SEVENTH FRAMEWORK PROGRAMME

Report on Y1 activities and new integration strategy

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Abstract:

The activities in the Virtual Centre of Excellence on In-Building Networks undertaken in the first year are described. Starting from an agreed modus of cooperation, the activities were structured according to the common interests as indicated by the partners. They comprised joint research activities, joint publications, joint workshops, and mobility by exchanging researchers. The activities of this first year have established a basis for extended joint activities in the second year, by which the integration of research activities in the domain of in-building networks among the institutes in Europe will be shaped.

Keyword list:

In-Building Networks, Joint Research, Mobility actions

Disclaimer

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1. Executive Summary

In this first deliverable of the BONE Virtual Centre of Excellence on In-Building Networks (VCE-H, i.e. WP16 in BONE), the activities undertaken in the first year of BONE are described. The scope of VCE-H addresses the important role which optical techniques (both fibre-based and free-space) can play in establishing a really broadband and versatile communication infrastructure to be applied inside buildings, which as an integrated network has to support a wide variety of services while efficiently interacting with both the access network and the user terminals.

The basis of the cooperation among the partners was laid by defining and agreeing on the mechanisms for integration within this VCE: identifying common interests, executing joint research activities, producing joint publications, organizing workshops, and exchanging researchers in the mobility programme. VCE-H's activities were defined within the eleven areas of common interest which were formulated as the common denominators of the interests stated by the partners.

For each of these areas, this deliverable describes the joint research activities in detail, as well as the publications which resulted from these and by which the jointly developed knowledge was disseminated. Also the mobility actions have been listed, which led to strengthening the cooperation between research institutes on a personal level. Two joint workshops have been held to align the activities and monitor their progress, and to define the next steps. Dissemination was also achieved by contributing to many other workshops and conferences.

These activities have created a sound basis on which in the second year the cooperation will be extended among the BONE research groups involved in architectures, systems and devices for in-building networks. It is expected that this will lead to a lasting framework for Europe-wide interaction in research in the domain of in-building networks.

2. Introduction

The major objective of VCE-H is

To align the research activities on architectures and techniques for optical in-building networks,

by

- Co-ordinating and integrating research efforts, encompassing
  - Exchange of researchers
  - Joint research and laboratory experiments
  - Joint publications
  - Joint dissemination by means of workshops
- Establishing benchmark platforms for different optical in-building techniques
- Providing guidelines for roll-out and deployment of optical in-building networks, including migration paths

In this report, after describing the integration mechanisms in chapter 3, the joint research activities undertaken and the publications which resulted thereof are described in chapter 4. Furthermore, in chapter 5 the mobility actions are listed.

3. Mechanisms for Integration

The integration within this VCE-H is to be established by various ways of cooperation, based on an inventory of common interests among partners.

These co-operations encompass

- exchanging researchers by means of BONE's mobility programme, such that the experience of (young) researchers can be widened and the base of co-operation between research groups can be broadened
- joint research and laboratory experiments
- joint publications, at conferences and in journals or books
- jointly organizing dissemination events such as workshops etc.

It should be noted that several co-operations between partners have already been started within the preceding NoE e-Photon/ONe, within its Virtual Department VD-H on Home Networks. Within VCE-H, there is a further intensification of these co-operations, which also extends to other FP7 projects such as ALPHA, OMEGA, FUTON, POF-PLUS, etc., and to national projects.

In order to facilitate the integration among the VCE-H partners, the key research areas of common interest to the partners have been identified (as reported before in Milestone M16.1):

1. In-building optical network architectures, for integration of services, wired and wireless
2. Hybrid (optical/copper/wireless) in-building networks, upgrading
3. Management and control of in-building networks, ambient intelligence, control of resources, user-tailored services
4. Fault & performance monitoring + protection mechanisms, assure QoS, ease maintenance
5. Gateways access/in-building; interfacing, security, service adaptation, …
6. Interfacing with user terminals, matching I/O formats
7. Flexible capacity allocation, capacity and QoS on demand

8. Radio-over-single/multimode fibre, antenna remoting, CS consolidation
9. High capacity data over SMF/MMF, BW efficient modulation formats
10. Wireless optical communication, for pico-cells
11. Sensor applications (bursty, low data rate, multiple access)
12. Techno-economic analysis, to optimise system design
13. Safety and health aspects (a.o. eye safety, automatic shut-down)

The partners have been invited to indicate in which areas they are interested, and to describe these interests in more detail. The common interests of the partners are listed in the table shown in the Annex. Starting from this table, joint research activities have been initiated and executed, as well as mobility actions to exchange researchers.

3.1 Advisory Board

The following members were willing to provide their advice regarding VCE-H organizational and research directions, and to act as a liaison person to other BONE VCE-s and TP-s:

- John Mitchell (UCL; leader VCE-Access)
- Piero Castoldi (SSSUP; leader VCE-Services and Applications)
- Ioannis Tomkos (AIT; leader TP optical Communication Networks in support of user mobility and networks in motion)
- Achille Pattavina (PoliMI; leader TO Optical Interconnects)
- Maurice Gagnaire (GET)
- Stuart Walker (UEssex)
- Mario Pickavet (IBBT)
- Evi Zouganelli (Telenor)
- Juan Pedro Fernandez-Palacios Gimenez (TID)
- Mikhail Popov (ACREO; leader ALPHA)
- Andreas Stöhr (UDE; leader IPHOBAC)

4. Joint research activities

4.1 In-building optical network architectures

4.1.1 Analysis of the requirements and architectural options for broad-band in-building networks supporting wired and wireless services and based on an optical backbone

- FT R&D: Anna Pizzinat

Research activities

For home area networks (HAN), we have identified the following requirements:
- installation ease, transparency, ability to adapt to evolving needs, interfaces and usages
- technology hybridisation
- long term home network infrastructures

A subjacent requirement for the HAN is to support data transmissions comparable to hard-disk to hard-disk transfer rates inside a single computer. Throughputs of about 500 Mbps have to be reached for that with, at the same time, high reliability for sensor networks and control applications. Moreover, higher rates will be necessary for uncompressed HDTV streams but these should be supported by short fixed links and not necessarily by the whole network. Lastly, analogue or quasi-analogue services could be added on top of these requirements to comply with the end-user requirements for a wireless end-connectivity enabling flexibility and even mobility within the house. Furthermore, the increase in available access rates makes it possible for applications requesting large transfer rates to run in parallel within the same home thus pushing higher the data rate demands for the HAN.

In this context the use of optical fibre to provide an Ultra Broadband HAN backbone for Future Internet is seen as key to the continued development of communications and infotainment. The deployment, architecture and fibre type used for such a backbone will be strongly influenced by economical factors, end-user requirements and installation constraints. In this first year of BONE activities we have identified the following directions for ultra broadband HAN backbone:

- Plastic Optical Fibre infrastructure to provide a point to point architecture suitable for already constructed houses where the installation of a new cable can be performed by the user itself. This infrastructure will be suitable for the performance required in a medium term scenario.
- Silica Fibre infrastructure for new houses where the optical cables will be installed in ducts running in the walls at construction time. The architecture will have the possibility to evolve from point to point offering sufficient performance again for a medium term scenario to fully transparent multipoint to multipoint network able to respond to any future bandwidth requirements. For this scenario, Single Mode Fibre is believed to be the best choice as it guarantees the long term suitability of the network and it benefits from the economy of scale and experience gained from current FTTH deployments.

Other solutions are also considered using silica fibre type resilient to bending loss suitable for retrofitting existing buildings or higher bandwidth plastic optical fibre which could be suitable for backbone deployments in new buildings, but these less technically mature solutions will need further survey and experience.

A demonstrator based on the multipoint to multipoint broadcast and select CWDM architecture using SMF integrating digital and analog services has been realised and new services are being added.

Publications

This activity has led to an invited presentation at ECOC workshop on short range optical networks: Jérôme Le Masson, "Towards Optical Home Networks".

Joint publications

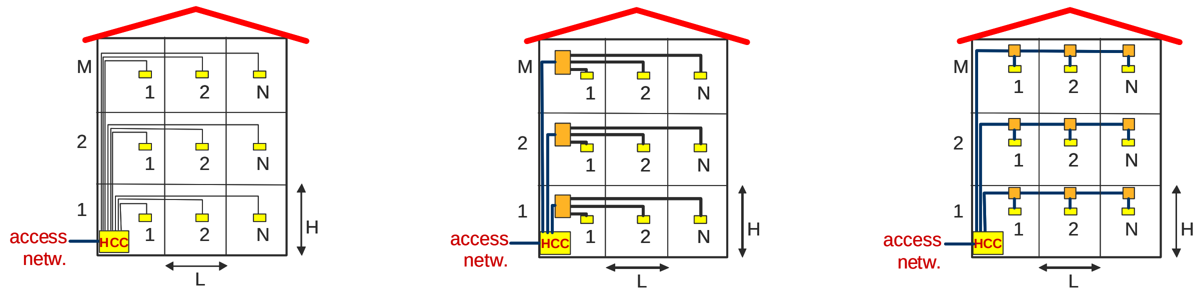
Moreover, with POLITO and UDE we have submitted a joint paper to "Future Internet conference and Technical workshops".

4.1.2 Cost considerations on in-building optical networks

- FT R&D: Anna Pizzinat
- TUE: Ton Koonen

Joint research activity

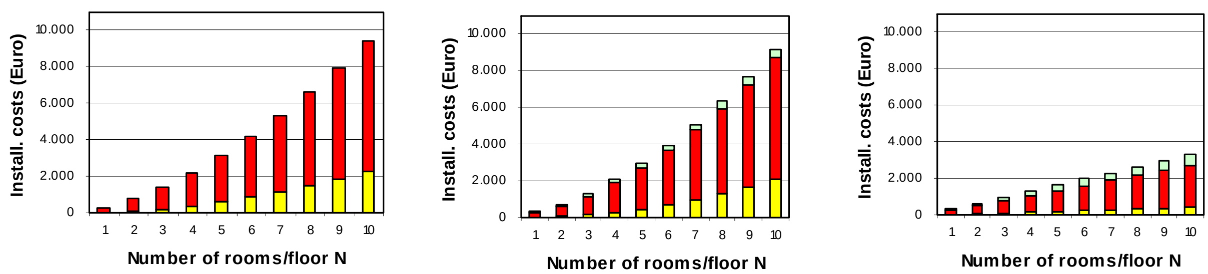
This activity aims at analysing cost-economics issues of different architecture options for in-building networks. A number of architecture options may be considered for the in-building optical fibre backbone network, using single-mode or (silica or plastic) fibre.



a) point-to-point b) tree c) bus

Fig. 1 In-building wiring topologies

A first analysis has been made of the dependence of the infrastructure costs on the topology choice. The cost items for each topology as a function of the number of rooms per floor *N* have been depicted in Fig. 2.a – c for a low-rise building, with *M*=3 floors. The other parameters assumed are: room height *H*=3 metres, room length *L*=5 metres, fibre cable costs € 3 per metre, single-fibre duct costs € 15 per metre (including trenching). Active in-line devices have been assumed, with costs of € 20 for an OEO hub, and € 15 per port for an OEO switch.



a) point-to-point b) tree c) bus

Fig. 2 In-building network cost items for a three-level building (*M*=3; per column, from top to bottom: light blue=in-line devices costs, red=duct costs, yellow=fibre costs)

From the viewpoint of costs, point-to-point topologies are most interesting for smaller buildings (typical residential ones), whereas in larger buildings (such as public or semi-public ones, or office buildings) a bus topology may be more interesting. In order to equalize the differences in link budget between the terminal nodes, optical power splitters with tailored splitting ratios may be used along the bus line.

