SEVENTH FRAMEWORK PROGRAMME

Final Report on Integration Activities

FP7-ICT-216863/TUE/R/PU/D16.3

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Abstract:

This Final Report describes the activities done in WP16, the Virtual Centre of Excellence on In-Building Networks, undertaken in the third and final year of BONE. Joint research activities have been done in many of the areas of common interest, as defined in year 1. There have been several exchanges of scientific personnel during mobility actions, in order to foster the exchange of knowledge and experience in the area of short-range communication techniques. Also a nice number of publications in the major international journals and at major international conferences have highlighted the expertise which has been built up by joint research in WP16. Next to their journal and conference publications, members of WP16 have organized and given key contributions to well-attended workshops. In the area of POF networks, valuable contributions to the standardization activities have been given. Also the foundations have been laid for some follow-up projects in FP7, thus securing and reaping the benefits from the research alliances built up in BONE.

In retrospect, we feel that the WP16 activities in BONE have created a more thorough understanding and defragmentation of the research activities in the area of optical in-building networks in Europe, both on the institutional and on the personal level. This is felt as a very useful foundation for strengthening the research capabilities in Europe in this area, which are highly relevant in view of many social trends such as the aging society, the increasing concerns about our environment, and the increasing healthcare needs. To meet the demands put by these trends, WP16-like research actions yielding smart and high-capacity in-building networks directly supporting the user are and remain indispensable.

Keyword list:

In-Building Networks, Joint Research, Mobility actions

Disclaimer

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1. Executive Summary

In the final year of BONE, a number of joint research activities have been executed in WP16 addressing the various topical areas of in-building (hybrid) optical networks as have been defined in year 1. These activities have comprised joint research work in the areas of optical network architectures and their techno-economics, of management and control of in-building networks, of radio-over-fibre in in-building networks, of optical wireless systems, of high-speed data communication techniques over SMF, MMF and POF using spectrum-efficient signal modulation schemes and advanced multimode fibre launching schemes.

In some more detail, the activities of the WP16 partners in 2010 in the various areas were:

- *In-building network architectures and their techno-economics*: PoliTo, FT, and UDE have outlined future perspectives for various home network technologies such as POF and silica multimode and single-mode fibre network infrastructures. TUE, FT and TID have made economical analyses of the capital and operational expenses for these infrastructures.
- *Management and control*: FUB analysed the Quality of Service management aspects of integrating wire-bound and wireless (WiMAX, LTE) services into a single fibre-based in-building network.
- *High capacity data transmission over wired links*: UDE and TUE investigated standarisation aspects for POF-based in-building networks. TUE and UniBo worked on solutions for a converged in-building network carrying both high-speed wired and wireless services. UCAM worked on bandwidth-efficient signal modulation formats for high-capacity multimode fibre links, and on bandwidth-improving launching schemes. UoA studied the performance improvement attainable by optical mode filtering in POF links.
- *Radio over fibre*: UCAM and UCL worked on Ethernet transport over hybrid radio over fibre links. FT worked on 60GHz coverage extension by means of radio-over-fibre tunnelling. TUE and UPV worked on bidirectional transport of multiband OFDM UWB signals over POF links. TUE worked on transport of impulse radio UWB signals over POF links.
- *Flexible capacity allocation*: TUE investigated flexible routing of radio-over-fibre signals by means of wavelength routing. UC3M and GET worked on liquid-crystal based switches for routing radio over fibre signals.
- *Wireless optical communication*: FHG worked on ultra-high capacity free-space optical communication techniques by applying frequency-domain equalized block transmission. UCAM worked on radio over free-space optical links.

Five mobility actions have been undertaken, strengthening the interaction between the WP16 partners.

A joint WP13/WP16 Workshop has been held at ECOC2010 in Torino, as well as a workshop in Duisburg to discuss and prepare standardisation activities regarding POF network techniques. Also a Special Symposium within ECOC 2010 on high-speed short-range optical communication was organised by WP16 partners, and a Workshop on the prospects of fibre solutions versus other solutions for in-home networks at OFC 2010.

WP16 partners published 11 joint papers in the major international conferences and journals, and 19 single-institution papers.

Several WP16 partners are also involved in other FP7 projects which address in-building networks, notably ALPHA, OMEGA, FUTON, and POF-PLUS. There is a close cooperation and an active exchange of information with these projects. Some new FP7 projects have been created jointly by WP16 partners.

In retrospect, BONE has created a valuable base for cooperation between European academic research groups in the area of in-building networks. Active maintenance of this base by BONE-like instruments is indispensable to further leverage the academic joint research and thus strengthen Europe’s position in the increasingly important area of broadband networks in the immediate user environment.

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 Perspectives for next generation home area networks [FT, UDE, PoliTo]

A joint activity has been carried out between FT, UDE and PoliTO on the perspectives for next generation home area networks (HAN). The results have been published in [1] and show the future requirements for home networking, advocating the need for optical fiber inside the apartment in the medium term, in order to have a high-bit-rate, low-delay, and high-quality wired backbone inside the house. The deployment, architecture and fiber type used for such a backbone will be strongly influenced by economical factors, end-user requirements, and installation constraints. We envision two main possible scenarios:

• Medium-term brown-field installation: POF infrastructure to provide a point-to-point architecture suitable for already constructed houses. Home gateways equipped with POF ports are today on the market, offering 100 Mb/s links. Recent EU projects show that 1 Gb/s is also possible for SI-POF, and even more for perfluorinated GI-POF.

• Long-term green-field installation: Silica fiber 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 a point-to-point to a fully transparent multipoint-to-multipoint network able to respond to any future bandwidth requirements. For this scenario, singlemode fiber is believed to be the best choice as it guarantees the long-term suitability of the network, and benefits from the economy of scale and experience gained from current FTTH deployments.

References

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

No activities of partners reported.

4.3 Management and control of in-building networks

4.3.1 In-building fibre access with integration of wireless systems: procedures to assure Quality of Service [FUB]

It is clear that optical fibre deployment is fundamental for future in building networks; however, in some cases, where the installation of optical fibres would be too expensive or even not feasible, wireless access technologies, as WiMAX and next LTE techniques [1], result to be of main importance to have high bandwidth connections [2]. However some issues have to be addressed. In particular, in the radio access networks, where bandwidth is shared among all users, Quality of Service (QoS) assumes a key importance role, requiring the identification of techniques that, in case of congestions or possible bottlenecks in the different network sections, are able to meet performance requirements of different services.

This contribution proposes an “end-to-end” QoS management (i.e. from source to destination) in an optical core network with WiMAX and LTE radio access. The tests are carried out by OPNET simulator.

During the migration from current networks to the Next Generation Networks (NGN), in all sections of the network there will be a transition towards packet switched paradigm, and Multiprotocol Label Switching (MPLS) represents one of candidate techniques to be used in the core network as packet transport technology. Among the advantages of this technique, there is certainly an efficient management of QoS, defining logical paths, Label Switched Paths (LSP), with a specific CoS (Class of Service). In particular, it can be defined up to eight CoSs using the Traffic Class (TC) field of the MPLS label.

In the edge network, Ethernet technology can be the next technology to employ due to its characteristics as simplicity and cheapness. In this case, the QoS is managed by means of Virtual LANs (VLAN), in particular by 3 bits in the VLAN Tag User Priority field, with a maximum of eight CoSs.

In this way, the QoS is managed end-to-end by mapping of CoSs defined in the VLAN and those defined in the LSP.

Integration with WIMAX

In this case, a BS is connected to the optical network to an EDGE point (Fig. 1). As example, it was reproduced the core-edge network representing the ISCTI-FUB test-bed (consisting of four routers).

In the simulation, four Best Effort IP flows are generated from Web Server to terminals SS_1, SS_3, SS_4, SS_5. Another IP flows (Video Stream with high priority CoS) from the Video Server to the terminal SS_2 is generated after 5 mins; such IP flow carries a Video Stream of about 20 Mbit/s and it is treated with guaranteed QoS by means of: VLAN Tagging between Video Server and router R1, LSP in the core network, and Classes of Service in WiMAX cell. Fig. 2 shows the traffic received from the WiMAX terminals. It can be observed that, when the terminals receives a Video Stream flow, only the throughput of the Web flows experiences degradation because of the congestion in the WiMAX cell; this is due to bandwidth reservation performed by the BS to the terminal receiving the Video Streaming.

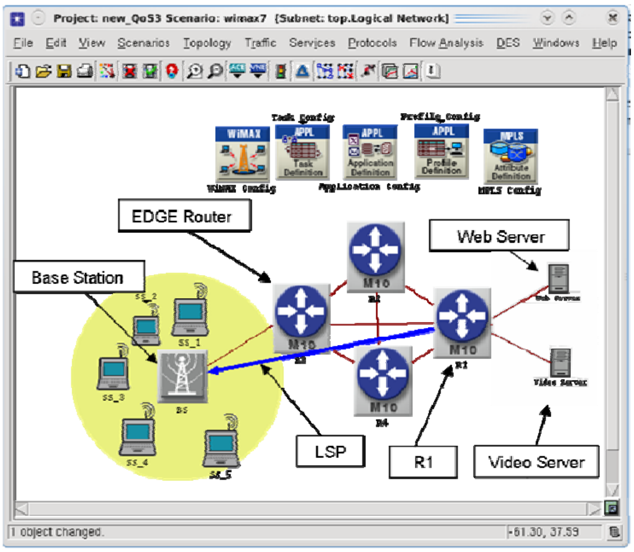

Fig. 1 Base Station in a building connected to an EDGEpoint

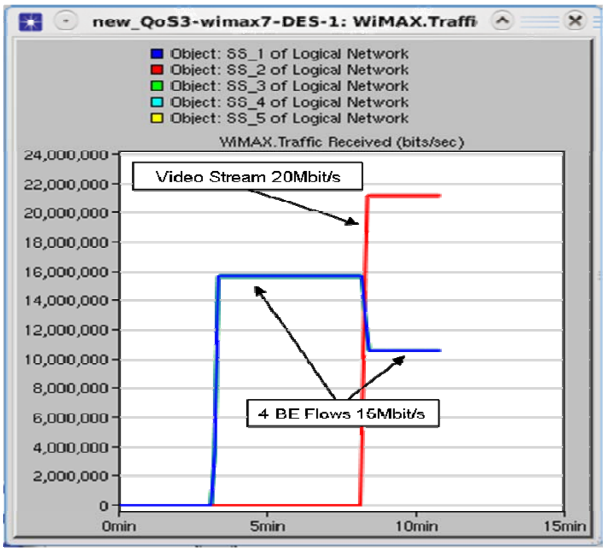

Fig. 2 Traffic received from WIMAX terminals

Integration with LTE

In this case, a LTE EPC, located in a building, is connected to the an optical network to an EDGE point (Fig. 3). LTE is one of the novel access able to operate with high bit rate, nomadic and mobile characteristics, keeping full backwards compatibility to Global System Mobile (GSM) and High-Speed Packet Access (HSPA) [3]. It can permit bandwidth up hundred of Mb/s.

In the simulation, LTE network parameters are set to have a max capacity about 17 Mbit/s: bandwidth of transmission channel 20MHz and Modulation and Coding Scheme (MCS) 9. Two IP flows, with CoS “Bronze”, are generated from Web Server to terminals UE2, UE3. Another IP flow (Video Stream with high priority CoS “Gold”) from the Server to the terminal UE1 is generated after 2 mins; such IP flow carries a Video Stream of about 16 Mbit/s and it is treated with guaranteed QoS by means of: VLAN Tagging between Video Server and router R1, LSP in the core network, and QoS Class Identifier in LTE cell. Fig. 4 shows the traffic received from the LTE terminals. It can be observe that, when the terminal receives Video Stream flow, only the throughput of the Bronze flows experiences degradation because of the congestion in the LTE cell; this is due to bandwidth reservation performed by the eNodeB to the terminal receiving the Video Streaming.

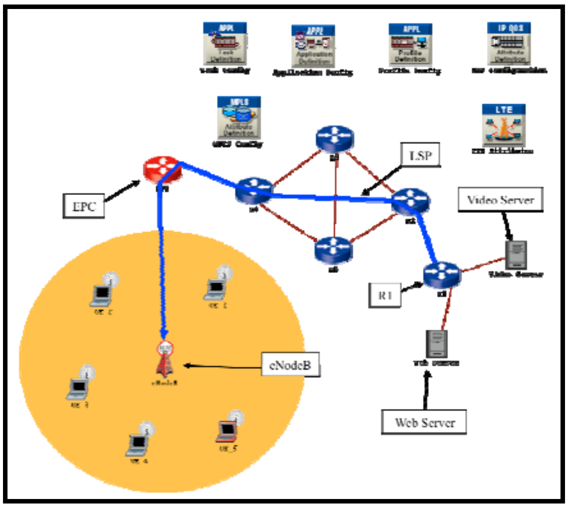

Fig. 3 LTE EPC connected to an EDGE point

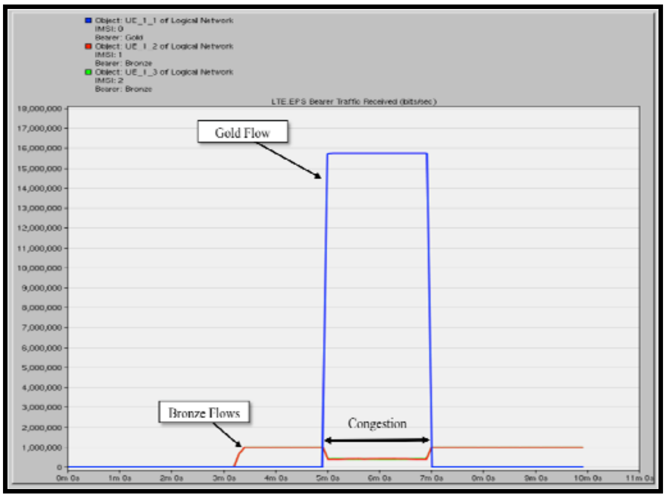

Fig. 4 Traffic received from LTE terminals

Conclusions

In this contribution we have shown how to integrate optical accesses in the building with wireless systems assuring the QoS as in wired networks. WIMAX and LTE techniques were considered. These architectures can be considered as the building boxes for future picocell and femtocell networks in which the QoS is managed also in shared bandwidth environments.

