessible customer locations. It offers also distinct advantages in comparison to traditional fixed wiring media such as coaxial copper cable and twisted pair copper cable: it offers significantly more bandwidth and lower losses, it is immune for electromagnetic interference, and it offers complete transparency to signal format and protocol. Similar advantages are obtained with silica large-core fibres, although these fibres are less flexible and ductile and thus less easy to install. However, in comparison to standard single-mode silica fibre, POF has per unit of length a higher attenuation, and a lower bandwidth (due to its higher dispersion caused by its multimode waveguiding behaviour). Therefore its applicability for broadband data communication is limited.

POF material compositions and index profiles are being explored to improve the fibre characteristics. Perfluorinated (PF) polymers have reduced the losses to below 10 dB/km in the wavelength range of 800 to 1300 nm [1]. PF graded-index polymer optical fibres (PF GI-POF) have reached bandwidth-length products of 5 GHz-km. In conjunction with these improvements in polymer fibre technology, research is needed regarding system techniques to extend the data transport capabilities of POF-based networks.

Next to improvements in the POF characteristics, a lot of progress has been made also on high-speed POF system techniques [2] [3] [4]. Recently, the TUE-ECO group has reported a Gigabit Ethernet PF GI-POF link with a length of about 1 km [5]. However, to further advance the capabilities of POF-based networks, new signal transport techniques have to be devised.

In this paper, mode group diversity multiplexing is proposed as an approach to increase the fibre’s data transport capability. By selectively launching and detecting subsets of the large total number of guided modes in the POF, and by using electrical signal processing in order to unravel the mode mixing incurred in the POF, mode group diversity multiplexing enables to create several independent communication channels in a single fibre infrastructure, and thus allows to integrate multiple services independent of each other in this infrastructure. Its functionality is comparable to wavelength multiplexing, but without requiring the more costly wavelength-specific sources and wavelength (de-)multiplexing system functions. Mode group diversity multiplexing may outperform wavelength multiplexing, when the costs of the electrical signal processing required are lower than the costs for wavelength multiplexing.

Moreover, sets of mode-group-diversity multiplexed signals may be stacked in a next hierarchical level with wavelength multiplexing, thus creating independent service groups in a unified POF-based transparent in-house
network. Thus e.g. broadband user terminals with fixed-wire connections (such as Gigabit Ethernet) may be supported, as well as broadband wireless terminals (such as in a wireless LAN); this method of service integration is illustrated in Fig. 1.

The mode group diversity multiplexing system concept encompasses two major fields of research activities: the mode-selective optical transmission system, and the electrical signal processing which has to reconstruct the signals corrupted by mode mixing incurred in the optical path.

2. Optical transmission system

From an information theory viewpoint, multimode fibre has a larger information transport capacity than single-mode fibre, as it guides a multitude of modes. However, usually many modes are excited simultaneously, and due to mode dispersion this results in a much lower transport capacity. Selective mode group launching may considerably increase the bandwidth [6], [7]. An up to fourfold increase of the bandwidth has been reported by injecting a small light spot radially offset from the fibre core centre, exciting less than 50% of the fibre modes [8]. Provided only a limited amount of mode mixing occurs, as is the case in high-quality multimode fibres, one may increase the fibre transport capacity by mode group diversity multiplexing [9]. As shown in Fig. 2, $N$ mode groups are selectively excited in parallel with separate data streams from $N$ laser diodes. At the receiving end, $M \geq N$ detectors produce $M$ signals which each contain a mix of the $N$ input data streams due to the mode mixing incurred in the fibre. A signal processing circuit subsequently inverts the $N \times M$ transmission matrix (using a training sequence of known bits). Thus the $M$ received streams are decorrelated, and the $N$ original data streams are recovered.

Experiments have shown the technical feasibility at 1 Mbit/s per channel for $N=M=2$; but the technique should be scalable to Gbit/s rates with appropriate high-speed processing circuits.

![Fig. 1 Transparent In-House Network with Polymer Optical Fibre, integrating fixed-wired and wireless services in a single infrastructure (MD = Mobile Device; FD = Fixed Device; RG = Residential Gateway)](image)

![Fig. 2 Mode group diversity multiplexing](image)

Measurements on POF reported recently indicated how the near field intensity pattern at the output facet of the POF indeed depends on the launching conditions at the input facet, thus basically showing how different mode groups can constitute different communication channels; see Fig. 3 [10]. Thus mode group diversity multiplexing may actually, after signal processing, enable a number of transparent communication channels in parallel on the same POF, allowing to host services with different signal formats into a single infrastructure.

The mode group diversity multiplexing unidirectional system concept can be extended to a bi-directional system. The inverted transmission matrix data deployed by the signal processing circuit and obtained with the downstream training sequence procedure may facilitate the selective launching for upstream transmission.

![Fig. 3 Near-Field Patterns at output of multimode POF, depending on launching conditions [10]](image)
a) Exciting low order modes only; NFP clearly focused in core centre
b) Exciting all modes, resulting in NFP spread out over whole fibre core
c) Exciting high order modes only; NFP concentrated in ring shape close to core-cladding boundary
The mode group diversity approach can also enable new medium access control strategies in point-to-multipoint architectures. The potential for this is being analysed.