More comprehensive studies of infrastructure and system costs will be done in the near future. This activity will be continued in 2009 and a joint paper will be prepared.

4.1.3 Coupling devices in-home networks

- UC3M: Carmen Vázquez (cvazquez@ing.uc3m.es)
- UDE: Dieter Jaeger
- Ericsson: Rebecca Chandy

Joint research activities

The main activity from Ericsson for this area has been the development of transmitter and receiver circuits and 1x2, 1x4 and 1x8 POF couplers for in-home networks. The receiver circuit converts the optical signal into an electrical signal.

The experimental results below show the tests done in the design and evaluation of the optimum spacing between the input fibre and output fibres for a 1x4 coupler; see Fig. 3. The PMMA POF used has a step-index refractive index profile, an outer diameter of 1mm and a core diameter of 0.98mm, and a numerical aperture NA=0.5. As an example, the tests done on the second output fibre by placing the first, third and fourth output fibres at different spacings are shown below.

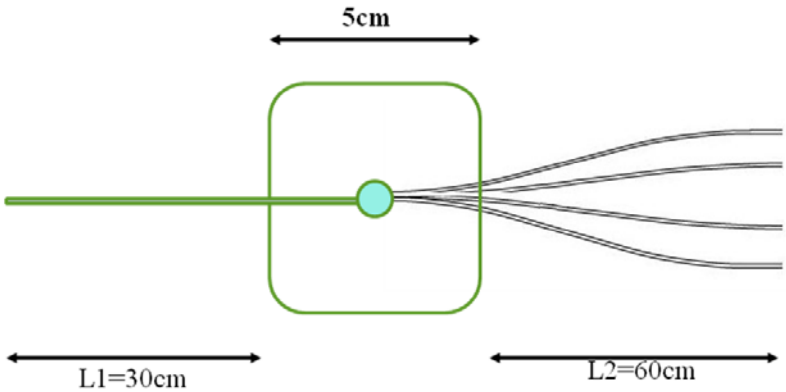


Fig. 3 Experimental setup of 1x4 POF coupler (with output fibre 1 at distance *d* from the input fibre)

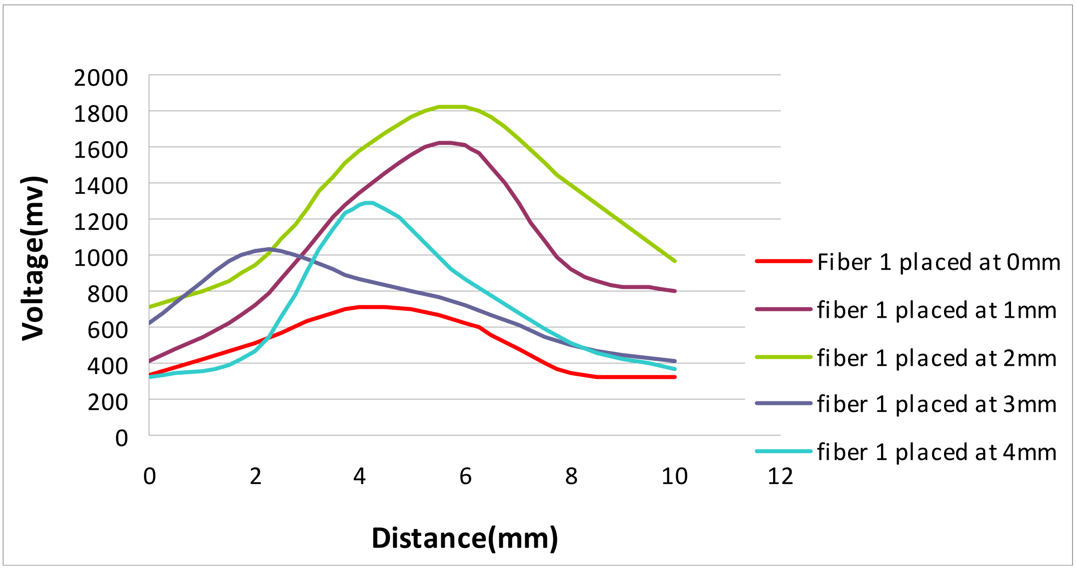


Fig. 4 Voltage from Output fibre 2 when output fibre 1 is at different spacings with respect to input fibre

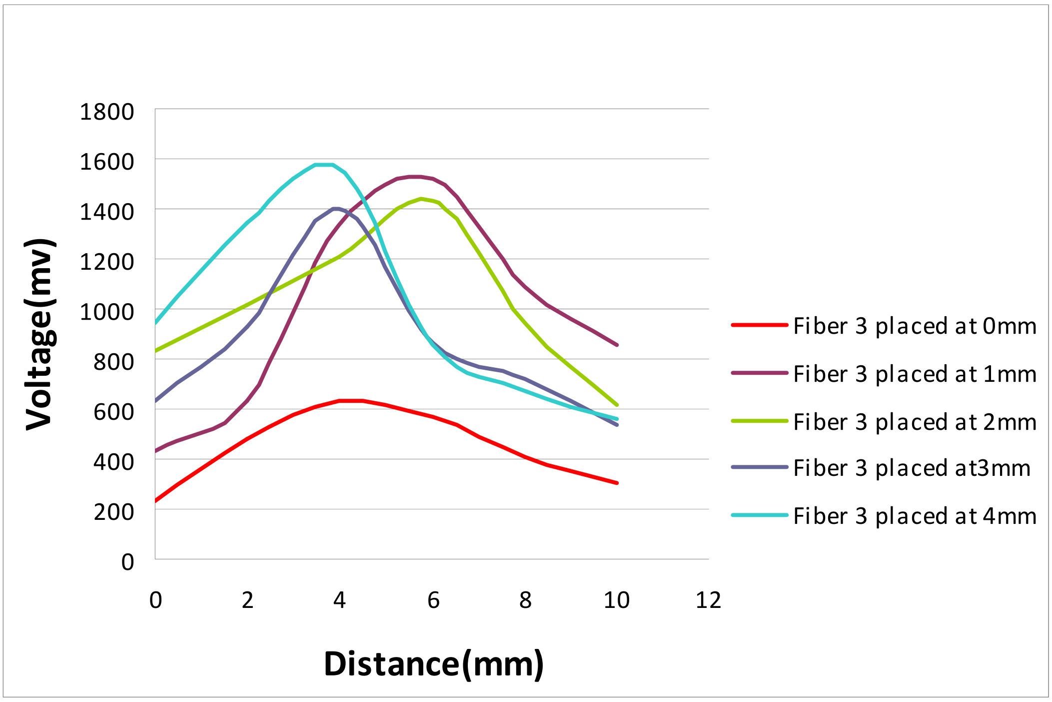


Fig. 5 Voltage from Output fibre 2 when output fibre 3 is at different spacings with respect to input fibre

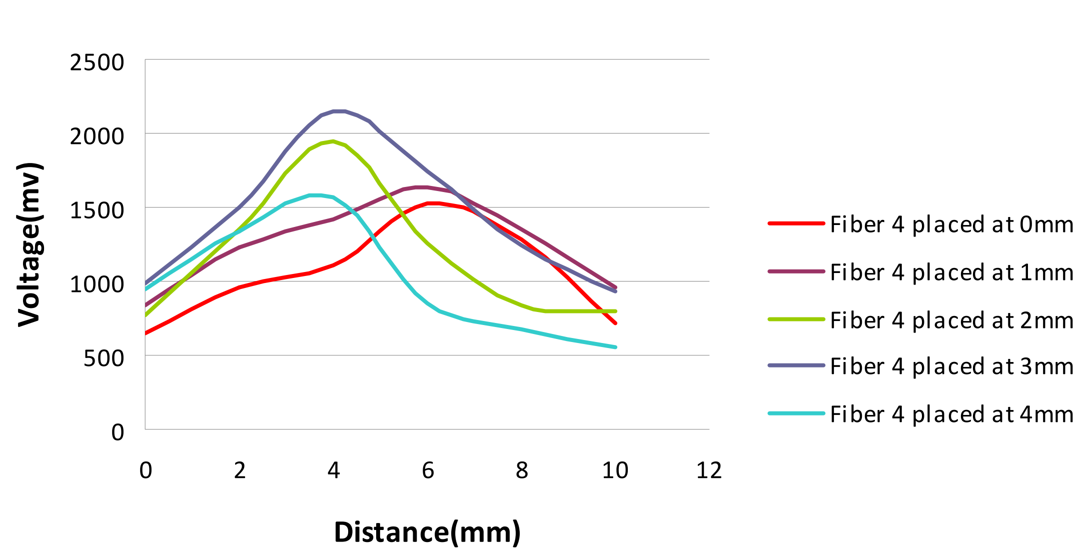


Fig. 6 Voltage from Output fibre 2 when output fibre 4 is at different spacings with respect to input fibre

4.1.4 In-house PON built with POF

- UoP: Chris Matrakidis

Joint research activities

For most home POF networks a Passive Optical Network (PON) topology can offer significant advantages with respect to point to point connections and to tree or bus topologies with active in-line devices:

- The tree (bus) topology allows the use of a single transceiver at the network entry point.
- All sockets are live (while unconnected), so simple plug and play operation is possible.

The benefits are obvious in terms of flexibility in cabling installation (smaller lengths, less required space) and expandability (additional/external splitting after initial installation with active switching equipment only when required). It also offers benefits in terms of reduced cost, since with one port on the central hub there is no need for employing multi-port switches, no need to schedule in advance the number of active ports and no need to add switches as the network grows.