References

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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

4.7.1 Flexible Radio-over-Fibre Signal Distribution in In-building Networks based on Modulated ASE Noise [TUE, SSSUP]

In recent years, the development of wireless communications allows people to be served with broadband seamless connection at anyplace and anytime. At in-building environments, however, this benefit is still not fully provided yet. In buildings, people can expect several wireless communications such as cellular communication, wireless LAN, wireless connection between devices like Bluetooth. But, each network works separately, which induces management issues and it is difficult to cover a whole building with a single large wireless network.

The Radio-over-Fibre (RoF) techniques, which transmit Radio signals through optical fibre link with unlimited bandwidth, low loss and immune to EMI, can offer valuable solutions for this problem. In addition, RoF system shift signal processing functionality from the base-station (BS)s to the central office (CO) and reduces overall system complexity.

A conventional RoF system has a passive ‘broadcast-and-select’ configuration. However, in order to manage dynamic traffic variation with time and place in the networks, RoF systems need to flexibly adjust its configuration according to the traffic situation. A reconfigurable system[1-5] can improve the traffic handling capability and network operational efficiency.

To implement a reconfigurable RoF system, we propose a new system configuration with a semiconductor optical amplifier (SOA). The combination of the modulated amplified spontaneous emission (ASE) noise and a tunable optical filter allows managing the distribution of Radio signals. We report on the realization of the proposed system and the transmission performance of Wi-Fi (802.11a/g)-compliant signal with 54Mb/s, 52 OFDM subcarriers centred at 2.4GHz. In the demonstration, the Radio signals are successfully delivered through the system including 3m wireless channel with 3% error-vector magnitude (EVM) penalty.

Operation Principle

Fig. 5 shows the configuration of the proposed RoF signal distribution system. An SOA in the remote node (RN) is free running with a certain bias current. When RoF signals (λ_0) are injected to the SOA, the radio signals modulate ASE noise signals due to the cross-gain modulation (XGM) of an SOA. Then, the modulated ASE noise signals are directed to an arrayed waveguide grating (AWG) router.

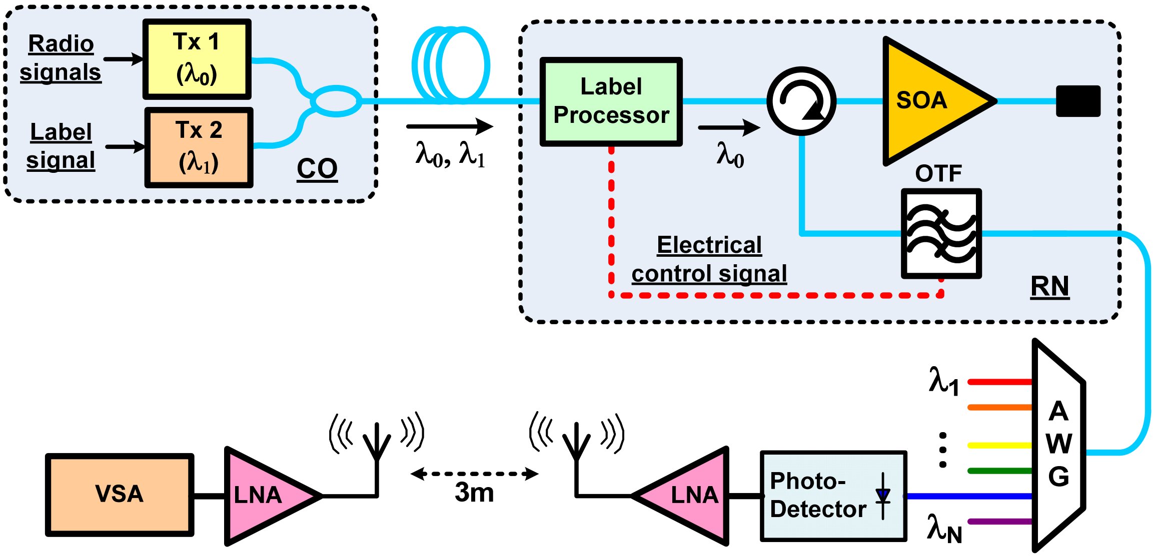

Fig. 5 Experimental Setup (CO: central office, RN: remote node, LNA: low-noise amplifier

In general, ASE noise has a broad optical spectrum. Due to that, radio signals can be distributed by the modulated (wavelength-converted) ASE noise signals. However, by introducing a tunable optical filter, RoF signals can be routed to particular output ports or network connections can be reconfigured. As shown in Fig. 5, a label signal on different optical wavelength (λ_1) is transmitted with RoF signals. The label processor takes out the label signal and decodes the label information. In the meanwhile, RoF signals modulate ASE noise by XGM. Then, the modulated ASE noise signals encounter an optical tunable filter (OTF) just before the AWG. The OTF filters the broadband modulated ASE signals according to the decoded label information so that the RoF signals can be routed to the particular ports (or places).

Experiments

The experimental setup consists of three parts: the transmitter in CO, the RoF signal distributor in RN, and the wireless channel as shown in Fig. 5. The CO has two optical transmitters; Tx1 and Tx2, those are for radio signals and labels, respectively. Wi-Fi (802.11a/g) -compliant signals with 54Mbps, 52 OFDM subcarriers centred at 2.412 GHz, which are generated from the vector signal generator (Agilent, N5182A), modulate an optical signal (λ_0) with the wavelength of 1546.12nm. After optical modulation, the optical signal (λ_0) is combined with the label signal channel (λ_1) and then transmitted to the RN.

At the RN, the label processor takes out only the wavelength with labels and decodes label information. However, the label processor is emulated at the moment of the demonstration. The RoF signals (λ_0) pass the label processor and are directed to the SOA (CIP, SOA-NL-OEC-1550). The SOA is free-run with the bias current of 350mA and the generated broadband ASE noise is modulated by the injected RoF signals based on the XGM. To avoid an optical filter to remove the optical seeding signal (λ_0) for the XGM, the modulated ASE noise signals are taken at the counter-propagation port with an optical circulator. For reconfiguring network connections, the OTF selects the proper ASE noise band based on the control information from the label processor and then the selected optical band is routed by AWG.

At the antenna site, the distributed modulated ASE signals get detected and transmitted to a wireless channel through the monopole antenna (Titanis, Swivel antenna with -1dBi gain). After 3m wireless transmission, the Wi-Fi -compliant signals are received at the counter antenna and the performance is evaluated by the vector signal analyzer (Agilent, N9020A).

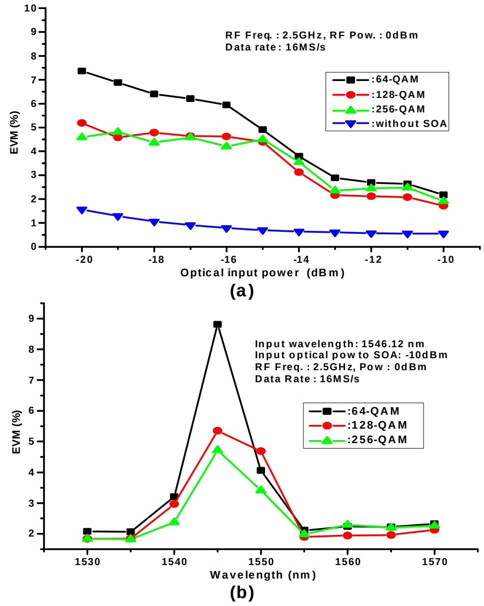

Fig. 6 EVM performance of a single RF carrier QAM signal for (a) the input optical power to SOA, (b) the selected passband of the modulated ASE noise

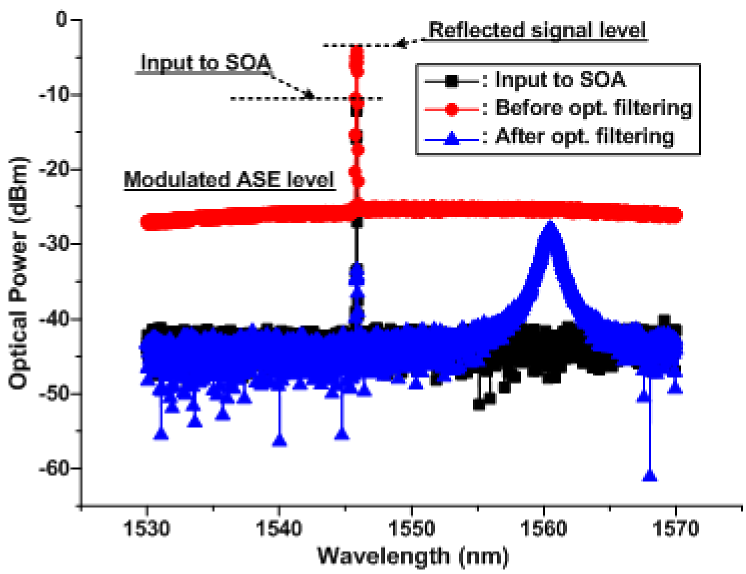

Fig. 7 Optical Spectra

To evaluate the performance of the proposed RoF distribution system, firstly we measured the EVM performance for the wired parts with single RF carrier QAM signals, which has 16MS/s data rate centred at 2.5GHz. Fig. 6 (a) shows the measured EVM against the input optical power to the SOA. Three different QAM-levels show almost the same performance. As increasing the optical power, EVM gets better because the cross modulation efficiency improves with optical power. The EVM penalty as compared to the B-to-B case is from the XGM conversion loss. In addition, the system shows quite even performance over the wide wavelength band as shown in Fig. 6(b). This is because the XGM covers the whole ASE noise band. However, the bad EVM performance around the seeding wavelength is due to the interference between the reflected seeding signal and the selected ASE noise band. As shown in Fig. 7, the power level of the reflected seeding light is very high even in the counter propagation configuration, which is different from what we expected.

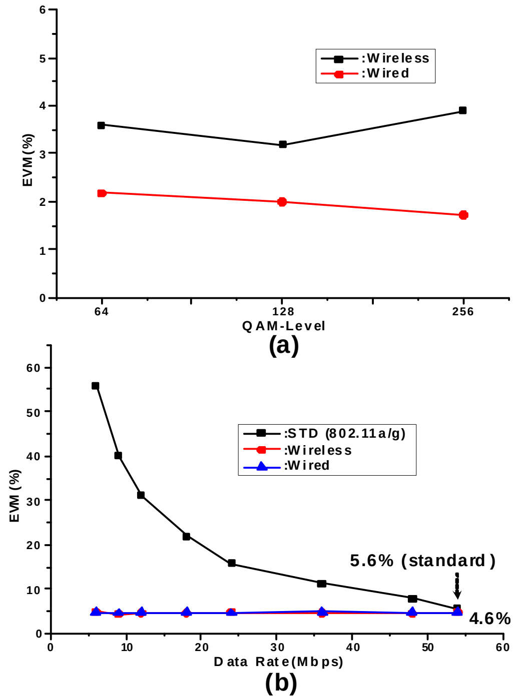

Fig. 8 EVM performance with wireless transmission (3m) (a) single carrier QAMs, (b) Wi-Fi (802.11a/g)

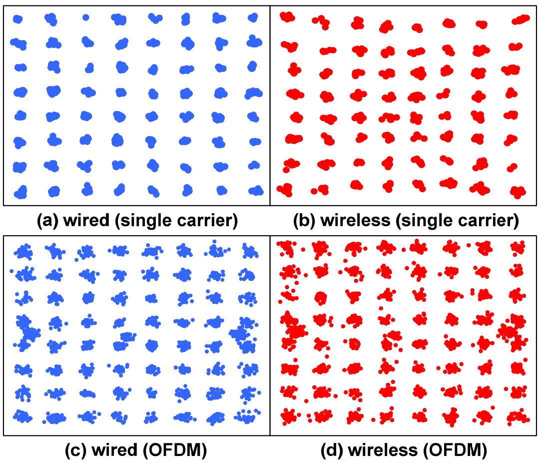

Fig. 9 Constellations for (a, b)single-carrier 64QAM, (c, d) multi-carrier OFDM (802.11a/g)

Two different types of radio signals are compared in the wireless transmission: single-carrier QAMs with 16MS/s data rate centred at 2.5GHz and multicarrier OFDM (802.11a/g) with 52-subcarrier centred 2.412GHz. In case of wired link in Fig. 8, single-carrier QAMs shows better performance than multi-carrier OFDM. We think the interference between adjacent OFDM carriers causes extra conversion loss during the XGM of the SOA. Nevertheless, the signals are still below the limitation of 802.11a/g standard.

