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Advanced Technologies for Service-Integrated Optical In-Building Networks

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ABSTRACT

Optical fibre is marching fast towards the user's doorstep, as witnessed by the many new Fibre-To-The-Home installations. The next challenge is to disclose the power of optical communication inside the home, so to bring the full broadband potential to the end user. The presentation will describe the latest advances in our research into low-cost in-home techniques, encompassing techniques for service integration, for high-speed data transfer over highly dispersive polymer optical fibre, and for dynamically providing high-capacity wireless services over fibre.

Keywords: in-building network, polymer optical fibre, mode group diversity multiplexing, radio-over-fibre, quadrature amplitude modulation, optical routing

1. INTRODUCTION

Optical fibre is bringing high capacity to the user's residences in Fibre-to-the-Home networks. To match this capacity and extend it all the way to the user, inside his home there should be a good versatile broadband infrastructure as well. Presently, there is a variety of in-building networks, each optimized to deliver a particular set of services (CATV, telephony, high speed data, control and monitoring signals, etc.). A single converged in-building network would considerably ease the introduction and upgrading of services, as well as the creation of relations between those services. The signal transparency of optical fibre makes it an ideal medium to realize such converged network. However, standard single-mode fibre needs delicate handling and accurate installation. Large-core multimode fibre, and in particular ductile Polymer Optical Fibre (POF), is much easier to install, and thus could become the medium of choice for in-building networks. As illustrated in *Fig. 1*, such a network must carry wired as well as wireless services, operating at a variety of standards.

Fig. 1. POF-based multi-service in-building network.

The POF attenuation characteristics are improved steadily, but are still considerably worse than those of silica fibre; however, this is not a decisive argument in short-range in-building networks. The bandwidth of large-core multimode fibres is strongly reduced by multimodal dispersion, in particular in step-index fibres. Advanced signal processing and multiplexing techniques are therefore required to accommodate multiple services in an in-building network. For carrying multi-standard wireless services in the POF network, radio-over-fibre techniques are required which are robust against multimodal dispersion.

2. MODE GROUP DIVERSITY MULTIPLEXING

The fibre's multi-mode guiding mechanisms may be advantageously exploited by not launching all modes simultaneously (thus creating significant modal dispersion), but to employ several subsets of guided modes in parallel by selectively exciting them with different signals. This technique, which we have termed 'mode group diversity multiplexing' (MGDM) [1], enables independent multiplexing of a number of services on a single

multimode fibre infrastructure, and allows the use of sources with nominally the same wavelength. A number of cheap laser diodes (e.g. VCSELs) is used, each exciting a subset of modes in the fibre link, and a number of photodiodes each detecting a (differently composed) subset of modes; see *Fig. 2*. Signal processing at both ends of the link is applied to counteract mode mixing which inherently is incurred in the fibre. This processing has commonalities with MIMO (multiple input multiple output) techniques deployed in multiple-antenna wireless communication systems. We have demonstrated the feasibility of a basic 2x2 MGDM system, showing a good stability under environmental temperature changes [2]. The adaptive signal processing is aided by pilot tone monitoring.

Fig. 2. Mode group diversity multiplexing system.

3. HIGH-CAPACITY POF LINKS USING QUADRATURE AMPLITUDE MODULATION

Step-index PMMA POF with a very large core diameter, i.e. 1 mm, is getting increasing interest for cheap do-it-yourself in-home network installation. However, the bandwidth of such fibre is severely limited due to its large multimodal dispersion; bandwidths of only some 10 MHz for fibre lengths of 300 metres have been measured. In order to nevertheless transport data rates of 100 Mbit/s to 1 Gbit/s, one has to apply comprehensive data modulation formats in order to carry more bits per transmitted symbol. In the European joint research project POF-ALL, up to 8-level Pulse Amplitude Modulated signals are being investigated. Alternatively, we are exploring in this project the deployment of Quadrature Amplitude Modulation (QAM) formats, in order to further increase the information content per symbol and thus to reduce the bandwidth requirements on the fibre link. QAM techniques are commonly used in wide-spread applications such as wireless LANs, and DVB-C and DOCSIS cable modems. Hence for POF systems one may benefit from low-cost QAM chip sets commercially available for these applications, and their derivatives. QAM basically deploys two orthogonal transmission channels to convey the in-phase (I) and quadrature-phase (Q) data signal components. QAM chip sets consist of quadrature modulator/demodulator circuits, as well as a Baseband Processor (BBP) which converts the serial binary input data stream into the multi-level I- and Q-signals. To emulate QAM transmission on a POF link, we consider two options [3, 4], shown in *Fig. 3*: direct QAM, and wavelength-sliced QAM.