As with all PON systems the main problem is the power budget. The high losses and attenuation inherent in POF systems stress this even more, with additional performance degradation parameters like connector losses and non-uniform splitting also being taken into account. The following figure shows a possible implementation with 8 terminals passively connected utilising 30:70 splitters and SI POF.

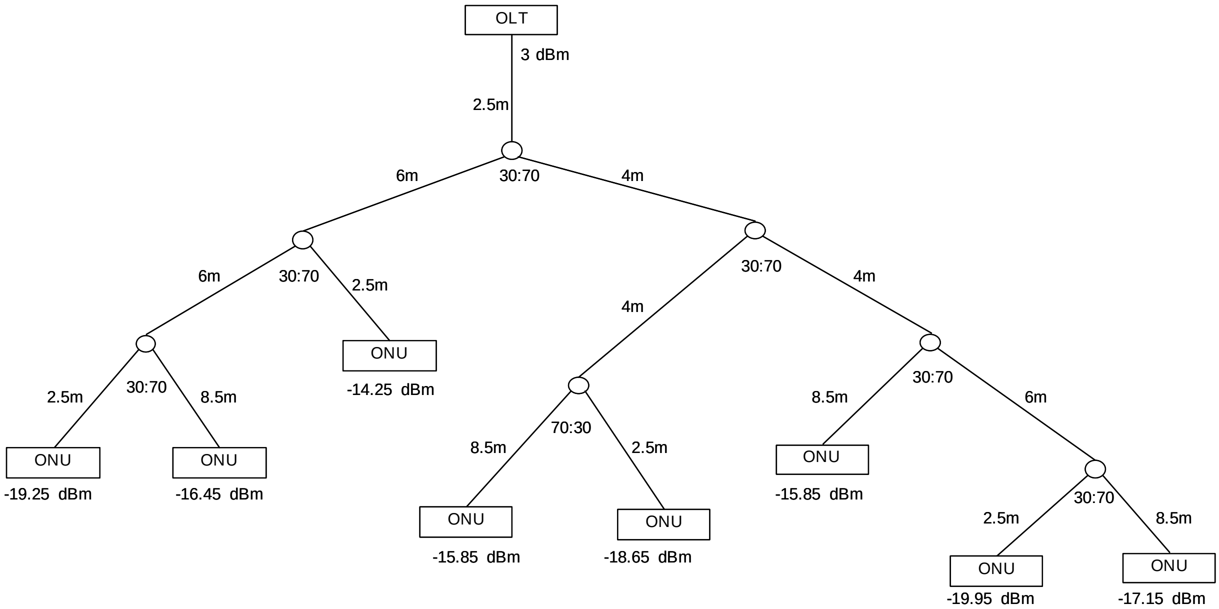


Fig. 7 Tree topology for an in-house POF network

4.2 Hybrid (optical/copper/wireless) in-building networks

4.2.1 Feeding data to a WLAN system via POF

- UDE: Ingo Möllers, Dieter Jäger

Research activities

In current consumer targeted short range and in-building networks the combination of wired and wireless solutions unifying a high quality-of-service and a certain range of mobility is widely investigated [1]. In many cases the focus lies on direct radio-over-fibre solutions supplying distributed antenna systems directly with the radio frequency (RF) signal [2]. For the development of very low cost solutions Step-Index (SI-)POF can be and are already being used for in-building networking with advantages of eye-safety, immunity against EMI, and with the feasibility of do-it-yourself installation [3]. Due to its high modal dispersion a transmission of RF signals is limited by using SI-POF to only a few meters what inhibits the use of these fibres for direct RoF systems. Hence, a solution for a convergence of both network infrastructures by creation of a POF based Fibre-Radio System for WLAN is presented.

<u>Design</u>

A D-Link DWL-G700 AP containing a usual unshielded twisted pair (UTP) (e.g. Cat5) electrical interface for Ethernet connection and WLAN antenna was rebuilt. The UTP interface and the corresponding inductor were exchanged by a POF-Transceiver. The embedded D-Link/Realtek phyceiver chip has been converted from 100BaseTX to 100BaseFX operation by resetting the electrical connections and fitting the voltage levels (PECL) to the POF transceivers requirements by a suitably built driving circuit (Fig. 8).

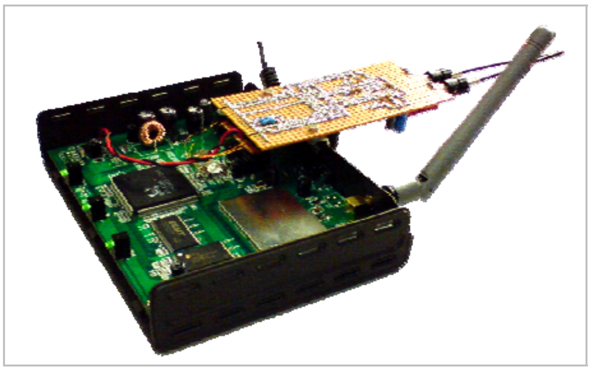


Fig. 8 WLAN-POF Access Point

In the optical domain the baseband digital Fast Ethernet signals are transmitted over up to 70 m of standard SI-POF at a wavelength of 650 nm using LEDs. This data is converted by the integrated System-on-Chip IC RLT 8186 into OFDM and mixed with an RF carrier to the corresponding 2.4 GHz and 5.5 GHz, respectively.

Experimental Results

Data rate measurements using NetIO 1.23 software with both standard D-Link WLAN-UTP AP (Fig. 9(a)) and rebuilt D-Link WLAN-POF AP (Fig. 9(b)) were carried out. The setup contains two laptops; one connected to a UTP-(UTP)-POF-Switch and a second one connected to the AP via WLAN radio connection with a distance between AP and laptop of 2 m. In order to compare both measurements the UTP cable and standard WLAN-UTP AP were substituted by a duplex SI-POF connection of 25 m together with the rebuilt AP. With the NetIO benchmark program running on both laptops - one in slave mode (laptop 1) and one in master mode (laptop 2) - data rates of 10.02 Mbit/s (sending direction: laptop 2 ->1) and 7.88 Mbit/s (laptop 1->2) were obtained for the POF based version (b). In comparison the data rates for the standard UTP connection using the WLAN-UTP AP (a) were recorded to be 11.49 Mbit/s and 8.04 Mbit/s, respectively. As a result it can be summarized that the POF based AP has a slightly lower performance. The low data rates of around 10 Mbit/s compared to 54 Mbit/s as given in the IEEE 802.11g standard could not be reached most likely due to interferences of multiple WLAN base stations.

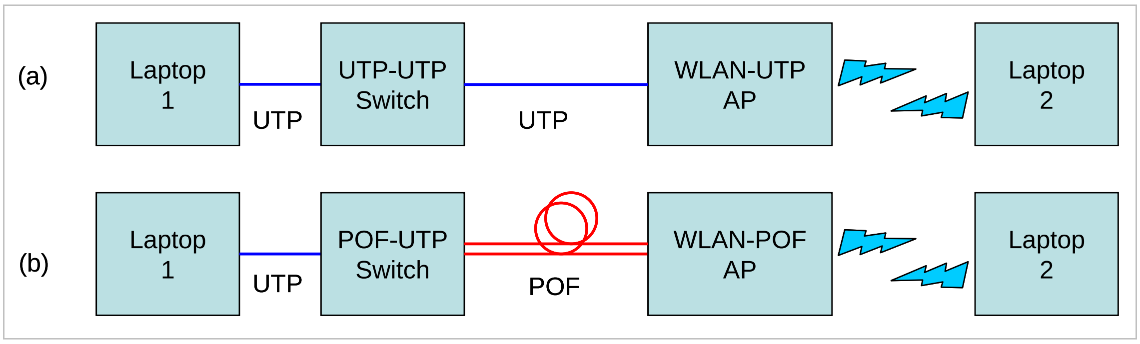


Fig. 9 Schematic of the setup for data rate and latency time measurements; (a) standard WLAN-UTP AP; (b) WLAN-POF AP

The average latency time (100 requests by laptop 2) using the same setups as shown in Fig. 9(b) is at 189 ms. Compared to the standard AP version (a) the average latency time only raised around 9 ms; Maximum values were seen to be around (a)914 ms ((b)1143 ms); the minimum in both cases at 2 ms.

The signal quality was tested using the setup depicted in Fig. 10.

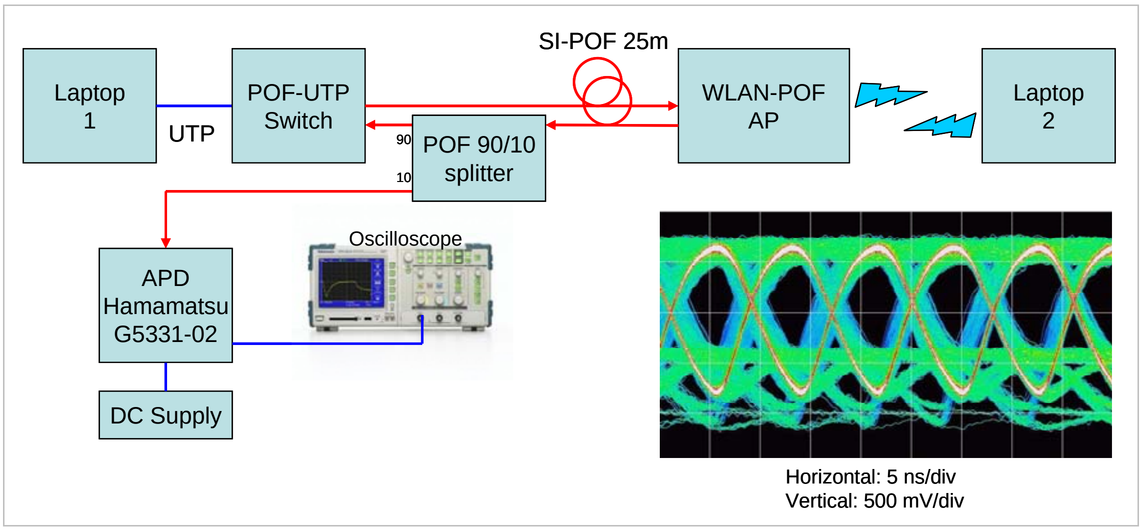


Fig. 10 Schematic of the setup for signal quality measurements with corresponding eye-diagram

The signal quality measurements in data transfer operation show an open eye for the optical signal sent by the WLAN-POF AP. The signal is split by a POF based y-coupler with a ratio of 90/10 in order to maintain the data transfer, and received by an APD (Hamamatsu G5331-02) and an Oscilloscope. No packet errors were obtained during the measurement.