However, when both types of signals were transmitted over 3m wireless channel, the single-carrier QAMs got distorted due to the multi-path fading. Fig. 9 (a, b) show the edge sides of the constellation are distorted after wireless transmission in case of the single-carrier QAMs. But, the multi-carrier OFDM signals showed almost the same performances even with the multi-path fading as shown in

Fig. 8(b) and Fig. 9(c, d). There is no big difference between wired and wireless cases. These results also show that OFDM-format signals are tolerant of the multi-path fading environments.

Conclusions

For in-building networks, we proposed and demonstrated a new configuration of a flexible RoF signal distribution system. For the proof of the concept, we showed successful distribution of radio signals (single-carrier QAMs and Wi-Fi (802.11 a/g)-compliant OFDM) including wireless transmission. The proposed system is based on XGM of an SOA and uses the sliced modulated ASE noise for the distribution. Due to that, the system is colourless and has a lot of flexibility. We believe that the proposed system is simple and robust for in-building applications.

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4.7.2 Simultaneous Generation and Routing of Millimetre-Wave Signals exploiting Optical Frequency Multiplication [TUE]

With increasing requirement for high-capacity in-building networks, radio-over-fibre (RoF) distribution antenna systems are gaining attraction due to the potential to extend radio coverage by the large bandwidth and transparency to signal formats available in fibre. To exploit this bandwidth, millimetre-wave frequencies (30-70GHz) are seen as a viable broadband wireless access technology for in-building RoF systems due to low spectrum congestion, low interference and potential for high data rates. In addition, the inability of millimetre-wave (mm-wave) to penetrate walls is ideal for creating picocells enabling high-capacity, secure and robust transmission within a particular room. However, difficulties in the generation, transmission and routing of mm-wave signals has limited its adoption for this application.

Currently, most methods of mm-wave generation are based on three main approaches: direct-modulation, external modulation, and remote heterodyning. Firstly, the bandwidth limitation of available direct-modulation lasers proves unsuitable for mm-wave applications and the use of external modulation requires a high-frequency signal to drive expensive optical modulators[1]. Another approach is to employ a local oscillator (LO) mixed with the intermediate frequency radio signals to up-convert to mm-wave signals requiring high-frequency oscillators and mixers[2]. Other methods based on optical heterodyning techniques exploit two optical sources operating at different wavelengths to beat at a photo-detector generating mm-wave signals[3]. These methods encounter issues including non-linear distortions when modulating and distributing mm-wave signals. Moreover, expensive high-frequency components and the use of several laser sources in the latter leads to higher complexity and cost.

Therefore, for low-complexity in-building network applications, optical frequency multiplication (OFM) allows mm-wave signals to be generated using low frequency components[4]. Various in-building network architectures have been studied showing that deploying mm-wave within a fibre-based bus architecture is the most cost-effective for RoF in-building networks[5]. Hence in this paper, mm-wave signals are generated in a bus architecture by using OFM and an add-drop multiplexer (ADM) based on an integrated passive micro-ring resonator at the antenna site. At the same time, the radio signals can be routed to individual rooms. By exploiting the highly selective filter characteristics of micrometer-radius micro-ring resonators, extremely small-area devices can be integrated with the antenna on the same compact optical chip, which leads to reduced power consumption and costs for wide-scale deployments.

We demonstrate the suitability for greenfield in-building installations using single-mode fibre by a proof-of-concept experiment. Successful optical up-conversion of 3.6 GHz radio signal encoded with 64-QAM data at up to 20MS/s (120Mb/s) to a 39.6 GHz mm-wave frequency is achieved. After routing to the remote antenna, the detected signal demonstrates an error vector magnitude (EVM) of only 4.9% (-26.4dB) at 39.6 GHz.

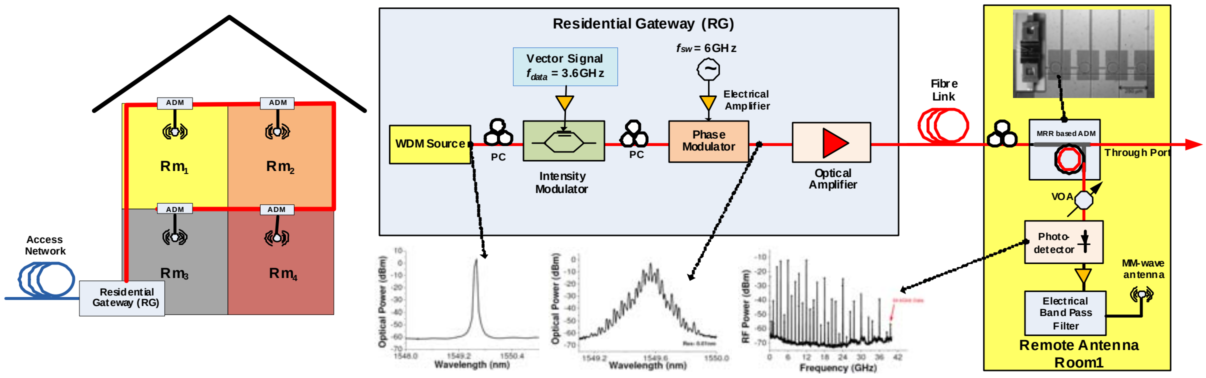

Fig. 10 In-Building bus network architecture with micro-ring resonator assisted routing and mm-wave generation at the remote antenna (inset: micro-ring resonator device).

Principle of Generation of Millimeter-Wave Signals using Micro-Ring Resonators

The envisaged network scenario is shown in Fig. 10. The transparent residential gateway (RG) terminating the access network, routes the radio data signals via the fibre infrastructure to the different rooms. At the RG, the wavelengths bearing the radio signals are phase-modulated by a sweep signal and sent to the rooms. At each room, an integrated micro-ring resonator near the antenna drops a specific wavelength to which the micro-ring is tuned. Simultaneously the periodic filtering function of the rings enables the PM-IM conversion necessary in the OFM method to generate the mm-wave RF carriers at multiples of the sweep signal[4]. The radio signals are hence up-converted and reproduced as double side-band signals at each harmonic. By employing an electrical band-pass filter (BPF) for selecting the appropriate harmonic, the mm-wave radio signal is extracted for air-transmission.

Experimental Procedure and Results

The experimental setup employed to demonstrate the micro-ring based routing and mm-wave generation system is shown in Fig. 10. The continuous wave (cw) light at a wavelength destined for a particular room is intensity-modulated by 64QAM radio signals at low frequency subcarrier generated by a vector signal generator at 3.6 GHz. The wavelength for room 1 (Rm_1) at 1549.6nm is phase-modulated (PM) with a sweep RF signal at f_{sw} =6 GHz. The signal is then input via polarisation controllers (PC) to minimise the polarisation-dependent loss (5dB) of the micro-ring resonator. The loss between input and drop ports of 19dB (consisting of coupling and waveguide loss) is compensated by the pre-amplifier before the micro-ring resonator.

The pigtailed vertically-coupled micro-ring resonator (MRR) was fabricated[*] using Silicon Nitride (Si_3N_4/SiO_2) materials system (high contrast material system, $\Delta n \approx 0.55$)[6] where the highly selective MRR-based filters allow for the fabrication of complex devices on a small footprint. It should be noted, however, that this device could also be realised readily in silicon waveguides using the vertically-stacked double silicon-on-insulator photonic system. The transfer function of the pass-through port is shown in Fig. 2a indicating the free spectral range of 4.4nm.

a) b)

Fig. 11 (a):Transparent Response of the Micro-Ring Resonator (b): A magnification of the notch at 1549.6nm

Corresponding to room 1, the filter notch at 1549.6nm is shown in Fig. 11b and indicates an amplitude of 20 dB. At room$_1$, the MRR drops this wavelength. The signal is then detected by a 70 GHz PIN photo-detector (U^{2}T XPDV3120R) with a flat-response sensitivity of 0.6 A/W and is analysed using an electrical spectrum analyser.

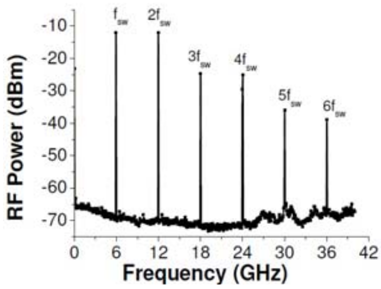

Fig. 12 Harmonics generated by OFM after photodetection with f_{sw}= 6 GHz

Fig. 12 shows the electrical spectrum of the resulting harmonics generated at the photodetector which appear at multiples of the f_{sw}. Note that in this experiment, the RF power injected into the phase modulator is varied to optimise the amplitude of the 6th harmonic at 36 GHz. The modulation index β was calculated to be 2.5.

By single-sideband (SSB) phase noise measurements of the 6th harmonic, a comparison against a reference high frequency carrier generated at 36 GHz from a synthesiser (Agilent E83505L) is obtained. From Fig. 13(c), the phase noise of the OFM-generated harmonic at 36 GHz is shown to be from -50 to -70 dBc/Hz in the 100Hz-1kHz region reducing to -104 dBc/Hz. The phase noise is shown to be of comparable quality as the synthesized source and hence robust for up-conversion. As data is input, the up-converted radio signals bearing data are generated double-sideband of the up-converted harmonics upto 39.6 GHz ($f_{RF} = n.f_{sw} \pm f_{data}$ where n corresponds to n^{th} harmonic, f_{sw} = 6 GHz and f_{data}= 3.6 GHz). Fig. 10 (inset) shows the spectrum of the up-converted data which appears at each harmonic.

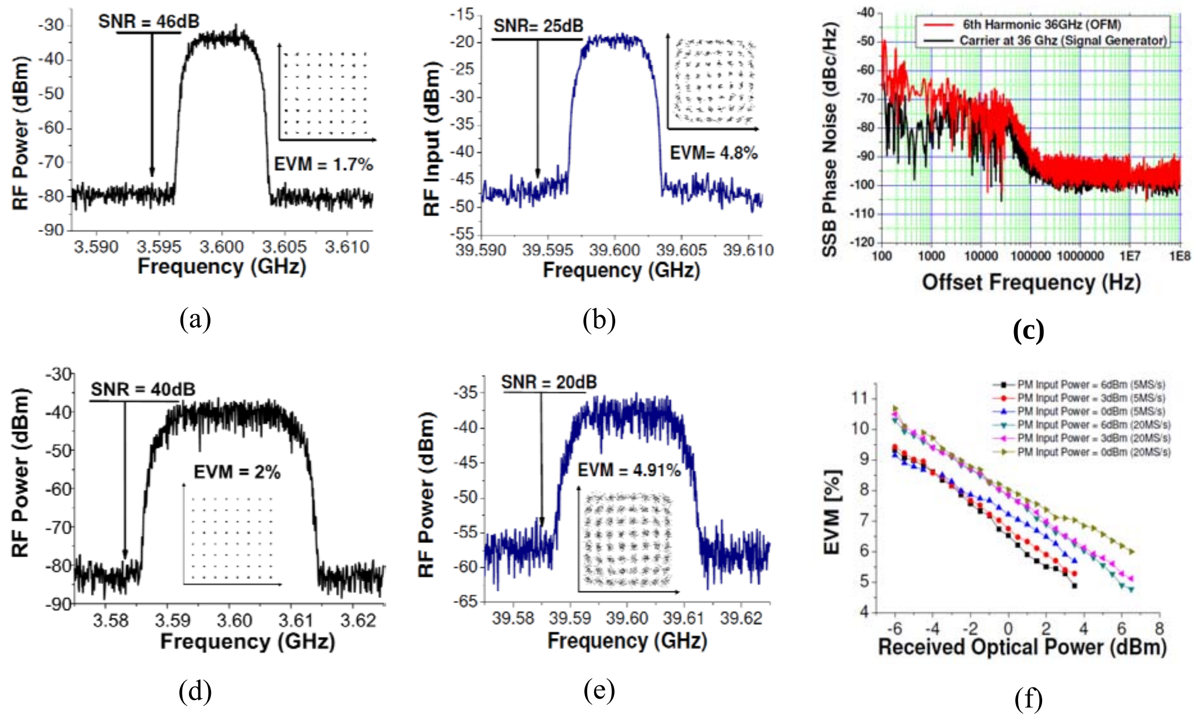

Fig. 13 (a): RF spectra of input 5MS/s 64-QAM signal at 3.6 GHz (inset: IQ constellation) (b): Received 5MS/s 64-QAM signal after up-conversion at 39.6 GHz (c): Phase noise performance of 6th Harmonic. (d): RF spectra of input 20MS/s 64-QAM (e): RF Spectra of up-converted 20MS/s 64-QAM at 39.6 GHz (f): EVM performance of up-converted data

The electrical input data from the VSA is shown to have an EVM of 5MS/s and 20MS/s input signals were 1.7% and 2.0% respectively. After up-conversion, the recovered data is shown to have an EVM of 4.8% (-26.37dB) and 4.91%(-26.18) for 5MS/s and 20MS/s, a penalty of 3.1% and 2.9% respectively. The inset in-phase and quadrature (IQ) constellation diagrams in Fig. 13 for 5MS/s and 20MS/s 64-QAM signals at 39.6 GHz shows clear separation between points. In Fig. 13(f), further measurements shows the EVM performance with respect to received optical power for different PM input powers. The EVM performance is similar for PM input powers of 3 and 6dBm achieving below 5%. However, when the PM input power is reduced to 0dBm, the EVM values are higher saturating at 5.9%.