Fig. 4 Modeling the optical system transfer function (for N=M=2)

From a mathematical viewpoint, the mode-group-multiplexed optical transmission system with its multiple inputs and outputs can be described with a signal transfer matrix. Given the N transmitters and M detectors, there is an N x M matrix of which element \( c(n,m) \) describes the signal transfer from transmitter \( n \) to detector \( m \); Fig. 4 illustrates this model for the case \( N=M=2 \). These complex elements \( c(n,m) \) have both an amplitude (representing attenuation) and a phase (representing phase delay) of the specific path \( (n,m) \). Due to random fluctuations in the mode coupling, fluctuations in the complex elements \( c(n,m) \) will occur. When the optical sources have a coherence time larger than the differential delay times between the modes, also speckle patterns caused by interference between the modes will contribute to fluctuations in the \( c(n,m) \) values \[11\]. Methods to deliberately reduce the coherence time of the sources to reduce the contrast of these speckle patterns are under study.

For multipath wireless systems such as multiple-input multiple-output (MIMO) wireless LANs, space-time codes and signal processing techniques have been suggested (cf. Lucent’s BLAST project \[12\]). There is some similarity with the transmission using several mode groups in a multi-mode optical fibre, and therefore derivatives of these techniques may be applicable in mode group diversity multiplexing.

When the transmitter knows the parameters of the actual channel, the overall transmission system performance can be optimised by means of signal pre-processing, e.g. by privileging the good mode group channels with respect to the (at that moment) bad channels; thus the system’s capacity can be increased. Also, by adding redundancy to the signal by means of a line code, error monitoring at the receiver site can be implemented. Feedback is necessary to inform the transmitter about the channel characteristics, in order to adjust the pre-processing when the channel characteristics alter. Once the receiver has determined the actual channel parameters, it can send these parameters back to the transmitter by a relatively low-speed return channel.

3. Electrical signal processing

In order to perform the electrical signal processing steps required for the mode group diversity demultiplexing process, a system as exemplified in Fig. 5 is required. This system consists of a photo detector IC (PDIC) followed by a signal processor equipped with an analog-to-digital (A/D) converter card and several FPGA cards. The multi-channel analog-to-digital converter samples the parallel output stream of the PDIC, i.e. one analog signal for each detector. Then a first high-density field programmable gate array (FPGA) takes care of the synchronisation and (adaptive) array equalisation, performing the transmission matrix inversion. A second FPGA performs the error detection and correction, and produces estimates of the transmitted symbols. Because of the signalling rates required, the speed of the cards and the power of the overall processor needs to be as high as possible. These experiments must eventually lead to a low-cost design in an application-specific integrated circuit (ASIC).

Fig. 5 Signal processing at the receiver site (example)

The equalizer function in the first FPGA can be trained in the initial transmission phase by means of special signal sequences sent by the transmitter. Also, when the error detector signals an error rate exceeding a certain level, via the feedback channel a new training period can be started at the transmitter end to re-initialise the system. Moreover, during the transmission process, the equalizer is adapted regularly by the control information that is produced by the error-correcting decoder. Thus temporal changes in the POF network transmission characteristics (as may occur due
to temperature changes, or modifications in the network infrastructure) can be accommodated.

The design of the transmitter is essentially simpler than that of the receiver; Fig. 6 gives an example of a possible setup. In the non-feedback case, the data is encoded, however only procedures are permitted then that allow decoding at a very high data rates. Therefore encoding cannot be very complex. In the feedback case the transmitter will be slightly more complex since the signaling procedure may depend on the state of the medium, but again the receiver will perform the major part of the processing. Via the feedback channel, also a new training period to re-initiate the system can be started, as mentioned above.

![Figure 6: Signal processing at the transmitter site (example)](image)

4. System implementation

To implement the system at low cost, integration of the optical and electrical functions is essential. An integrated array of vertical cavity surface emitting lasers (VCSELs) can advantageously be deployed for launching the different mode groups at the transmitter end; it may be coupled easily by means of a simple lens system, or even by butt-joining to the large-core multimode POF. At the receiving end, an array of integrated photodetectors can be easily coupled to the fibre's large core, and perform the spatially resolved detection of the mode groups.

The electrical signal processing is implemented first in FPGA-s, offering design flexibility. After having demonstrated the technical feasibility, the functions can be more cost-effectively integrated in ASIC-s.

5. Conclusions

Mode group diversity multiplexing allows to integrate multiple independent services in a single highly multimode polymer optical fibre network. It may offer the same functionality as wavelength multiplexing at lower costs, provided the required electrical signal processing and arrayed optical sources and detectors can be realised cheaply. In combination with wavelength multiplexing, several classes of mode-group-diversity multiplexed services may be carried in a single in-house network infrastructure, thus supporting e.g. fixed-wired Gigabit Ethernet user terminals as well as broadband wireless LAN terminals.

References