Conclusion and future work

A prototype WLAN-POF access point for fibre-wireless systems was realized. It was shown that the performance of the system is comparable to standard WLAN systems using the D-Link DWL-G700 AP. Further improvements could include the miniaturization of the driving circuit and the design of only one printed circuit board for all ICs and the optical interface.

References

[1] L. Pergola, R. Gindera, M. Bülters, I. Möllers, R. Vahldieck, D. Jäger, "Dual Band LTCC-Based Wireless Transceiver with Optical Interface using Polymer Fiber", IEEE MTT-S IMS 2007, pp. 59-62, Honolulu, USA, June 2007

[2] Ingo Möllers et al., "High-Speed Transceiver for Radio-over-POF Applications", Proceedings of Int. Conf. on POF 2007, pp. 48-51, Turin, Italy, 2007

[3] R. Gaudino et al., "Status and recent results from the POF-ALL EU project: large-core plastic fibers for low cost, high-speed short reach applications", Proceedings of ECOC 2007, Vol. 2, pp. 113-115, Berlin, Germany, 2007

Publications out of the joint research activity:

1) Ingo Möllers et al., "High-Speed Transceiver for Radio-over-POF Applications", Proceedings of Int. Conf. on POF 2007, pp. 48-51, Turin, Italy, 2007
2) I. Möllers, F. Wetzel, G. Rebner, T. Rähder, D. Jäger, "Polymer Optical Fiber Based Fiber-Radio System for Wireless LAN Applications", 6th ISIS Workshop 2008 on FTTH, Wireless Communications and their interaction, Stockholm, Sweden, June 2-4, 2008
3) I. Möllers, M. Bülters, D. Jäger, "Radio-over-Fiber in-Building Communication Using an Integrated Electro Optic Transceiver", Photonics and OptoElectronics Meetings (POEM 2008), Wuhan, China, 2008

4.3 Management and control of in-building networks

4.3.1 Performance evaluation of an optical transparent access tier

- TUE: Bas Huiszoon, Ton Koonen
- UAM: Javier Aracil

Joint research activities

The increasing amount of bandwidth requirements and quality of service needs for the next-generation access networks has boosted extensive research in the fibre-optics communication field. In this light, passive optical networks (PONs) combined with optical code division multiple access (OCDMA), provide a potentially cost-effective solution to meet such bandwidth demands. An optical transparent architecture is proposed which enables all-optical communication between the network nodes. The network architecture is shown in Fig. 11. It may be implemented in various network environments, such as large campus or office networks.

The ONUs encode their data bits using incoherent spectral codes and the optical address of the destination is employed during transmission of a packet, that is, each ONU is uniquely identified in the network via a {wavelength, code}-combination. It is noteworthy that the selected coding technique transmits complementary codes to represent the two binary input levels. Figure 1 clearly shows that the encoded data streams are multiplexed at two merging points in the network which results in multiple user interference (MUI) on the fibre after that node, thereby significantly reducing the network throughput.

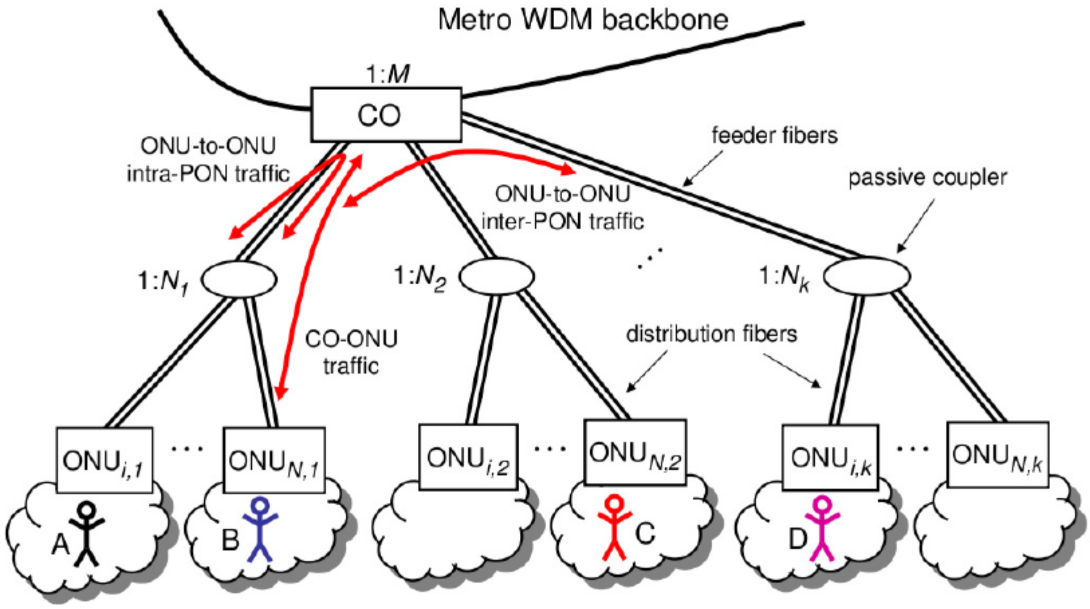


Fig. 11 Passive optical network-based access network and the traffic streams

The network is enhanced such that user activity sensing is possible. As a result, the networking nodes are able to monitor and record user activity in the PON, and additionally, further register the (past) state of activity at the first merging point which is the passive coupler.

Essentially, the coherence between the observed state at the network node and the real (future) state at the first merging point is evaluated at the packet level, thereby simplifying the analysis. A set of experiments are carried out for a number of realistic scenarios in case of four different packet size distributions and a fixed propagation delay between the network node and the first merging point. In all considered cases, the coherence of state is shown to depend on the packet size distribution and on the sampling rate. Regarding a single active user, the observed and future states are found to be coherent with respect to the transmission distance and memorylessness may be assumed for decreasing sampling rates. Concerning multiple active users, the coherence of state is shown to depend on the packet size distribution when the number of transmitting ONUs is small, but to approach exponential behaviour (memorylessness) as the number of simultaneous ONUs increases.

Additionally, it is shown that the a-priori knowledge of user activity can be exploited, for instance by allowing the ONUs to anticipate and decide whether or not to transmit a packet and, if so, when to schedule its transmission. Such scheduling must take into account the network design parameters, such as propagation delay and the number of ONUs per PON. Finally, the mathematical framework introduced in the work sets the grounds for further development of medium access protocols in such transparent optical access architectures.

References

Bas Huiszoon, Optically transparent multiple access networks employing incoherent spectral codes. PhD thesis, Eindhoven Univ. of Technology, June 10, 2008

Publications out of the joint research activity:

[1] B. Huiszoon, J.A. Hernández, H. de Waardt, G.D. Khoe, J. Aracil, A.M.J. Koonen, "Performance evaluation of an optical transparent access tier based on PON and spectral codes", accepted for publication in *IEEE Journal of Selected Areas in Communications*, special issue on *Broadband Access Networks*, pp. 1-13. Scheduled for publication: February 2009

Mobility actions

Bas Huiszoon, M.Sc. (TUE, P36) to UAM (P11), from 01-03-2008 until 10-07-2008

Future Activities

Joint OCDMA experiments TUE-UAM, spring 2009

4.4 Fault & performance monitoring + protection mechanisms

No activities of partners reported.

4.5 Gateways access/in-building

No activities of partners reported.

4.6 Interfacing with user terminals

No activities of partners reported.

4.7 Flexible capacity allocation

No activities of partners reported.

4.8 Radio-over-single/multimode fibre

4.8.1 Design and integration of transparent NxN fibre switches for controlling the inter-room communications between Radio-over-Fibre links

- UC3M. Carmen Vázquez (cvazquez@ing.uc3m.es)
- GET. Telecom Bretagne: Bruno Fracasso

Joint research activities

The topic addressed is the integration of transparent NxN MMF–switches for controlling the inter-room communications between RoF links. The required system functionalities are described in [1] and preliminary integration results of a dynamic multiplexer based on polarisation switching in liquid crystals are reported in [2]. Two further steps were adressed during a two-months mobility action (P. Contreras at GET-Telecom Bretagne, 18 Sep.-28 Nov.), namely (i) new liquid crystal cells fabrication and characterisation and (ii) 3x1 dynamic multiplexer integration and tests (both static and dynamic). This work is described with more details in the following.

The multimode fibre switches will be based on Liquid Crystals (LCs), so LC cell fabrication and characterization is developed; oriented to their application as part of those switching devices to be used in in-home networks for keeping connectivity between different rooms. Those rooms will have broadband access capability by using RoF to reach each pico-cell at each individual room.

This device will perform some of the functionalities reported in [1] if available.

As a first step, a multifunctional device able to switch by splitting and attenuating has been developed and characterized. It is a combination of a multiplexer and a variable optical attenuator in the same device (VMUX) for being used in Polymer Optical Fibre. A schematic of the developed device can be seen in Fig. 12.

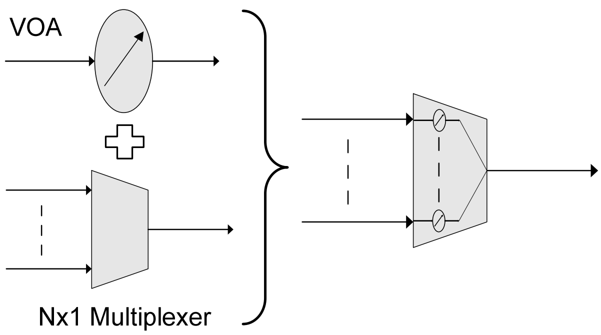
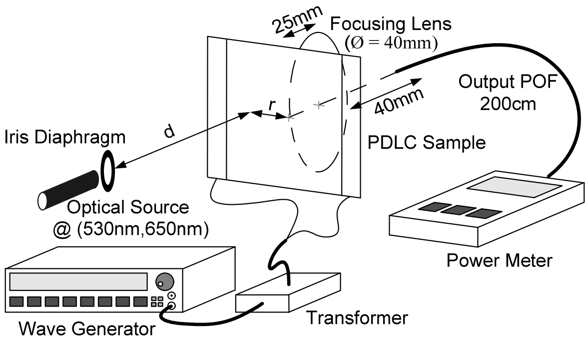
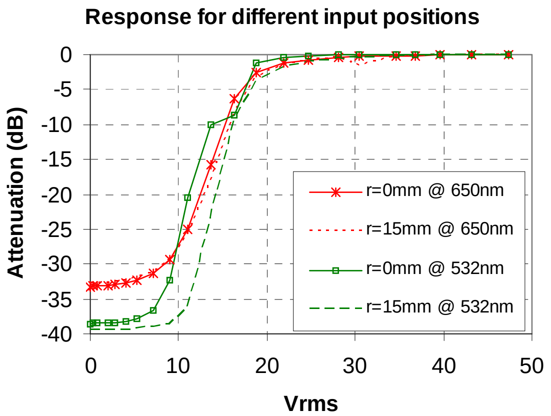


Fig. 12 Symbol of the VMUX

Polymer Dispersed Liquid Crystals (PDLC) are polarization independent, have high contrast and gray scale capability. For these reasons, PDLC cells with pixels can be used as switching elements in the device. Characterization of the PDLC has been carried out at two wavelengths. The experimental set-up for a single pixel configuration can be seen on Fig. 13.a. On the other hand attenuation range versus excitation voltage for different VMUX pixel configurations, depending on the offset between input fibre and PDLC can be seen on Fig. 13.b.