The main contribution to the penalty can be seen in Fig. 13(d) and (e) where the reduced signal to noise ratio (SNR) is approximately 20dB between the input and up-converted RF signals. The SNR penalty can be attributed mainly to the ASE noise from the optical amplifier used to compensate the loss of the integrated micro-ring resonator. Despite the SNR penalty, the performance of the up-converted data at 39.6 GHz for both 5MS/s and 20MS/s is shown to meet the EVM requirement of 5.6% for the 64 QAM (¾ code rate) IEEE 802.11a/g wireless standards.

Conclusions

The successful generation and routing of mm-wave signals is presented using a micro-ring resonator integrated at the antenna site for in-building networks. Optical up-conversion of radio signals from low-frequency to the mm-wave frequency region is achieved. At the receiver, the data-bearing wavelength channel exhibited an EVM performance of 4.8% and 4.91% for 5MS/s (30Mb/s) and 20MS/s (120Mb/s) 64QAM data at 39.6 GHz, respectively, meeting the requirements for IEEE802.11a/g. By exploiting silicon-on-insulator materials, the viability and low-complexity of this system can be further enhanced by the compact integration of lower loss micro-rings, the receiver and the antenna on a low-loss compact chip.

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4.7.3 Switching devices in-home networks [UC3M, GET]

The design and integration of transparent *N*x*N* fiber switches for controlling the inter-room communications between Radio-over-Fiber links are under study. Those multimode fiber 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.

On the other hand, Polymer Optical Fiber (POF) is being used in a large numbers of applications. New home applications demand larger bandwidths, and POF networks are a good choice because in short distances, less than a hundred of meters, they have a wide bandwidth, and their installation is easy which makes them cheaper than other technologies.

Device structure

The structure proposed for the advanced multifunction optical switch, shown in figure 1, was reported in [2]. A set of polarizing beam splitters (PBS), nematic liquid crystal cells (NLC) and lenses act over the optical path modifying it.

When no voltage is applied to the liquid crystal cells, *OFF Status*, light form the *"Inputs a"* are guided to the *"Output Port a"*, and consequently, light from the *"Inputs b"* are guided to the *"Output Port b"*. On the other hand, when the liquid crystal cells are excited, *ON Status*, the optical path is modified and the light that come from the *"Inputs a"* goes to *"Output Port b"*, reciprocally, *"Inputs b"* goes to *"Output Port a"*.

Cells used in the implementation of this device have three pixels, then three pairs of input ports are possible and it can work as a 3x1 dual multiplexer; see Fig. 14. In addition, each pair of inputs, the *"a"* port and the corresponding *"b"* port can act independently of the rest. The same device can work as a Switch if only a port is used. Intermediate optical power transmission from the inputs to the outputs can be achieved by applying to the liquid crystal cell intermediate voltage values. In this way Variable Optical Attenuator, Variable Optical Splitter, Multiplexer and Switch can be integrated in the same device.

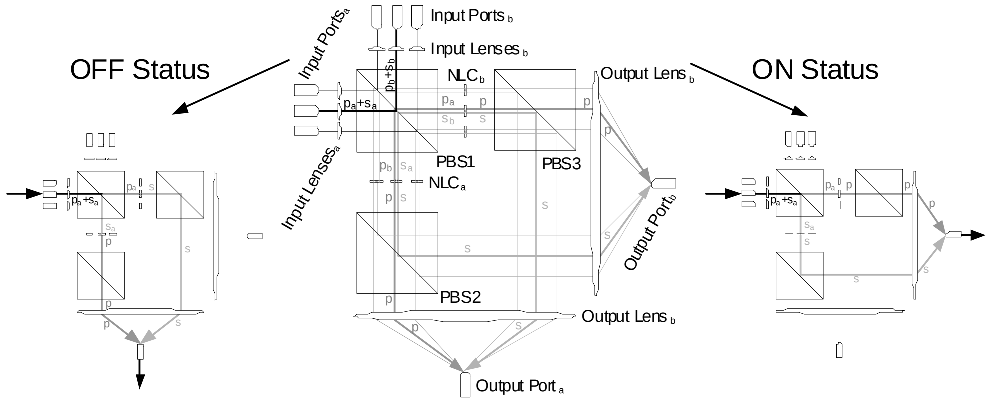


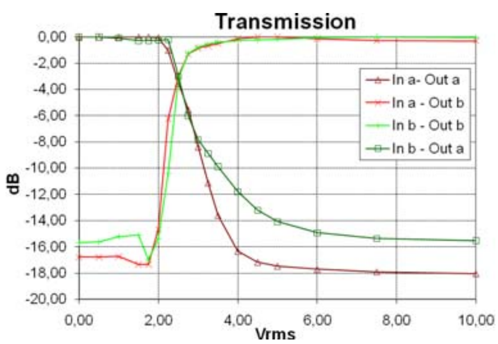
Fig. 14 Structure and operation of the multifunction switch

Measurements

Two Nematic Liquid Crystal cells with three pixels each, optimized for working in the 850 nm – 1300 nm wavelength range, have been used in the implementation.

A 650 nm laser was placed at the *"Input a"* of the device and a 550 nm laser was applied to the *"Input b"*. Measurements have been done using an optical power meter. Only the light that comes from one of the inputs is measured each time.

A 10 kHz frequency square wave with different voltage levels has been applied to the suitable pair of pixels in order to obtain the transmission graph that is shown in left part of Fig. 15. As the voltage increases the device switches from the *OFF status* to the *ON status*. The two pictures shown in right part of Fig. 15 were taken when the switch was in OFF status and ON status respectively.




OFF status


ON status

Fig. 15 Results obtained for both outputs and experimental set-up for two different statuses

A flexible integrated system with more functionality and compactness into one device for being used in POF or GI-POF networks has been proposed [3]. Variable Optical Power Splitter, Variable Optical Attenuator, Switch and 3x1 multiplexer can be implemented using the same device. Low consumption and low losses are expected. Capable of operating in a wide wavelength range thanks to the use of Nematic Liquid Crystal. In addition, contrasts higher than 14dB at 550nm and higher than 17dB have been obtained in the characterization carried out.

A summary of different types of switches based on LC as this one is reported in the joint chapter by UC3M and Telecom Bretagne in reference [4].

This work has resulted in an international conference paper:

[1] P. C. Lallana, C. Vázquez, D. Sánchez, B. Vinouze "Advanced multifunction optical switch for being used in polymer optical fiber networks" 3rd International Workshop on Liquid Crystal for Photonics (LCP 2010), September 2010, p.113-115, Elche (Spain).

and in a book chapter published in Nov. 2010:

[2] *Optical switches: materials and design.* Editores libro: Soo Jin Chua and Baojun Li, U. Singapore, chapter 9 “Liquid Crystal Optical Switches” Carmen Vázquez, I. Pérez, P. Contreras, B. Vinouze, B. Fracasso. Editorial: © Woodhead Publishing Ltd. 2010

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[3] P. C. Lallana, C. Vázquez, D. Sánchez, B. Vinouze “Advanced multifunction optical switch for being used in polymer optical fiber networks” 3rd International Workshop on Liquid Crystal for Photonics (LCP 2010), September 2010, p.113-115, Elche (Spain).

[4] *Optical switches: materials and design.* Editores libro: Soo Jin Chua and Baojun Li, U. Singapore chapter 9 “Liquid Crystal Optical Switches” Carmen Vázquez, I. Pérez, P. Contreras, B. Vinouze, B. Fracasso. Editorial: © Woodhead Publishing Ltd, November 2010

4.8 Radio-over-single/multimode fibre

4.8.1 Hybrid Radio over Fibre Systems [UCAM, UCL]

Radio over fibre systems have become established for in-building distributed antenna systems. While they are capable of supporting multiple wirelesses services, in practice, there is also a reasonably large amount of data which must be transferred between the remote unit RU and hub in digital form. Such information can be carried in the base band below the RF frequencies of interest. However care must be taked to ensure that non-linear effects don’t result in corruption of the RF services by the digital signal.

Research at UCAM under the DTC project with UCL demonstrated the ability to simultaneously support 100Mbit Ethernet alongside an RoF link. Fig. 16 shows the experimental setup.

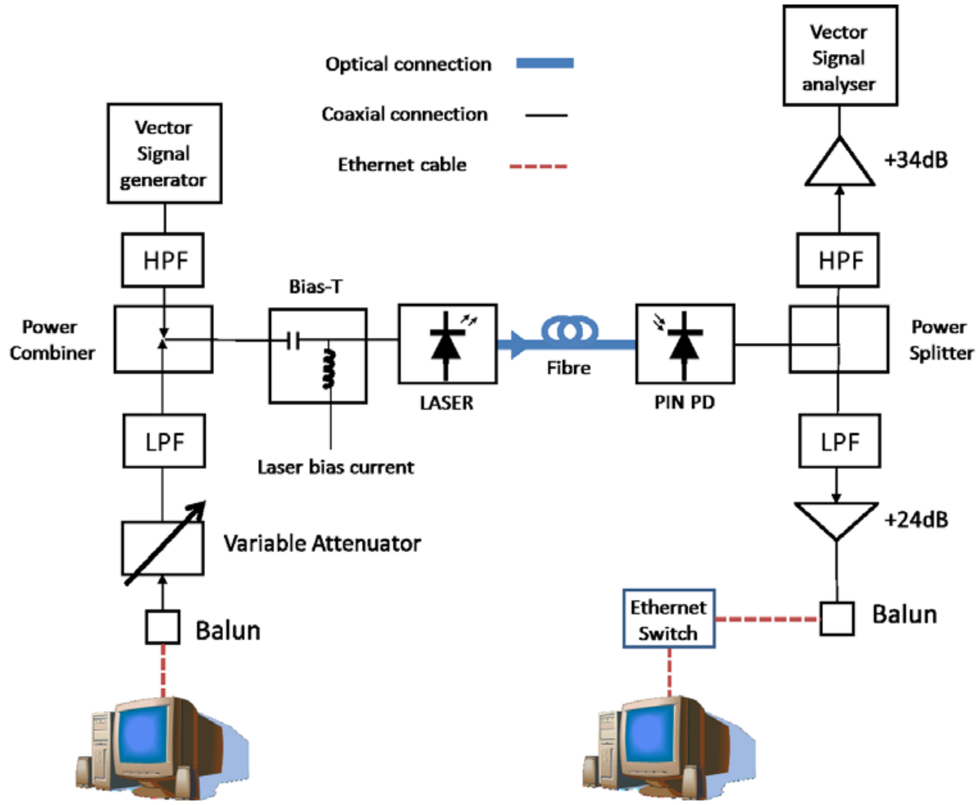


Fig. 16 Hybrid RoF System supporting 100Mbit Ethernet

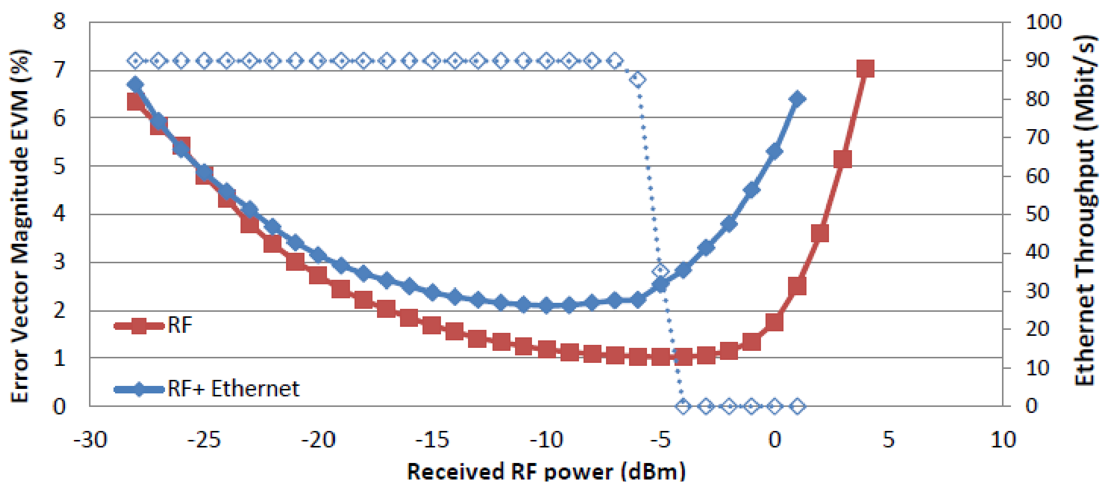


Fig. 17 EVM of IEEE 802.11g signal (solid line) and Ethernet throughput as a function of the IEEE 802.11g input power to the link

Some results are shown in Fig. 17 indicating a range of RF input powers where a low EVM can be achieved alongside ~90Mbit/s throughput.