In the direct QAM method, the I- and Q-signals are modulated on the orthogonal cosine and sine versions of an electrical harmonic carrier. This is the approach commonly used in today's large volume applications mentioned before. For a data rate of R bit/s, and a QAM- N scheme, the symbol rate is $R/\log_2 N$. In double-sideband quadrature modulation, as rule of thumb the carrier frequency f_c needs to be at least $0.7 \cdot R/\log_2 N$, and the bandwidth of the link at least $1.4 \cdot R/\log_2 N$. In the wavelength-sliced QAM method, the I- and Q-signal are both carried in baseband on two separate wavelength channels, which may be formed by e.g. two complementary sliced parts of a broad spectrum light source such as a LED. This option requires a link bandwidth of at least $0.7 \cdot R/\log_2 N$.

Fig. 3. Options for QAM transmission over a POF link.

Of these two options, the direct QAM one is interesting because of the re-use of readily available QAM chip sets, and the wavelength-sliced one as it requires clearly the least link bandwidth. Experimental measurements of the relative Error Vector Magnitude (EVM) have been made for direct QAM over a link of 100 metres of 1 mm core diameter step-index PMMA POF, using a directly modulated 658 nm FP laser diode emitting 5 mW, or a 520 nm LED emitting 2 mW. The results are depicted in *Fig. 4*. At a symbol rate of 7 MBaud, the results show that the LED system performance is limited by the POF link bandwidth, whereas the laser-based system performance is limited by system non-linearities. The curves indicate also that for this 100 metres SI-POF link the EVM requirements for QAM-64 (i.e. $\text{EVM} < 5\%$) as well as those for QAM-256 ($\text{EVM} < 3.5\%$) can be met by both the LED-based system and the laser-based system. System experiments over the POF link reached 60 Mbit/s using QAM-16 with the 520 nm LED, and more than 150 Mbit/s using QAM-64 with the 658 nm Fabry-Perot laser diode. Using multi-tone techniques with 80 subcarriers and QAM-256, even 1 Gbit/s throughput over a 100 metres 1 mm core SI-POF link has been obtained using a 650 nm DVD-player laser diode [5].

Fig. 4. Measured EVM versus carrier frequency for direct QAM system over 100 metres SI-POF.

4. HIGH-CAPACITY FIBRE-WIRELESS NETWORK

The in-building network should preferably carry wired (e.g. Gigabit Ethernet) as well as wireless services (e.g. WLAN). Optical routing may improve the flexibility and the efficiency with which the network resources can be used. The in-building (polymer) optical fibre network concept shown in *Fig. 5* is being investigated for providing reconfigurable connectivity between broadband wireless pico-cells confined to rooms. Each room may have one or multiple antennas, and these antennas are each connected to a central unit, the Home Communication Controller (HCC). The wireless signals from one room to another room are carried by radio-over-fibre techniques to the respective antennas, without causing any interference into the other rooms. These connections between rooms are established by an optical crossconnect in the central HCC, which switches the analog radio-over-fibre signals transparently between its fibre ports. This optical transparency enables the support of multiple wireless standards, such as WiFi, WiMAX, emerging 60 GHz WLANs, etc. Thus, by optical routing virtual private wireless LANs can be established between rooms, and reconfigured upon user demand.

HCC: Home Communication Controller

Fig. 5. Flexible inter-room wireless communication using switched radio-over-fibre links.

The in-building network is preferably using multimode (polymer) optical fibre, so the radio-over-fibre technique should be able to overcome modal dispersion. Our Optical Frequency Multiplication technique [6] has been shown to be very robust against this dispersion. The OFM principle is shown in *Fig. 6*. A wavelength-tunable

laser is deployed, of which the optical frequency is periodically varied with a relatively low sweep frequency. A subsequent Mach-Zehnder Interferometer (MZI), or other periodic optical bandpass filter, performs an FM-to-IM conversion of this signal, by which a multitude of harmonics of the sweep frequency are generated. At the antenna site, after opto-electronic conversion in the photodiode a suitable electrical bandpass filter extracts the desired microwave harmonic component. It has been found (and also can be theoretically proven) that the generated microwave carriers are very pure, independent of the laser line width (as long as this linewidth is much smaller than the free spectral range of the MZI, which typically is the case). Thus comprehensive modulation schemes can be transported allowing high data rates. This OFM technique can be shown to be robust against modal dispersion in multimode fibre [7]. A 64-QAM system with 120 Mbit/s at a carrier of 17.2 GHz has been successfully demonstrated over 4.4 km dispersive 50 μm core silica graded-index multimode fibre [8].

Fig. 6. Optical Frequency Multiplying.

5. CONCLUDING REMARKS

The wealth of bandwidth offered by fibre in the metro and access network may be effectively unleashed inside buildings by advanced yet low-cost multimode fibre network techniques, enabling to integrate various types of services into a single fibre network infrastructure. In particular polymer optical fibre is an attractive medium, as it is very easy to install. Mode group diversity multiplexing allows service integration by deploying several mode groups in parallel. Using quadrature amplitude modulation, high capacity data services can be transported in highly-dispersive optical fibre, and using the optical frequency multiplication technique also high-capacity wireless services can be delivered through such a fibre. Optical routing techniques may be deployed for increasing the flexibility of the network, and for improving the efficiency with which the equipment is used.

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