VMUX Complete switching is reached for driving voltages of 20Vrms, with insertion losses less than 1.6dB, attenuation larger than 31dB, rise time less than 2.6ms and decay time better than 12.4ms have been obtained.





a) Experimental set up for measuring PDLC characteristics

b) PDLC response for different input port positions

Fig. 13 Switching with a Polymer Dispersed Liquid Crystal device

Further collaboration with UC3M on the MM fibre switching/multiplexing topic is planned for the year to come. Alternative NxN fibre switching architecture assessment using free-space optics and 3D beam deflection will be considered (see e.g. [3]). This issue is of particular interest if large swiching capacities are required (i.e. several tens of input/output fibres). Additionally, the use of Polymer optical fibres (POF) is of particular interest when room cabling is considered, owing to the low cost and easier handling of POFs compared to silica fibres. Hence, first switch prototype dimensioning and integration will address POF arrays.

References

[1] Koonen, A.M.J., Garcia Larrode, M., Ng'Oma, A., Wang, K., Yang, H., Zheng, Y., Tangdiongga, E. (2008). Perspectives of radio over fiber technologies. Proceedings of the Optical Fiber Communication and National Fiber Optic Engineers Conference (OFC/NFOEC 2008). (pp. OThP3). San Diego

[2] P. C. Lallana, C. Vázquez, D. S. Montero, K. Heggarty , B. Vinouze, Dual 3x1 Multiplexer for POF Networks, Proceedings of the POF'07 Conference, Torino.

[3] C. Letort and B. Fracasso, Design and fabrication of a high-density 2D fiber array for holographic switching applications, Optical engineering, vol. 47, n°4, 2008

Publications out of the joint research activity:

1) [1] P. C. Lallana, Carmen Vázquez, B. Vinouze, K. Hegartty, David Sánchez Montero, “Multiplexer and Variable Optical Attenuator based on PDLC for Polymer Optical Fiber networks” *Journal of Liquid Crystals* , 2008
2) [2] P. C. Lallana, Carmen Vázquez, B. Vinouze, K. Hegartty, David Sánchez Montero, “Multiplexer and Variable Optical Attenuator based on PDLC for Polymer Optical Fiber networks” International Workshop On Liquid Crystals For Photonics, LCP08, Cambridge (UK) 21-23 July 2008

Mobility actions

1) PhD student Pedro Contreras from UC3M has spent more than 3 months in Telecom Bretagne: 18 sept-28nov
2) Prof. C. Vázquez & B. Fracasso discussions at 2 days visit at Telecom Bretagne of C. Vázquez (13-15 February 2008) and 3 days visit at UC3M of B. Fracasso (April 2008)

Future Activities

- A new mobility from Prof. C. Vázquez to Telecom Bretagne will be done on February 2009

- A new paper is under development.
- Another way of providing space-connectivity between MM fibre arrays is to use free-space connections (or switching). The main advantage with this technique is that the number of fibres that could be connected is probably much larger than with the solution currently developed. Some experiments to confirm this will be designed.

4.8.2 Fibre-fed distributed antenna system for passive RFID

- UCAM: I. H. White, R. V. Penty, J. D. Ingham, M. J. Crisp, C. H. Kwok

Research activities

A test bed has been implemented to study the effects of a fibre-fed distributed antenna system (DAS) on passive RFID, in particular the elimination of nulls and increasing the probability of a successful read. In addition, we have implemented a dual-function passive RFID sensing and communications DAS and carried out initial experiments on the use of Si APDs for low-cost RoF. The RFID work has been performed in collaboration with University College London.

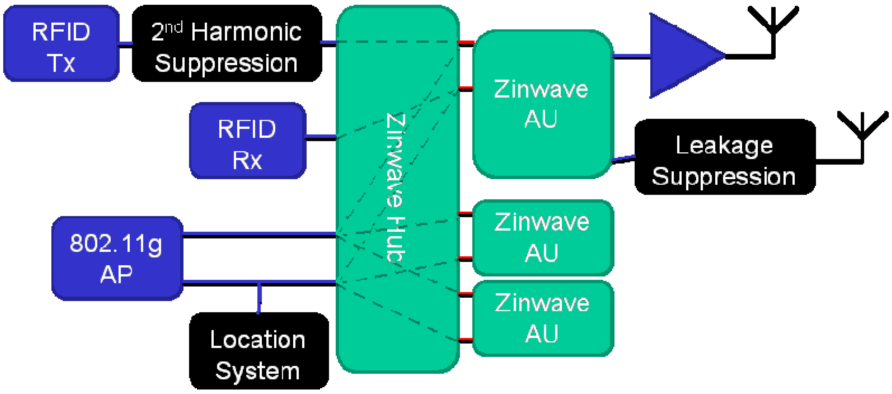


Fig. 14 Experimental arrangement for the investigation of the reduction of 2nd-harmonic spurious emissions in a wideband multiservice distributed antenna system

Publications

- I. H. White, "Optical systems and RoF," (invited) *Asia Pacific Optical Communications 2008*, Hangzhou, China, Oct. 2008
- M. J. Crisp, E. T. Aw, A. Wonfor, R. V. Penty, I. H. White, "Demonstration of an SOA efficient 32x32 optical switch for radio over fiber distribution systems," *Optical Fiber Communication Conference 2008*. San Diego, CA, USA, Feb. 2008

4.8.3 VEAT as novel bidirectional full-duplex passive RoMMF Transceiver

- UDE: Ingo Möllers, Dieter Jäger

Research activities

There is a general agreement that the future market of broadband WLAN communications and in-building networks will lead to a convergence of fibre and radio systems. A very attractive solution is radio-over-fibre (RoF) technology where low-cost and low-power base stations are being studied.

This paper is intended to give an overview and recent results on short range RoF communications where a novel high-speed photonic component is used for optoelectronic conversion for full-duplex up- and downlink. The key device is a multifunctional vertically integrated transceiver based on electro absorption and photo detection in a semiconductor structure.

The RoF transmission system (Fig. 15) is based on WDM technique with only one multimode glass (GOF) or polymer optical fibre (POF). A new Vertical Electro-absorption Transceiver (VEAT) is developed for O/E and E/O conversion in the Base Station. This device is a totally passive bidirectional full-duplex optoelectronic component which provides very low power consumption. The measurements are performed with a 50/50 MM-GOF Y-coupler instead of a MM circulator see Fig. 15.

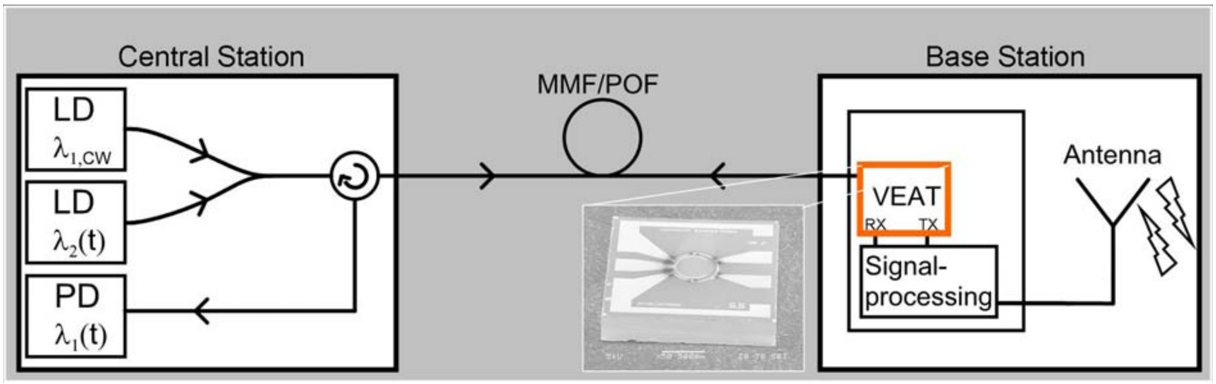


Fig. 15 Radio-over-Fibre communication system with vertically integrated transceiver

Device Characterization - Modulator

The reflectivity contrast of the modulator and its linearity in the I-P_{opt}-characteristic is an important value modulation depth. A linear contrast leads to a linear change in modulated optical power dependent on applied voltage. The reflectivity contrast is shown in Fig. 16 and defined as CMOD:

$$C_{MOD} = \frac{P_{opt}(0V) - P_{opt}(xV)}{P_{opt}(0V)}$$

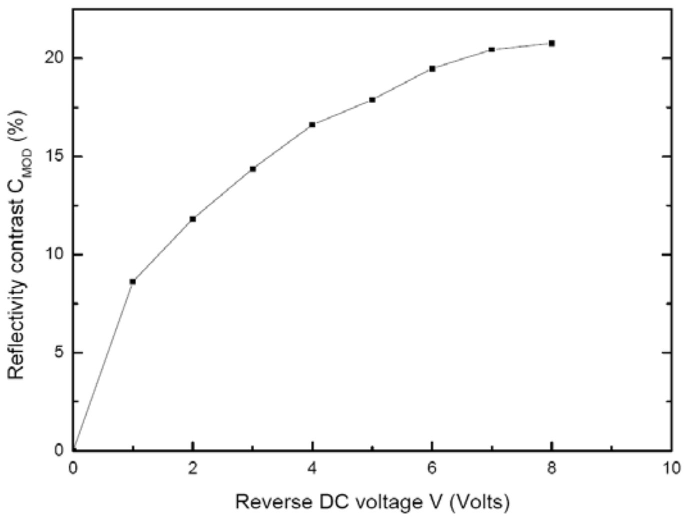


Fig. 16 Reflectivity contrast of Modulator vs. rev. Voltage

Between 0V and 6V the reflectivity contrast is detected to be ~17%. For high modulation depths the linearity compensation will be considered.