4.8.2 60GHz radio coverage extension by using RoF [FT]

Research activities were carried out on 60GHz radio coverage extension by using RoF at intermediate frequency with two hops in the air (this work was also part of the French FUI8 ORIGIN project). MMF and low-cost photonics are used. Real-time transmission between two commercial Wireless-HD devices at 3Gbit/s is achieved. The results of these activities will be presented at OFC 2011 [6].

Inside the home, users are accustomed to wireless connectivity as it is a convenient and flexible technology. Wi-Fi IEEE 802.11n achieves data rates higher than 100Mbit/s, but new radio standards as IEEE 802.15.3c, IEEE 802.11ad or Wireless-HD move towards multi-Gbit/s data rates thanks to the use of the 57-66 GHz unlicensed frequency band. However, the drawback of such mm-wave signals is their short range limited to a single room, due to the strong absorption of atmospheric Oxygen. A promising solution to extend their coverage and interconnect the home devices whatever their location consists in using Radio over Fiber (RoF) technology to distribute the radio signal to several Access Points (AP) spread around the home/building. The RoF systems can be transparent for the wireless standard because the radio signal is transmitted in its native format after transposition onto an optical carrier. Moreover, the introduction of optical fibers as infrastructure in the HAN is future proof in terms of data rates increase, capacity of delivering a multiplicity of parallel services with high quality of service and minimization of the electromagnetic fields exposure. The transmission of Intermediate Frequency (IF) transposed radio signals over fiber is worth to be investigated as it can lead to good performances with the advantage of a low system cost with respect to other solutions. We present, for the first time to our knowledge, experimental results on 60 GHz RoF transmission at IF with two hops in the air.

Proposed solution to extend the coverage of mm-wave radio signals

We implement a point-to-point RoF link with two hops in the air that we call "RoF tunnel" as shown in Fig. 18. The advantage of this scheme is that it allows two wireless devices located in two rooms far away from each other to communicate as if they were visible to one another, however, it is at the same time quite demanding as the RoF system must tolerate the losses and the distortions introduced by the two air links.

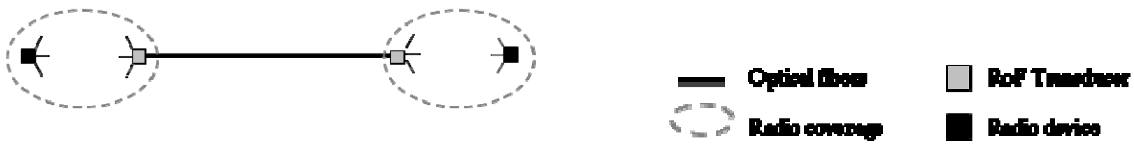


Fig. 18 RoF tunnel at the left (point-to-point link) and RoF transducers at the right

A RoF system may be of interest for the context of HAN only if it is low cost. For this reason we chose to realize electro-optic (E/O) and optic-electronic (O/E) conversions by means of VCSELs (Vertical-Cavity Surface-Emitting Laser) and PIN with transimpedance amplifier typically used for 10Gbit/s digital communications over multimode fiber (MMF). Consequently, in each transmission direction, the mm-wave radio signals are first down-converted by a local oscillator (LO) to a lower frequency (IF) before directly modulating the laser, then they are up-converted after the optical reception. Additionally, the RF power is optimized, firstly at the E/O conversion input to minimize the distortion, and secondly at the O/E conversion output to respect the emitted maximum power level. For the radio coverage, two different antennas are used (Tx and Rx) in order to reduce coupling issue between the two directions.

Experimental setup and results

As a baseline, we have realized the setup shown in Fig. 19 for the mm-wave radio generation, propagation and reception. A radio OFDM signal with QPSK constellation at 3.08 Gbit/s is generated with Matlab according to one 2.16GHz bandwidth channel of the High Speed Interfaces mode of the IEEE 802.15.3c standard, composed of four channels. The baseband signal is generated by a 10GSamples/s dual output Arbitrary Waveform Generator (AWG). The in-phase (I) and quadrature (Q) signals are combined and transposed to an IF of 6 GHz. A system of amplifiers and attenuators optimizes the signal power that we fixed at -12dBm at the input of the mixer used for the final up-conversion around 60.5 GHz, corresponding to the center of the IEEE standard second channel. An up-converted radio power of 8.6dBm is applied to a Tx directional antenna with a gain of 20dB. The Equivalent Isotropically Radiated Power (EIRP) is then 28.6 dBm, very close to the maximum indoor

EIRP permitted in USA, i.e. 27 dBm. After the air propagation, the signal is picked up by the Rx directional antenna, boosted by amplifiers, down-converted by means of an electrical mixer fed with a 52.6GHz LO and finally, captured by a 40 GSamples/s real-time oscilloscope. The signal is finally demodulated offline with Matlab and Error Vector Magnitude (EVM) is then calculated. To optimize the link two variable attenuators have been introduced before each mixer. For a reference measurement, we have placed the oscilloscope in point A of Fig. 19 and obtained EVM values lower than 4% for input RF powers ranging from -30dBm to 10dBm. We then included the air link and measured a stable EVM of 14% for air distances between 5m and 10m.

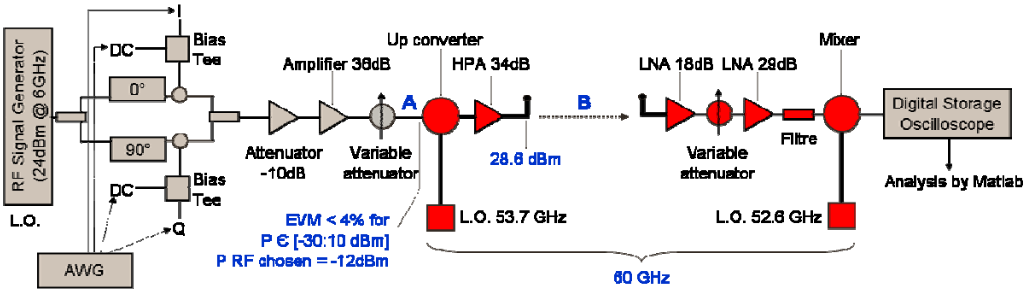


Fig. 19 Experimental setup for the mm-wave radio link

The RoF tunnel is finally added by introducing the setup of Fig. 20 in point B of Fig. 19. The optical link is designed with a VCSEL and a GaAs PIN photodiode at 850 nm from Finisar, and 300m OM3 MMF. The IF is 4.5 GHz since the frequency of the first LO is 53.7 GHz.

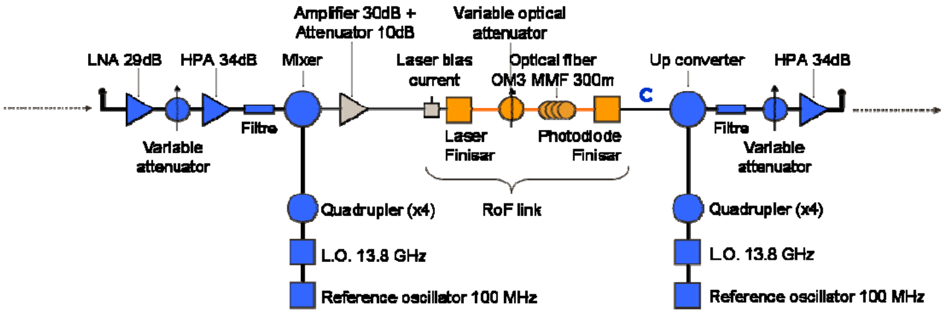


Fig. 20 Experimental setup for the optical tunnel acting as a repeater

The EVM has been measured for distances varying between 2 and 5 meters for the two hops in the air, 300m OM3 MMF and additional optical losses varying between 0 and 3 dB. For a point-to-point link EVM is always lower than 25%, corresponding to a theoretical BER better than 10^{-5}, i.e. error-free transmission after coding implementation. There is no significant difference between 5m plus 2m and 2m plus 5m, thus meaning that any of the two hops is more limiting for the system performances. Fig. 21 shows the OFDM spectrum signal and constellation at the final reception. The center frequency is 7.1 GHz since the frequency of the second LO is 52.6 GHz.

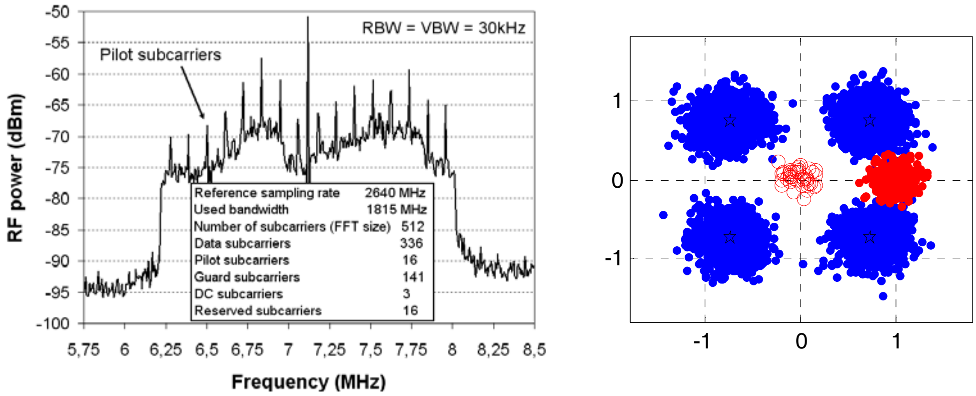


Fig. 21 IEEE 802.15.3c OFDM spectrum and constellation at the reception, for 300m OM3 MMF, 1dB optical losses and 5m + 5m air distance. The corresponding EVM is 22%

In conclusion we have demonstrated that RoF technology allows two 60GHz wireless devices located in two rooms far away from each other to communicate as if they were visible to one another. Inside each room, the distance between the AP and the 60 GHz device can be 5m, and between the rooms it can be 300m of OM3 MMF. We have also realized a real data transmission using commercially available 60 GHz transmitter/receiver modules. Further studies will focus on more advanced RoF network architectures, as multipoint-to-multipoint based on a passive optical splitter and integration of the RoF AP.

4.8.3 Bi-directional Transmission of WiMedia-Compliant UWB Signals over 100m Perfluorinated Graded-Index Plastic Optical Fibre for In-Building Networks [TUE, UPV]

The growth of ultra-wide band (UWB) radio for personal area networks (PAN) is mainly attributed to its robust and spectrally efficient ability to coexist with other radio signals whilst providing high data-rates up to 480Mb/s. However, a significant shortcoming of UWB is the FCC regulated power spectral density (PSD) which restricts the transmission range to typically 10m or less [1]. Therefore, for the purpose of extending the range of UWB radio whilst reducing the complexity of the architecture required for distributed antenna systems, the benefits of radio-over-fiber (RoF) techniques for in-building/home networks is gaining momentum.

Recently, several scenarios have been presented for UWB-over-fibre transmission including a half-duplex, bi-directional transmission system over single-mode fibre [2]. However, for short-range in-building infrastructures, plastic optical fibres are more attractive than silica single/multi-mode fibres due to ease of installation and maintenance, less stringent alignment tolerances and smaller bending radius (<5 mm). Hence, further developments in this direction have lead to the demonstration of arbitrary generated MB-OFDM UWB signals transmission over 62-µm core diameter perfluorinated (PF) Graded-Index plastic optical fibre (PF GI-POF) [3].

Full duplex and bi-directional transmission still raises some difficulties that have to be addressed. Therefore, an in-building network architecture using directly modulated lasers at 1.3µm wavelength for transmission over a single fibre is an attractive solution for low-cost implementation. Therefore, this paper presents the first demonstration of bi-directional transmission of WiMedia-compliant MB-OFDM UWB signals over a single 100m PF GI-POF of 50µm diameter. An error vector magnitude (EVM) penalty of 1% and 1.3% is achieved for the downlink and uplink respectively.

WiMedia Compliant MB-OFDM UWB

The format for the UWB signal is based on Orthogonal Frequency Division Multiplex (OFDM) employed to combat the effects of multipath fading. Each OFDM symbol is composed of 128 orthogonal subcarriers placed with a spacing of 4.125 MHz. Although the FCC UWB spectral mask ranges between 3.1 and 10.6 GHz, band group 1 which occupies 3.168-4.752 GHz is of interest in this work. Each UWB band occupies 528MHz. The PSD is limited to -41.3dBm/MHz to respect the FCC spectral mask for air transmission.

Experimental setup

The experimental setup is as shown in Fig. 22. The UWB signal generated at the residential gateway (RG) uses an off-the-shelf UWB transceiver (Wisair UWB module). For the downlink, the MB-OFDM data is at the time-frequency code 5 (TFC 5), meaning that the transmitter only sends one sub-band data at the centre frequency of 3.432 GHz corresponding to band group 1, sub-band 1. After an electrical power amplifier, the signal is used to directly modulate (IM) an O-Band distributed feedback (DFB) laser at 1302.56 nm with a bias in the linear regime at 50mA. The laser is specified for up to 10Gb/s on-off keying with a small signal modulation bandwidth of 12 GHz.

The transmitted signal is launched via a multimode optical circulator (OC_1) into the POF with an optical power of -2 dBm. After transmitting the signal over ∅ 50-µm POF of 100m, a 25-µm multimode photo-detector with a sensitivity of 0.8A/W was used to directly detect (DD) the signal. The received signal is electrically amplified before being sent via two electrical circulators to a real-time oscilloscope (DPO) running at a sampling rate of 25GSamples/s for WiMedia compliance evaluation.

For bidirectional transmission, the electrical circulator (EC_1) enable the simultaneous transmission of the uplink (and downlink) UWB signal at TFC-7 with centre frequency of 4.488GHz chosen to avoid interference within the same wavelength. EC_2Transmitted at port 1 of the second electrical circulator (EC_2), the uplink signal propagates through port 2 to electrical circulator 1(EC_1). At port 3 of EC_1, the signal is electrically amplified and used to modulate uplink O-Band DFB laser running at the same wavelength of 1302.56nm. Note that a fixed transmission rate of 200Mb/s is used for both directions. After transmission over the same 100m POF link, the signal is received at the RG for evaluation.

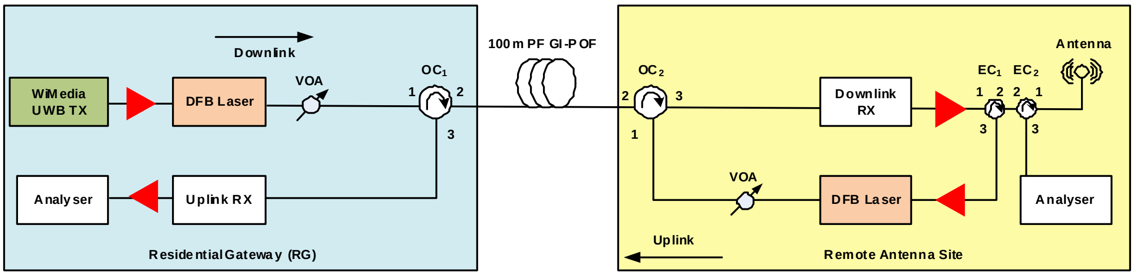


Fig. 22 Concept and experimental diagram (Downlink: MB-OFDM UWB TFC5, Uplink: TFC7)

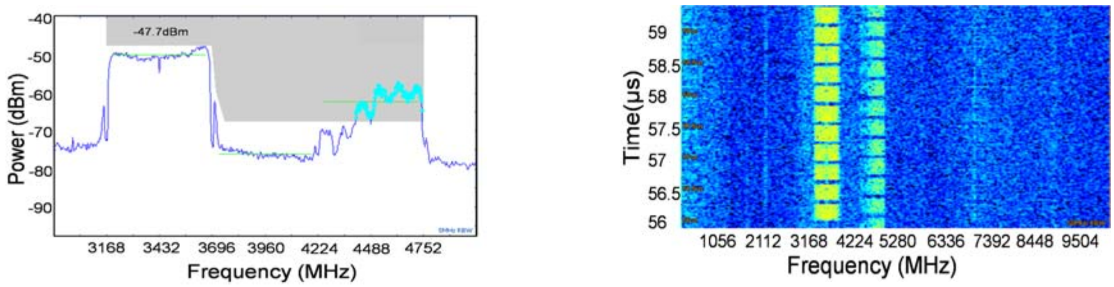
Experimental Results and Discussion

The compliance of the received signals for both directions with the spectral mask was measured. Fig. 23 and Fig. 24 show the power spectral density and spectrograms as obtained using a real-time oscilloscope (Tektronix DPO72004).

Notice in Fig. 23.a, that the crosstalk in the downlink appears to be more severe due to the interference between uplink and downlink signals at the electrical circulator (EC_2) near the antenna.

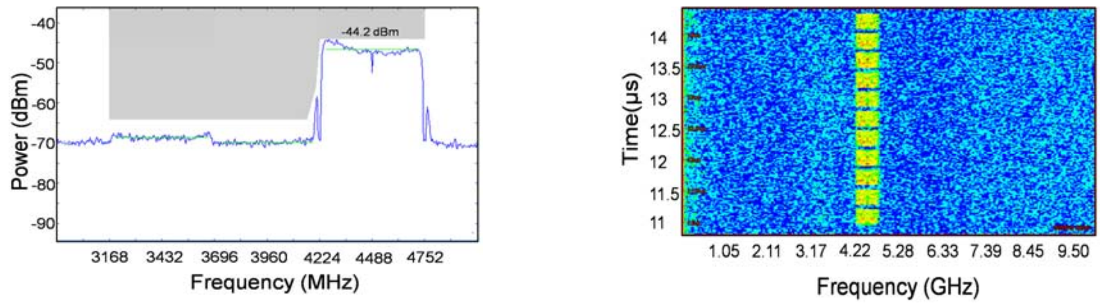
From standard spectrogram measurements shown in Fig. 23.b, the variation of the spectral density can be observed with time. The coexistence of the two bands centred at 3.432 and 4.488 GHz at the same time indicates crosstalk

Despite the detected crosstalk, the downlink signal passes the FCC spectral mask requirements for air transmission with a power of -47.7dBm.



a) b)

Fig. 23 a) Downlink Power spectral density; b) Downlink Measurements Spectrogram



a) b)

Fig. 24 Uplink Measurements: a) Power spectral density; b) Spectrogram (right)

For the uplink direction, the electrical spectrum shown in Fig. 24.a indicates a power of -44.2dBm with very low crosstalk from the downlink signals (centered at 3.432 GHz). The spectrogram in Fig. 24.b indicates the negligible influence of crosstalk in this direction.

With both uplink and downlink signals transmitted simultaneously, Fig. 25 shows the measured EVM values of the received UWB-OFDM sub-band. In the best case, the EVM value for downlink back-to-back is 7.3% for a received optical power of -3dBm. After 100m POF transmission, the penalty is negligible indicating excellent performance. For the worst case (i.e. at receiver optical power of -8dBm), the EVM for the back-to-back case is 9.4%.

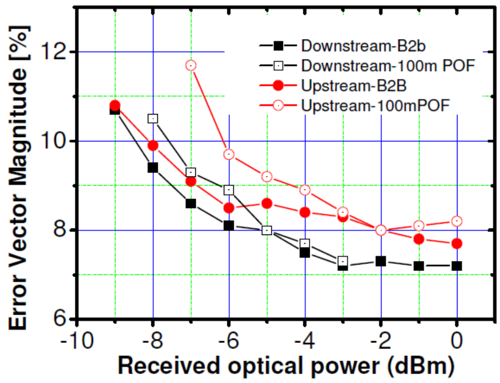


Fig. 25 EVM performance measurement for upstream and downstream links after 100m POF transmission compared with back-to-back

After 100m transmission with the same received optical power, the measured EVM is 10.4%, indicating a penalty of 1%. For the worst-case in the uplink direction, the minimum received optical power is -7dBm with the EVM of 11.8%.

The higher penalty of 1.8% obtained for the uplink is attributed to the lower modulation swing for the directly modulated laser due to the losses at the electrical circulators. Note that the standard EVM requirement for WiMedia compliance is 15% (-16dB), and all measurements obtained are well below this requirement.

The demodulated signals for downlink and uplink are shown in Fig. 26 and Fig. 27. The benefits of MB-OFDM are such that although some subcarrier indices have higher than the average EVM, the overall system performance still meets the required standards. The constellation diagrams of Fig. 26 (right) and Fig. 27 (right) shows clear separation between the points of the demodulated QPSK signals. Both figures indicate good performance for either direction during simultaneous transmission.

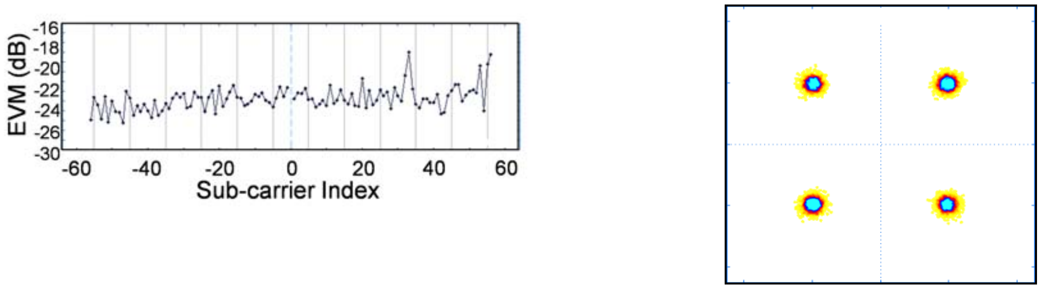


Fig. 26 EVM (dB) of demodulated MB-OFDM UWB sub-carriers with corresponding constellation diagrams for downlink transmission over 100m POF

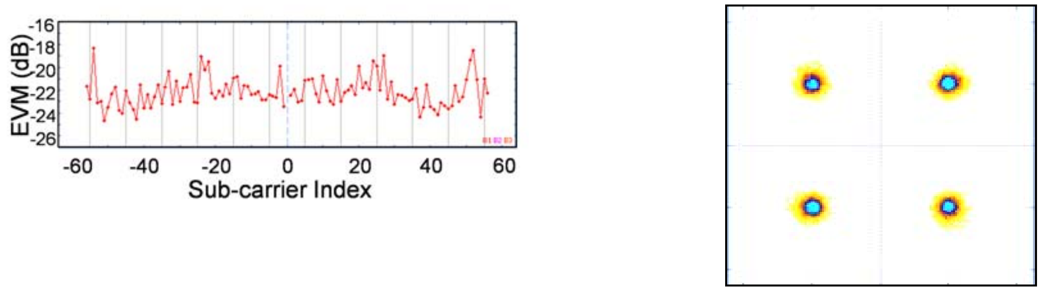


Fig. 27 EVM (dB) of demodulated MB-OFDM UWB sub-carriers with corresponding constellation diagrams for uplink transmission over 100m POF

Conclusions

We reported for the first time bi-directional transmission of WiMedia-compliant MB-OFDM UWB over a single PF GI-POF. Using off-the shelf UWB modules, good performance across all sub-carriers allows low penalty to be obtained during simultaneous transmission of uplink and downlink signals. An overall system penalty of 1% and 1.8% has been measured for downlink and uplink 100m transmission respectively indicating that that a low-cost, large-scale deployment for in-home infrastructure employing PF GI-POF is feasible.

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4.8.4 Transmission of Impulse Radio Ultra-wideband signals over Plastic Optical Fibre [TUE]

A carrier-free Impulse Radio Ultra Wideband (IR-UWB) is one of the UWB system approaches that do not need a complicated frequency mixer, intermediate frequency carrier and filter circuits. Furthermore, it also has good pass-through performance and localization capability with high resolution due to the base-band transmission and high bandwidth respectively. Hence, the cost can be greatly reduced compared to that of multi-band orthogonal frequency multiplexing scheme and much more suitable for indoor wireless communications. However, one of the fundamental points which need a great consideration in IR-UWB circuits and systems design is the selection of the impulse signal type as it determines the performance of IR-UWB systems. Gaussian based monocycle pulses and doublets can provide better bit-error rates and multipath resilience among different impulse signals[3]. However, these pulses do not fully satisfy the FCC rules. Hence, more sophisticated pulse generation techniques based on higher order Gaussian derivatives such as the fifth order is introduced [4] as well as a linear combination of two low-order derivatives of Gaussian pulse with different pulse shaping was proposed [5,6]. However, all previously proposed pulse generation concepts show either increasing complexity or power inefficiency.

We have investigated a simple and new pulse generation concept which has the potential to reduce complexity and cost of the system. Our approach is based on the concept of weighted sum of a modified doublet with its inverted and delayed version. By this process, the proposed pulse has more zero crossings in the temporal response, leading to more power efficient and fully FCC-compliant pulse even in the most severely power-restricted GPS band from 0.96-1.61GHz. This proposed approach is simulated and experimentally demonstrated.

IR-UWB transport using plastic optical fibers

For large-scale short-range applications, multi-mode fibers (MMFs) offer the advantage of easy installation as their larger core diameter and numerical aperture allow large alignment tolerances. More importantly, plastic optical fibers (POFs) can enable short-range low-cost broadband transmission links, best suited to in-home and in-building networks environments. When compared to silica MMFs, graded-index POF (GI-POF) offers further advantages such as smaller bending radius (<5mm), better tolerance to tensile load and stress, and simpler connectorization[7]. Therefore, impulse radio UWB (IR-UWB) over GI-POF provides an attractive solution for simple and low cost in-building networks.

Theory and Simulation Results

A general form of the modified doublet $x(t)$ can be written as :

$$x(t) = \left[1 - 4\pi k\left(\frac{t}{\sigma}\right)^2\right]\exp\left(-2\pi\left(\frac{t}{\sigma}\right)^2\right)$$

Where k is an arbitrary scaling parameter and σ is the pulse width. The spectrum of this signal does not fit completely within the FCC mask; hence additional signal processing is required. We propose the use of a weighted sum of a modified doublet with its inverted and delayed version. The weighted sum $y(t)$ is given by

$$y(t) = a_{11}x(t) + a_{12}x(t-\tau)$$

Where $x(t)$ and $x(t-\tau)$ are the inputs, one is delayed from the other, $a_{11}=+1$ and $a_{12}=-1$. The effect of the pulse shaping factor, σ and delay component, τ is to vary the pulse width and the central frequency of the modified doublet and the resulting pulse. The smaller the delay component, the narrower the pulse in the time domain and hence becomes wider in the frequency domain. In our analysis k=1.13, σ=152 ps and τ =38 ps are the optimal values obtained from optimization processes regarding the power efficiency within the FCC spectrum. Simulation results of normalized doublet pulses in the time-domain before and after a linear combination of the pulses are given in Fig. 28. Note that the resulting pulse has more zero crossings compared to the monocycle and modified doublet pulses, which causes its energy to move to higher frequency ranges. This linear combination concept has in principle the same effect as higher-order derivative operations of Gaussian pulses.