The link loss of the system (Fig. 17) is plotted versus frequency in Fig. 18. For WLAN-RoF applications at around 2.5GHz the link loss is detected to be 75dB with an SNR of around 28dB in the system using Y-coupler. The usage of a circulator could provide a higher power budget.

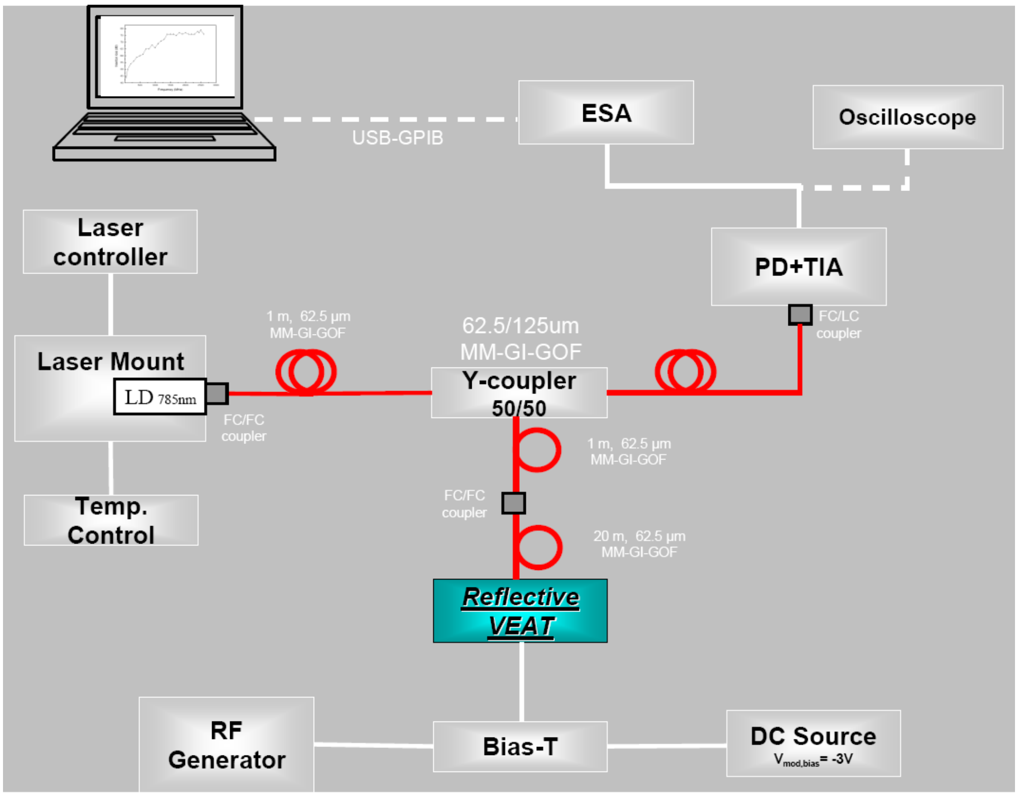


Fig. 17 Measurement setup for characterization of VEAT-Modulator

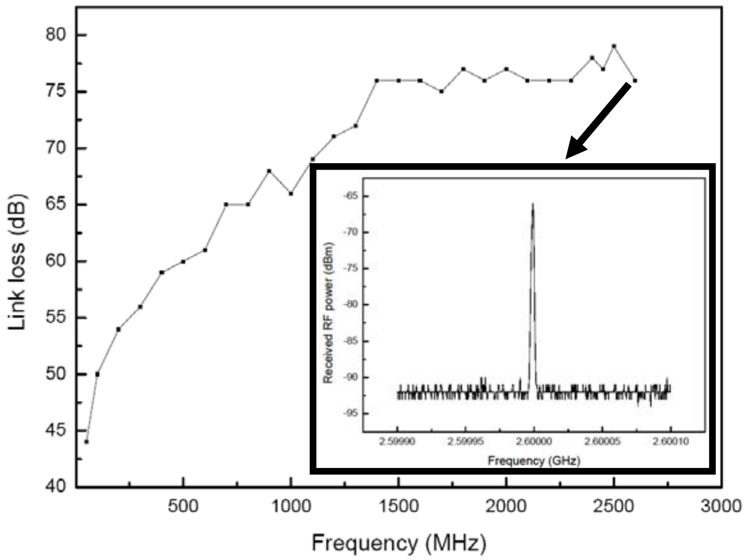


Fig. 18 Link Loss the system vs. frequency

Device Characterization – Photodiode

The frequency response of the photodiode is depicted in Fig. 19. The SNR at 2.5 GHz is detected to be > 39 dB.

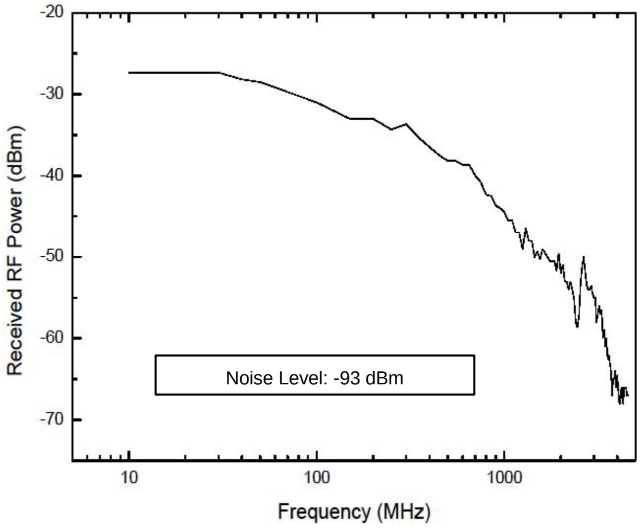


Fig. 19 Frequency Response of PD of VEAT

Summary

A Radio-over-Multimode-Fibre system containing a new reflective VEAT as low power and non-active bidirectional OE/EO-component has been presented. It has been shown that the transceiver is able to send and receive RF signals higher than 2.5 GHz addressing WLAN applications. EVM measurements will be carried out in Y2 of the project.

Publications

1) Ingo Möllers, Mike Bülters, Amanuel Geda, Dieter Jäger, „Radio-over-Fiber Communication Using a Vertically Integrated Transceiver", IEEE International Mini-Symposium on Electromagnetics and Network Theory and their Microwave Technology Applications (EMNT), Munich, Germany, October 8-9, 2008
2) I. Möllers, M. Bülters, D. Jäger, "Radio-over-Fiber in-Building Communication Using an Integrated Electro Optic Transceiver", Photonics and OptoElectronics Meetings (POEM 2008), Wuhan, China, 2008

4.8.4 60GHz RoF System for In-Home

- UDE: Andreas Stöhr, Dieter Jäger
- FT: Anna Pizzinat

Joint research activities

Indoor wireless 60GHz measurements (Fig. 20) with a data rate of 2Gbit/s over more than 10m have been achieved at FT. For details please refer to the listed joint publications together with FT.

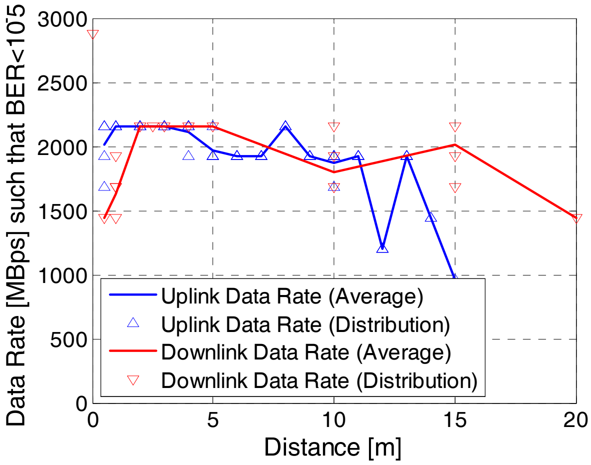


Fig. 20 Data Rate of 60GHz Wireless Transmission vs. Distance

Joint publications

- A. Stöhr, M. Weiß, S. Fedderwitz, D. Jäger, M. Huchard, B. Charbonnier, 60 GHz Wireless Photonic Link System for 12.5Gb/s Data Transmission, 9. ITG-Fachtagung Photonische Netze, 28-29 April, Leipzig, Germany, pp. 101-104, 2008
- M. Weiß, M. Huchard, A. Stöhr, B. Charbonnier, S. Fedderwitz, D. Jäger, 60GHz Photonic Millimeter-Wave Link for Short to Medium-Range Wireless Transmission up to 12.5Gb/s, Special Issue of the IEEE Trans. Microw. Theory Tech. and J. Lightw. Techn., pp. 2424-2429, 2008, (invited)
- M. Weiß, A. Stöhr, M. Huchard, S. Fedderwitz, V. Rymanov, B. Charbonnier, D. Jäger, Broadband 60GHz Wireless Radio-over-Fibre System for up to 12.5Gb/s Wireless Transmission, ISIS Summer School & Workshop 2008, June 2-4, Stockholm, Sweden, 2008
- M. Huchard, M. Weiß, A. Pizzinat, S. Meyer, P. Guignard, B. Charbonnier, Ultra Broad Band Wireless Home Network based on 60GHz WPANs cells interconnected via RoF, Special Issue of the IEEE Trans. Microw. Theory Tech. and J. Lightw. Techn., pp. 2364-2372, 2008, (invited)
- A. Stöhr, M. Weiß, V. Polo, R. Sambaraju, J.L. Corral, J. Marti, M. Huchard, B. Charbonnier, I. Siaud, S. Fedderwitz, D. Jäger, 60GHz Radio-over-Fiber Techniques for 10Gb/s Broadband Wireless Transmission, 20th Wireless World Research Forum, Ottawa, Canada, 2008
- B. Charbonnier, P. Chanclou, J.L. Corral, G.-H. Duan, C. Gonzalez, M. Huchard, D. Jäger, F. Lelarge, J. Marti, L. Naglic, L. Pavlovic, V. Polo, R. Sambaraju, A.G. Steffan, A. Stöhr, M. Thual, A. Umbach, F. van Dijk, M. Vidmar, M. Weiß, Photonics for broadband radio communications at 60 GHz in access and home networks , Int. Topical Meeting on Microwave Photonics, Sept. 30 - Oct. 3, Goldcoast, Australia, pp 5-8, 2008, (plenary, invited)

4.9 High capacity data over SMF/MMF

4.9.1 Shannon capacity studies on MMF links

- UCAM: I. H. White, R. V. Penty, J. D. Ingham, M. J. Crisp, C. H. Kwok

Research activities

Research has progressed on techniques for high-speed operation of datacommunication links over single-mode fibre (SMF) and multimode fibre (MMF), with an emphasis upon supporting legacy in-building infrastructure. Modelling and experimental work has been performed on multilevel modulation formats and novel forms of equalisation, especially for MMF links. Data rates of 10 Gb/s and 20 Gb/s have been considered, for relevance to standards being developed within IEEE 802.3 and T11 Fibre Channel. In addition, studies to determine the ultimate capacity of MMF links, under single channel operation, have continued, using Shannon theory techniques.