A simulation result shown in Fig. 29 suggests that the spectrum of our pulse has a central frequency of 6 GHz and a 10-dB bandwidth of 7.5 GHz. The proposed pulse fits the FCC-mask better than modified doublet even in the most severely power-restricted GPS band from 0.9−1.61 GHz. Furthermore, the proposed approach avoids the requirement for higher order derivatives of Gaussian pulses [4] and different pulse shaping factors [5,6]. Hence, the novelty of our approach lies in its simplicity to generate pulses by combining low-order derivatives with fixed constant pulse shaping factors in order to match optimally the FCC requirement. Furthermore, our IR-UWB pulse is efficient for air transmission using an antenna because the absence of a DC-component and also most of its energy occupies higher frequency ranges compared to conventional pulses.

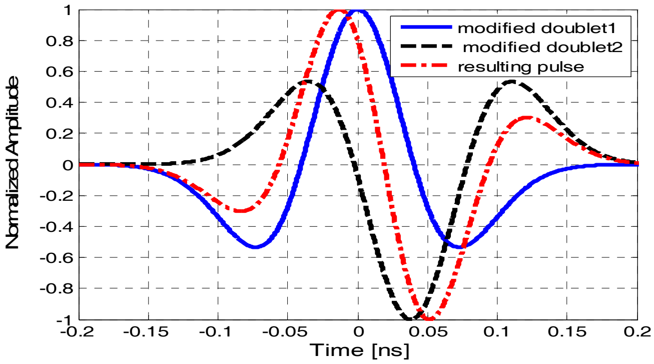

Fig. 28 Simulation result of modified doublet and resulting pulse

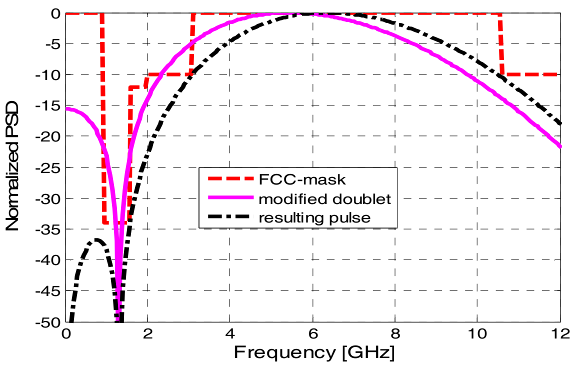

Fig. 29 Simulation result of FCC mask and PSD of modified doublet and resulting pulse

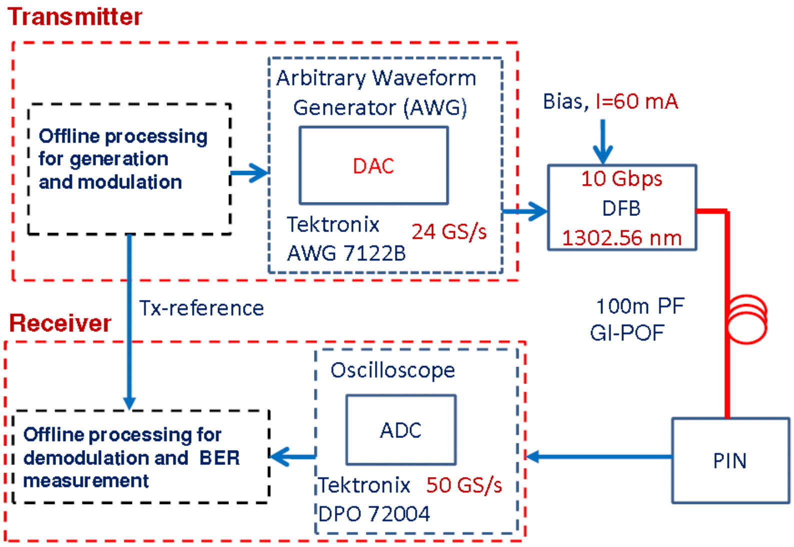

Fig. 30 Experimental Setup

Experimental results and discussion

Based on the above principle, an experimental setup is shown in Fig. 30. Our IR-UWB pulse has been constructed off-line using MATLAB and sent to the arbitrary waveform generator (AWG) running at 24 GSamples/s. The generated electrical IR-UWB pulse from AWG was used to directly modulate a DFB laser at 1302.56 nm wavelength which was biased at 60 mA. Then the modulated signal is then tranmistted over 100 metres of 50-µm core perfluorinated GI-POF (PF GI-POF) and detected by a 25 GHz photo-detector (PD) with a photosensitive area of 25µm. We use a real-time oscilloscope running at a sampling rate of 50 GSamples/s to show the time-domain waveform and obtain data for BER measurement. Finally, the the electrical spectrum of the pulse is obtained FCC mask compliance analysis.

Several modulation formats can be used for IR-UWB , however for simplicity and low-cost, on-off keying (OOK) is employed to directly modulate the DFB laser. The received data durng the optical back-to-back case is shown in Fig. 4a. The PSD of the pulse of the optical back-to-back case is shown in Fig. 4b. Due to the OOK modulation scheme, the discrete spectral comb-lines appears in the spectrum and the spacing between each comb-lines is 2 GHz which is corresponds to the bit-rate of the transmission system. Notice that resulting spectrum is narrow compared to the optimally simulated pulse this is due to the low sampling frequency of the AWG which indirectly forces the delay to be large, $\tau = 41.67$ ps. After 100m PF GI-POF transmission, the time-domain waveform and PSD of the pulse are shown in the fig. 4c and fig.4d respectively. The results clearly show a successful transmission of 2 Gbps without any significant distortion which is mainly due to the high bandwidth PF GI-POF fiber.

Fig. 31 shows the BER results of 2 Gbps IR-UWB signal transmissions. For each BER measurement point, 8190 IR-UWB bits following a 2^{13}-1 PRBS pattern are transmitted and recorded using a 25 GSamples/s Digital Phosphor Oscilloscope. The BER is subsequently computed using a DSP algorithm in a bit-for-bit comparison between the transmitted and received data. The DSP algorithm distinguished between binary “1” and “0” by comparing the average power within the central window of each bit-slot to an adaptive decision threshold. According to the result of the BER measurement, the 100m PF GI-POF transmission shows a penalty of around 2 dB, due to the random mode mixing and modal noise at the receiver.

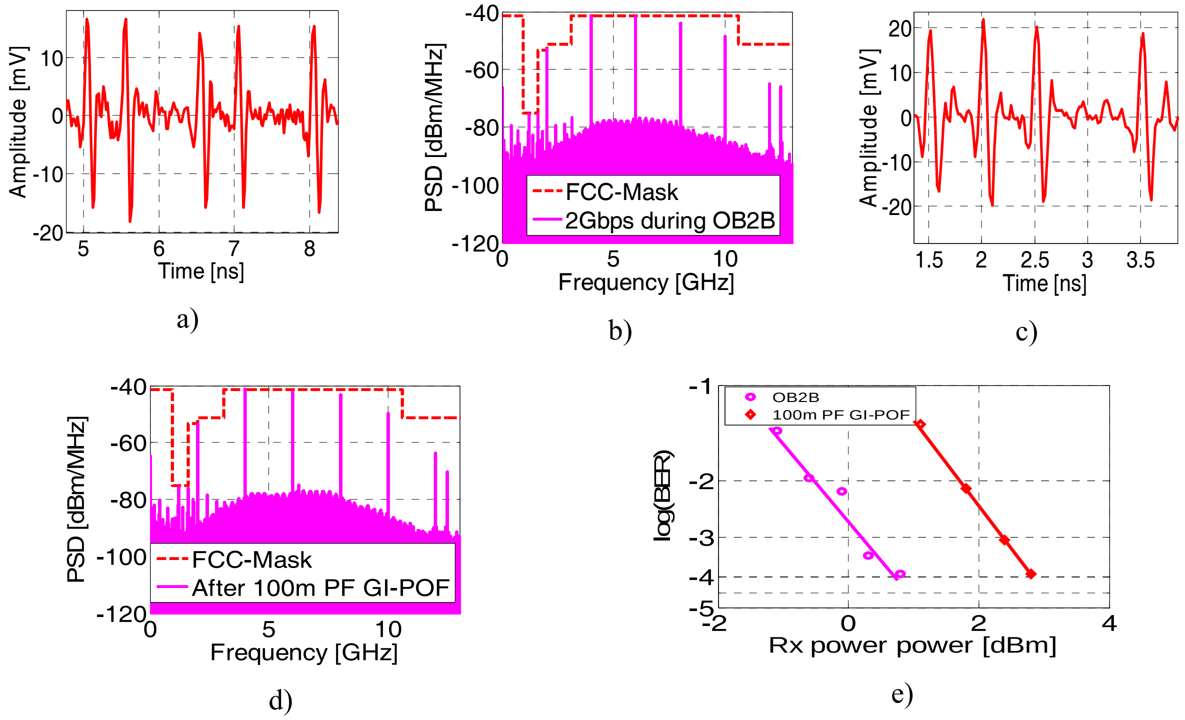

Fig. 31 IR-UWB pulse optical back-to-back (b): FCC mask and PSD of 2 Gbps transmission during optical back to back (C): IR-UWB pulse after 100m PF GI-POF (d): FCC mask and PSD of 2 Gbps transmission after 100m PF GI-POF (e): BER measurement

Conclusion

We have proposed a novel generation technique of IR-UWB pulse by weighted sum of modified doublet with its inverted and delayed version. We experimentally demonstrate for the first time an FEC-limit DSP based BER measurement of 2 Gbps IR-UWB over 100m PF GI-POF. The generated pulse fully complies with the FCC-indoor spectrum mask even in the most severely power-restricted band from 0.96 GHz to 1.61 GHz. We believe that our newly proposed IR-UWB over PF GI-POF has a potential application in a simple and low cost high speed short-range communications networks for in-building networks.

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4.9 High capacity data over SMF/MMF

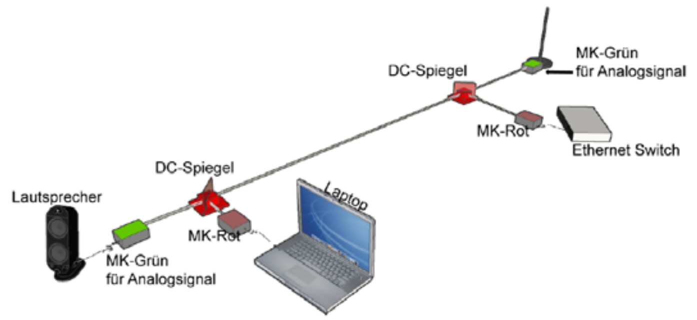
4.9.1 DKE/AK 412.7.1 Working Group Polymer Optical Fiber (POF) [UDE, TUE]

Today often wireless technologies such as W-LAN or existing wired technologies such as PLC provide most of the (so far low-speed) in-house connections in the customer’s premises. Polymer Optical Fibers (POF) can be installed by non-specialists and will allow for fast, reliable and electromagnetic interference-free point-to-point connections. Ethernet media converters with more than 100 Mbit/s and more than 120 m link length are available already now.

The DKE/AK 412.7.1 working group aims to fill the gaps in POF standardization. It is the objective of the team to design a robust and easy-to-install transmission system for data rates of 1 Gbit/s over up to 50 m transmission distance. This range will be sufficient for apartments and most of the multi-dwelling units.

WDM over POF

At UDE, different activities have been started to integrate different services into one optical fiber. One possibility investigated is focusing on changing all services to the Ethernet standard. Another possibility exists in the separate transfer by using the WDM technology. In this case an independent, effective and low-cost solution has to be developed.



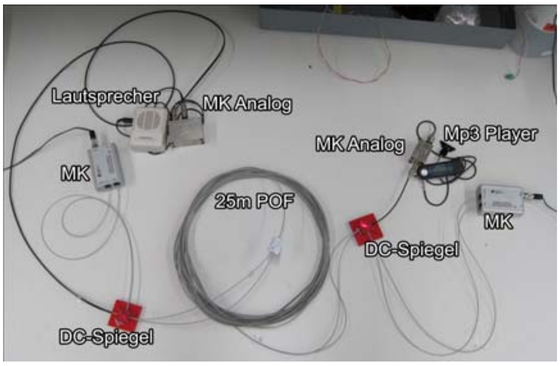


Fig. 32 Structure and realized network of low-cost WDM-POF-connections

Within the scope of a thesis first research activities have been started to find an efficient low-cost solution to expand a POF-based Ethernet network to a WDM network for different services.