The Shannon capacity formula derived is

Channel capacity with NRZ coded spectrum

$$C = \frac{1}{2}\int_F \log_2\left(1 + \frac{\theta}{N_0/2}\left|H_{NRZ}(f)\right|^2\left|H_G(f)\right|^2\left|H_{Fiber}(f)\right|^2\right)df$$

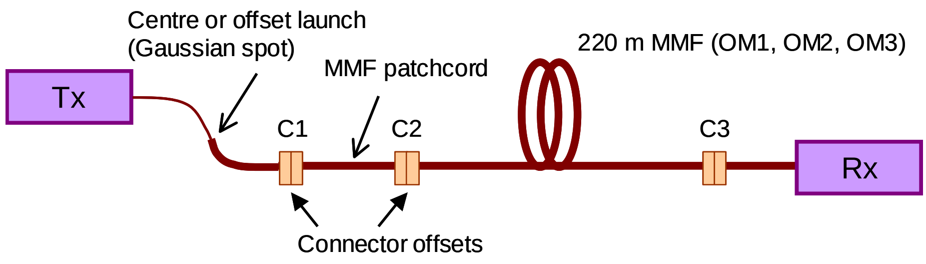


Fig. 21 Modelled MMF link

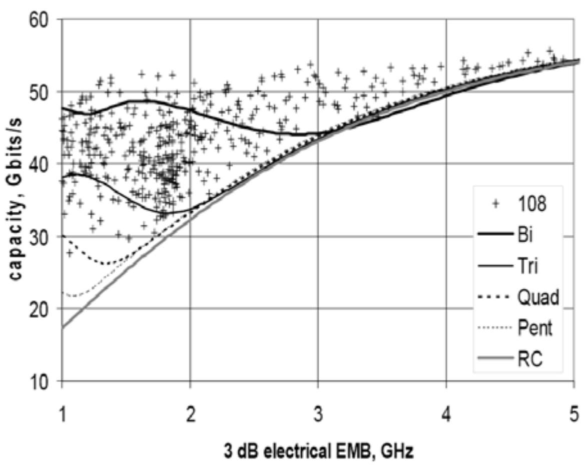


Fig. 22 Typical capacity results

Publications

1) C. H. Kwok, D. G. Cunningham, I. H. White, "Shannon capacity calculation on multimode fibres," (invited) to appear in *IET Optoelectronics*, October 2008.

2) C. H. Kwok, D. G. Cunningham, I. H. White, "Multimode fibers with asymmetric impulse response for an improved Shannon capacity," accepted for presentation at *Asia Pacific Optical Communications 2008*, Hangzhou, China, October 2008.

3) J. D. Ingham, D. G. Cunningham, I. H. White, R. V. Penty, "Ultimate (Shannon) capacity of multimode fibres," *13th European Conference on Networks and Optical Communications* (invited), Krems, Austria, July 2008.

4) J. D. Ingham, R. V. Penty, I. H. White, "10 Gb/s & 20 Gb/s extended-reach multimode-fiber datacommunication links using multilevel modulation and transmitter-based equalization,"

Optical Fiber Communication Conference 2008, paper OTuO7. San Diego, CA, USA, February 2008.

Joint publications

1) Möllers, R. Gaudino, A. Nocivelli, H. Kragl, O. Ziemann, N. Weber, T. Koonen, C. Lezzi, A. Bluschke, S. Randel, D. Jäger, “Plastic Optical Fiber Technology for Reliable Home Networking – Overview and Results of the EU Project POF-ALL”, submitted to IEEE Comm. Mag.
2) R. Gaudino, D. Cardenas, P. Guignard, S. Meyer, I. Möllers, M. Bellec, B. Charbonnier, N. Evanno, A. Pizzinat, D. Jäger, “Future Internet in Home Networks: Towards Optical Solutions?”, submitted to Future Internet Conference and Technical Workshops, Prague, May 2009

4.10 Wireless optical communication

4.10.1 Rate-adaptive transmission for indoor optical wireless communication

- FHG-HHI: Klaus-Dieter Langer, J. Grubor, L. Fernández del Rosal

Research activities

Research has progressed on design and performance analysis of a rate-adaptive optical wireless (OW) transmission system for broadband indoor communications. The focus of this work was on throughput maximization in an OW system for a typical indoor WLAN application (Fig. 23) by means of efficient signal processing.

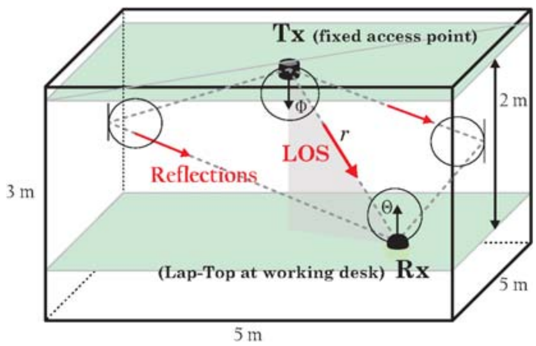


Fig. 23 Scenario of indoor optical wireless communication

To exploit the dynamics present in the considered channel we have investigated potentials of a modulation-adaptive OFDM technique. Since the main complexity of such approach lies in digital signal processing, simple key components of the optical link front-ends can be assumed; see Fig. 24.

In our work we have shown that an optimal loading algorithm, as proposed for power-limited systems, needs to be adjusted to rigorously fulfil the specific constraints of the OW channel on the transmit signal waveform. It was concluded that the dynamically adaptive system can provide great transmission rate enhancements compared to a statically operating one, even under a conservative constraint on the electrical signal waveform (i.e., no clipping).

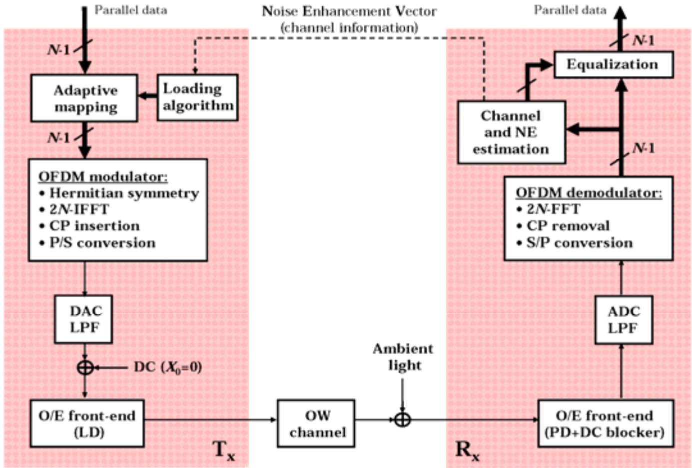


Fig. 24 Block scheme of an adaptive OW system based on real-valued OFDM (CP = cyclic prefix, LPF = low-pass filter, NE = noise enhancement)

To further increase the transmission rates and to enhance the system power efficiency in the simplest manner, controlled symmetric clipping of the transmit signal was introduced. The effect of clipping was investigated in terms of both error and transmission rate performance. It was shown that once clipping is allowed by relaxing the non-negativity constraint, the system can be regarded as power-limited, with the conventional loading algorithms rendering the best performance. We have also shown that significant further rate improvements can be achieved by accepting a minor increase of the error rate due to clipping and that the achievable rates much more approach the upper bound of the system capacity, see Fig. 25.

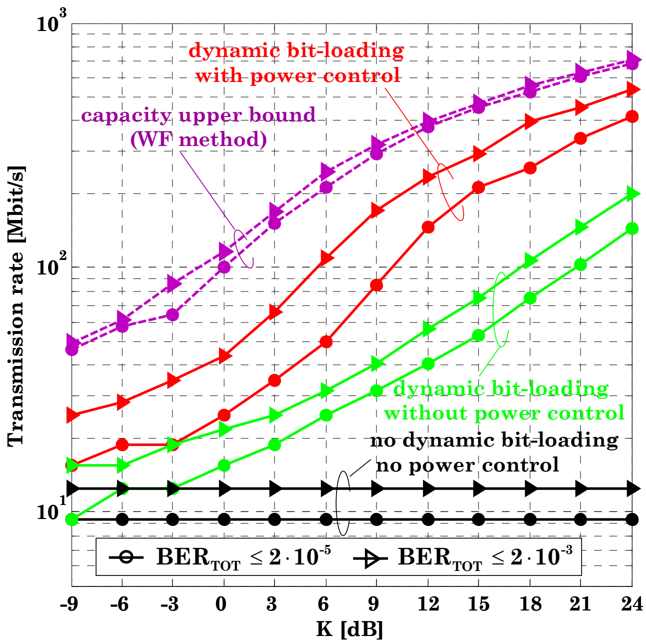


Fig. 25 Comparison of the achievable rates in the considered system where (i) no adaptation, (ii) adaptation with loading algorithm only, or (iii) adaptation with both loading algorithm and power control is implemented. Assumptions: N = 64 and DC= 400 mW

Additional improvements in both power efficiency and transmission rate can be expected if errors introduced by clipping were corrected using suitable procedures at the cost of an increased overhead.

Related investigations are for further study. FPGA-based implementations for experimental verification of our findings are in progress.

Presentations

- Luz Fernández del Rosal, “OFDM Modulator and Demodulator Design for Optical Wireless Communication”, presentation and discussion at BONE workshop on “Optical Transmitters and Receivers for Optical Wireless”, Siemens labs Munich, June 23, 2008. Further BONE participants were from UoA and TUE.
- Luz Fernández del Rosal, “Digital Signal Processing for Optical OFDM Transmission”, presentation at BONE Summer School on “The Role of Electronics and Signal Processing in Optics” Mons, Oct. 15-16, 2008.

Publications

- J. Grubor and K.-D. Langer, “Efficient Signal Processing in OFDM-based Indoor Optical Wireless Links”, submitted to Journal of Networks, Dec. 2008 (14 pages).

Future activities

In a spectrum range which is largely unregulated and unlicensed, Line-of-sight (LOS) optical wireless communications in buildings may theoretically provide very high throughputs (several Gbit/s) with relatively low loss and no multipath dispersion, compared to diffuse RF and optical links. However, this potential performance might be reached (i) at the cost of limited spatial coverage, (ii) with possible link blocking between the emitter and the transmiter and (iii) under the constraint of eye-safety condition fulfilment. This has led researchers to design complex transceiver components to maintain reliable high-speed communications over particular coverage areas [1]. The alternative approach we propose to assess here –both theoretically and experimentally– is twofold :

- to use tracking devices at the emitter or receiver side (or both) and multiple connecting beams to avoid blocking while providing mobility. Optical technologies like 3D beam deflectors (e.g. liquid crystal or MEMS based) can be considered at that step). GET/Telecom Bretagne has a recognized expertise in that field.
- to design low-complexity optical emitting points (with remotely located sources) by using the capabilities of micro-optics (refractive or diffractive) coupled to multimode fibres (possibly POFs).

Given that several WP16 partners (e.g. GET, UVIGO, TUE, UC3M, UDE, and HHI) have shown their interest for optical wireless communications in the M16.1 (Table 1, pp. 10-11), we will start discussions will be started, leading to potential mobility actions of researchers between the institutes.

Reference

[1] F. P. Parand, G. E. Faulkner, D. C. O'Brien, and D. J. Edwards, "Optical wireless testbed system using a multiple source transmitter and a segmented receiver to achieve signal tracking.," Optical Wireless Communications IV, proc. SPIE, vol. 4350, 2001

4.11 Sensor applications

4.11.1 Sensor applications in-home networks

- UC3M. Carmen Vázquez (cvazquez@ing.uc3m.es)
- UDE. Dieter Jaëger/Ingo Moellers
- Ericsson. Rebecca Chandy

Joint research activities

Since recently, Polymer Optical Fibres (POF) have been widely used in industry and automotive networks. New technologies and applications like VDSL, FTTH and IPTV require reliable high-speed but low cost networks with simple installation, high security and low space consumption [1]. POF technology could satisfy these requirements [2] and, hence, show that in-home POF based networks are very attractive candidates to be installed.

Coevally, the increasing networking feasibility in the home can enhance the home automation and integration of sensor applications and systems. Recently, one seventh of all fabricated sensors were used for home appliances [3]. This rate will increase with a higher demand on home automation and security applications by supporting higher integration and networking of devices in the home.

For sensing in the home there are three different fields of sensors that could be required:

- Environment Sensors: air pressure, temperature, wind, humidity,
- Monitoring Sensors: health care, movement, lighting/illumination,
- Building Sensors: statics, burglary/hold-up alarm, fire, gas and liquid detection, et al.

In the optical sensing field, POFs are also experiencing a big growth because they present numerous advantages such as easier handling (more flexibility) and lower cost compared to glass optical fibres. These are some reasons why new POF sensors have appeared and are still appearing, most of them based on optical power intensity detection.

In the framework of this integrated action we have developed a temperature characterization on a self-reference level sensor [4] to be used in condominium having biomass or other combustion mechanism which needs a liquid level monitoring. And other types of sensors are currently under study.

References

[1] T. Koonen, "Fiber to the Home/Fiber to the Premises: What, Where and When?" in *Proc. of the IEEE*, Vol. 94, Issue 5, May 2006 pp. 911–934.

[2] Sebastian Randel et al., "1 Gbit/s Transmission with 6.3 bit/s/Hz Spectral Efficiency in a 100 m Standard 1 mm Step-Index Plastic Optical Fibre Link Using Adaptive Multiple Sub-Carrier Modulation", *32nd European Conference and Exhibition on Optical Communication ECOC 2006,* paper Th4.4.1, 24.-28.09.2006, Cannes, France.

[3] Luo, R.C.; Chih-Chen Yih; Kuo Lan Su, "Multisensor fusion and integration: approaches, applications, and future research directions", *Sensors Journal, IEEE* Vol. 2, Issue 2, pp. 107 – 119, April 2002.

[4] C. Vázquez "Sensor De Fibra Óptica Auto-Referenciado Para La Detección De Líquido Y/O Medida De Nivel De Líquido" P200701937, 10-07-07

Publications out of the joint research activity:

- 1 paper under preparation

Future Activities

- A new mobility from I. Möllers to UC3M
- Further discussions with Dr. Chancy for selecting another sensor to be developed and tested

4.11.2 *Optically Controlled and Powered Camera System*

- UDE. Dieter Jäger/Ingo Möllers

Research activity

An optically controlled and fully powered camera system is being developed. The transmission of video data and power as well as bidirectional I²C control data was demonstrated.

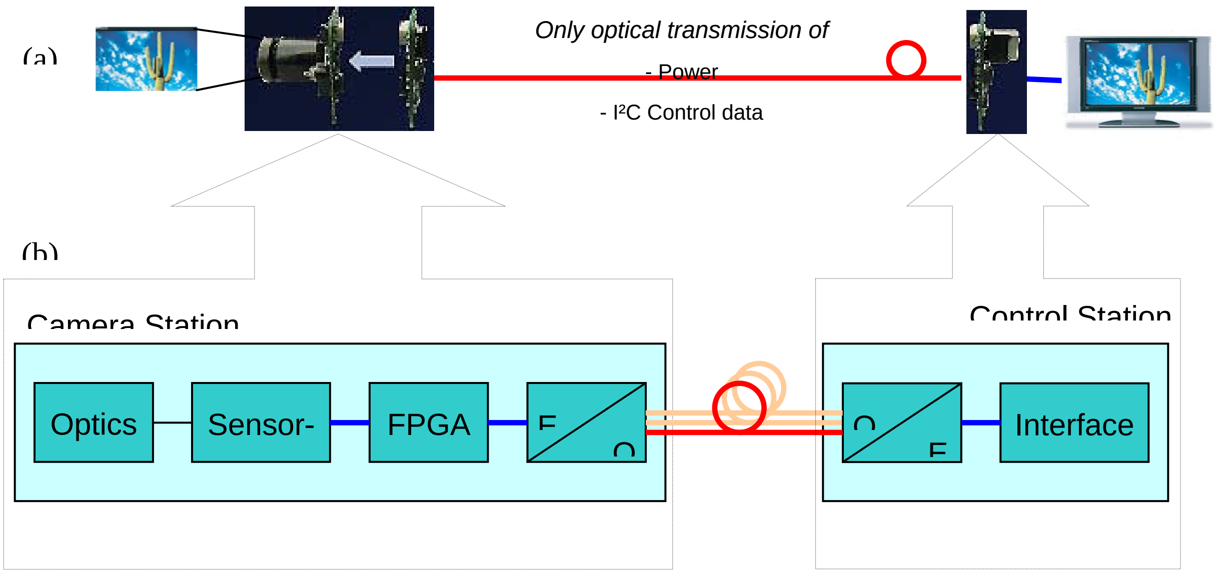


Fig. 26 Optically Controlled and Powered Camera System (a) principle and (b) block diagram

4.12 Techno-economic analysis

No activities of partners reported.

4.13 Safety and health aspects

No activities of partners reported.

5. Mobility actions

- FT-UDE — 14.01.-18.01.08 "Set-up of measurement facilities for commercial 60 GHz components" (Mathieu Huchard (FT) to UDE)
- Ericsson-UDE — February 2009 “Reliability Testing of POF Systems and Components according to international standards in telecom” & “POF-Fiber-Radio system + POF sensors for sensing and transmission of signals”
  - VEAT Devices (UDE)
  - POF Components (Ericsson)

  Mobility planned for Febr. 2009:
  Dr. Rebecca Chandy to UDE, or Dipl.-Ing. Ingo Möllers to Ericsson
- UC3M-UDE — Mobility: planned

- TUE-UAM 1-3-2008 to 10-7-2008 “Performance evaluation of an optical transparent access tier”; Bas Huiszoon from TUE to UAM

6. Joint workshops

In order to establish the dissemination of knowledge built up in the joint activities, and to coordinate these activities, two joint workshops have been held in this first year:

- in Torino, on Jan. 30, 2008
- in Rome, on Oct. 20, 2008

In these workshops, the status of the running joint activities in VCE-H was discussed and checked against the goals. Also presentations of the research results were given by the partners. The plans for starting new activities and how to proceed with the current ones were formulated and agreed upon.

VCE-H researchers have contributed to many other workshops and conferences by disseminating the jointly built knowledge, such as at ECOC 2008 in Brussels, ICTON in Athens, and the BONE summer school in Mons.

7. Concluding remarks

In this first year, the VCE-H activities have created a sound basis for joint activities integrating the research activities in the area of in-building networks. This cooperation has yielded a successful dissemination of the jointly created knowledge by means of journal and conference publications, workshops, and a fruitful exchange of researchers.

In the second year, the cooperation will be extended. It is expected that this will lead to a lasting framework for Europe-wide interaction in research in the domain of in-building networks.

Annex 1: Partner interests in VCE-H key research topics

		P4	P6	P12	P16	P17	P18	P22	P23	P36	P45	P49
		FHG-HHI	UDE	UC3M	UVIGO	FT	GET	UoA	UoP	TUE	UCAM	Ericsson
1	**In-building optical network architectures,** for integration of services, wired and wireless	X	X		X	X	X	X	X	X		
2	**Hybrid (optical/copper/wireless) in-building networks,** upgrading strategies, network evolution	X	X	X	X	X	X	X		X	X	
3	**Management and control of in-building networks,** ambient intelligence, signal routing, control of resources, user-tailored services		X		X					X		
4	**Fault & performance monitoring + protection mechanisms,** assure QoS, ease of maintenance, service availability	X										X
5	**Gateways access/in-building;** interfacing, security, service adaptation, local server, …	X	X						X			
6	**Interfacing with user terminals,** matching I/O formats		X									
7	**Flexible capacity allocation,** capacity and QoS on demand								X	X		

8	**Radio-over-single/multimode fibre,** antenna remoting, central station consolidation, smart antennas		X	X		X	X	X		X	X	
9	**High capacity data over SMF/MMF,** BW efficient modulation formats, such as multilevel, QAM, …; dispersion compensation	X	X	X		X		X	X	X	X	
10	**Optical wireless communication,** for pico-cells	X	X		X		X			X		
11	**Sensor applications** (bursty, low data rate, multiple access)		X	X	X							X
12	**Techno-economic analysis,** to optimise system design and network architecture		X			X						X
13	**Safety and health aspects** (a.o. eye safety, automatic shut-down)	X	X	X								X