POF presentations at conferences

At the conference „17th Kommunikationskabelnetze“ (Dec. 14-15, 2010, Cologne) current joint activities, products and certifications have been presented by Mr. Bentz (HouseComSolutions GmbH) as system integrator and by a common booth at the attended company and institutes presentation booths; see Fig. 33. The joined conference and workshop is focused on Fibre in the Home (FITH) and Fibre to the Home (FTTH). The goal was to show to the users the manufacturer-independent technology solutions. Different developed components and systems (software and hardware) have been shown to work efficiently together.

Fig. 33 Common booth to present a POF-based in-house network

4.9.2 *Wired and wireless multi-service transmission over large-core GI-POF for home networks [TUE, UniBo]*

Delivery of multiple services through in–home networks is a bandwidth-hungry necessity. The transmission capacity needed for delivering current and emerging home services can even exceed the access line capacity [1]. Currently, a plethora of delivery methods and cable media are employed for different kinds of services; e.g., coaxial cable for video broadcast, Cat–5 cable for computer data, twisted pair cable for wired telephony, and wireless LAN for Internet. Such multiple network infrastructures lead to a complicated consumer experience and high service and maintenance costs.

To provide a simplified and easily upgradable in–home network, a single common backbone infrastructure is required, as shown in Fig. 34. Single mode fibre has been considered as a future–proof transmission medium for access and in–building networks. However, single–mode hardware, installation and maintenance costs are prohibitive for mass deployment. Hence, for cost–sensitive in–home networks other solutions should be considered.

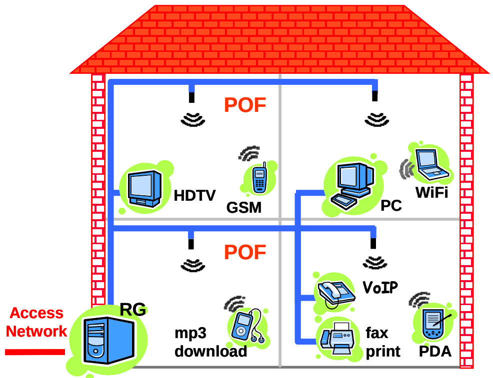


Fig. 34 In–home POF infrastructure for converged transport of wired and wireless services

Plastic optical fibre (POF) is a cost–effective solution, especially when sharing the existing ducts with electrical power line cables [2]. Specifically, ∅1mm core poly–methylmetacrylate (PMMA) POF is becoming increasingly important, due to the high potential for “do–it–yourself” installation, easy maintenance and its tolerance to bending.

A comprehensive study on large–core POF systems has been carried out to achieve multi–gigabit transmission [3], and to transport broadband wireless signals [4].

This paper presents for the first time simultaneous transmission of broadband baseband and radio frequency (RF) signals using ∅1mm core PMMA graded–index (GI) POF.

We demonstrate the successful transmission of a DMT signal at a data rate of 2.2 Gbit/s and a WiMedia–compliant multi–band (MB) OFDM UWB radio signal at 200 Mbit/s over a 50 meters link of PMMA graded–index POF.

Experimental setup and results

The proposed system is based on a simple intensity–modulated direct–detection (IM–DD) optical link. The main bandwidth limitation of the system is attributed to the POF link bandwidth and the optoelectronic components. In particular, the photo–receiver has only a 1.4 GHz –3 dB bandwidth.

The experimental setup is depicted in Fig. 35. We split the available bandwidth into two separate spectra, for DMT (~0 to 0.8 GHz) and UWB (0.8 to 1.4 GHz) signals. A WiMedia–compliant UWB transmitter generates a real–time MB–OFDM signal centered at 3.96 GHz (TFC6: 3.696 – 4.224 GHz). Although the standardized full UWB bit–rate is 480 Mbit/s, our available UWB transceiver was limited to 200 Mbit/s. In order to fit within the limited low–pass bandwidth of the POF, down–conversion of the UWB signal from the RF to an intermediate frequency band (0.836 –

1.364 GHz) is required. An arbitrary waveform generator (AWG) working at a sampling speed of 1.6 GSamples/s is used to generate the DMT signal. A bit and power–loading algorithm is used to adjust the right signal constellation format for every subcarrier.

The electrically combined signal is used to directly modulate a VCSEL at 667 nm with an eye safe optical emitted power of 0 dBm. The VCSEL is followed by ∅1mm core 50 meters PMMA GI–POF and a photo–receiver based on a ∅230µm Si–APD, followed by a 2–stage electrical amplifier with a gain of 40 dB. The detected signal is fed to a digital phosphor oscilloscope (DPO) in order to capture a time–window of the received signal for off–line performance evaluation. The maximum data rate at a bit–error–rate below 10^{-3} for DMT and error vector magnitude (EVM) for UWB is measured.

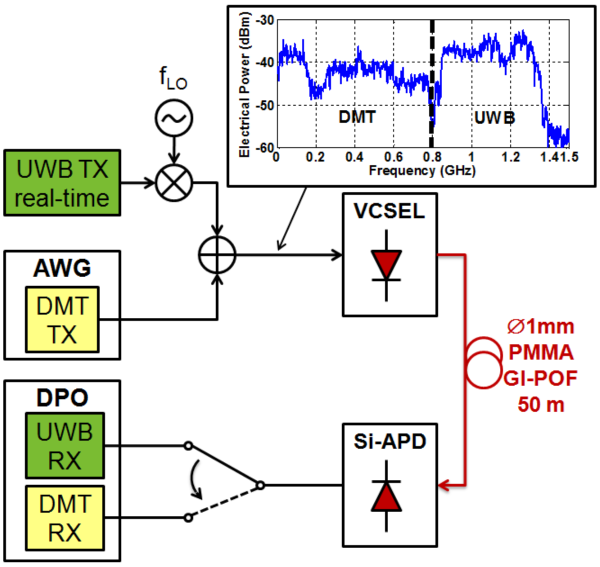
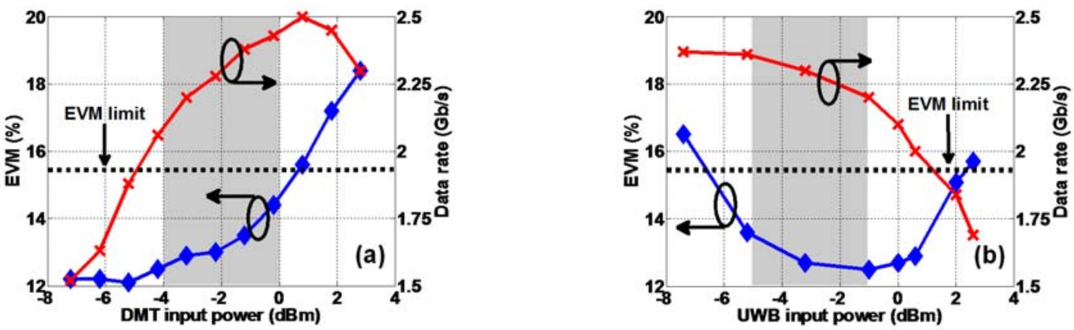


Fig. 35 Experimental setup for simultaneous transmission of DMT and UWB signals over POF. Inset: spectral allocation of DMT and UWB in the available bandwidth

Fig. 36(a) shows the performance of the two signals with UWB power fixed to −1 dBm while for the DMT power several values are considered. For DMT power below 0.8 dBm, the UWB EVM performance complies with the standard EVM limit of 15.5%. The recommended operating region is where the difference between the two curves is the largest, i.e. between −4 and 0 dBm. With DMT power fixed to −3.2 dBm, we repeat the experiment by varying the UWB power, as in Fig. 36(b). The recommended region of operation is between an UWB input power of −5 and 0 dBm. In particular, we set the DMT and UWB signal power to −3.2 and −1 dBm, respectively, to achieve 2.2 Gbit/s DMT transmission with the UWB EVM below 13%.



a) b)

Fig. 36 DMT and UWB performance as a function of DMT and UWB input power, respectively

In Fig. 37, the received constellation for the subcarriers of the DMT signal with 3 bits allocated, and the QPSK constellation of the UWB signal are shown.

Fig. 37 Constellation diagrams of the received signals after simultaneous transmission over 50m POF

Conclusions

We have experimentally demonstrated for the first time a combined transmission of wired and wireless signals over ∅1mm core 50m PMMA GI-POF. Two broadband signals are simultaneously transmitted: 2.2 Gbit/s DMT signal with BER < 10^{-3}, and a 528−MHz WiMedia−compliant UWB signal with EVM < 13%.

This work validates the use of ∅1mm POF links as a common infrastructure for in−home networks capable of transmitting wired and wireless in−home services. In addition, implementation costs are minimized by employing simple transceivers, IM−DD optical systems, and advance modulation formats.

This work has been presented as a joint effort of TUE and UniBo at the IEEE Photonics Society Annual Meeting, Denver, Nov. 2010.

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4.9.3 Bandwidth-efficient modulation formats [UCAM]

The continuing rise in traffic in local-area networks (LANs) is motivating the development of new standards for data communication links. For example, IEEE 802.3 is currently finalizing the standardization of the initial forms of 40 Gigabit Ethernet and 100 Gigabit Ethernet. In contrast to previous standards, such as 10 Gigabit Ethernet, operation at 40 Gb/s and beyond necessitates multiplexing of several lower-rate channels, e.g. at 10 Gb/s, to achieve high aggregate line rates at a commercially acceptable cost. Indeed, the standards under development are considering the application of multiple optical channels, through the application of wavelength-division multiplexing (WDM). However, it would be preferable to employ multiple electrical channels on a *single optical wavelength*, thereby avoiding the cost of multiple lasers, photodetectors and the associated optical multiplexing components. Until recently, high-spectral-efficiency microwave modulation formats, e.g. quadrature amplitude modulation (QAM), have been dismissed as unsuitable for such applications, primarily due to the difficulty of achieving low-cost implementation of the modems in current integrated-circuit (IC) technology.

Research at UCAM has demonstrated how the implementation of high-spectral-efficiency modulation formats in optical data communication links may be significantly simplified through the application of low-cost microwave transversal filters. The technique of carrierless amplitude and phase (CAP) modulation, previously considered in relation to communication links over electrical cables, allows the use of such IC filters to generate orthogonal and multilevel pulse shapes without the requirement for high-speed mixers. Moreover, the required transversal filters are now available as high-speed, low-power-consumption commodity components, due to their widespread application to electronically-equalised links, e.g. in the recent 10GBASE-LRM variant of 10 Gigabit Ethernet.

Fig. 38 illustrates the principle and Fig. 39 indicates initial experimental results at an aggregate data rate of 10 Gb/s.

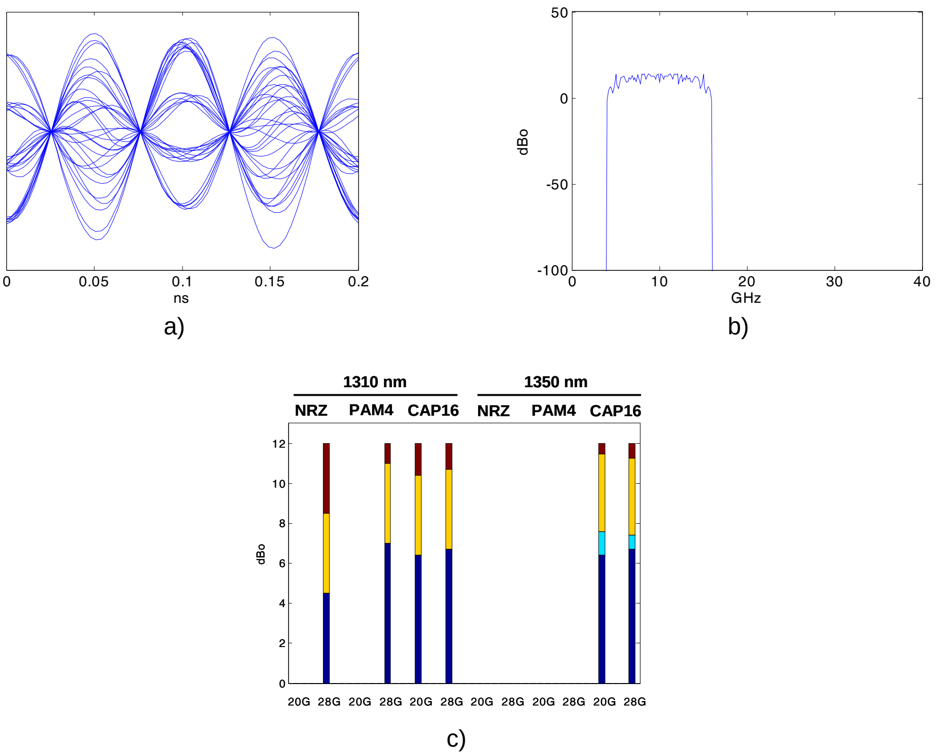

Fig. 38 (a) Eye diagram of in-phase CAP16-encoded waveform corresponding to 20 Gb/s transmission (40 Gb/s aggregate); (b) corresponding electrical spectrum indicating 10 GHz bandwidth; (c) 10 km power budget comparison at 40 Gb/s between NRZ, PAM4 and CAP16, where dark blue indicates relative receiver sensitivity, pale blue indicates SMF dispersion penalty, yellow indicates SMF attenuation and red indicates unallocated margin in the 12 dBo budget. For clarity, power budget bars are not shown if the total penalty exceeds the budget

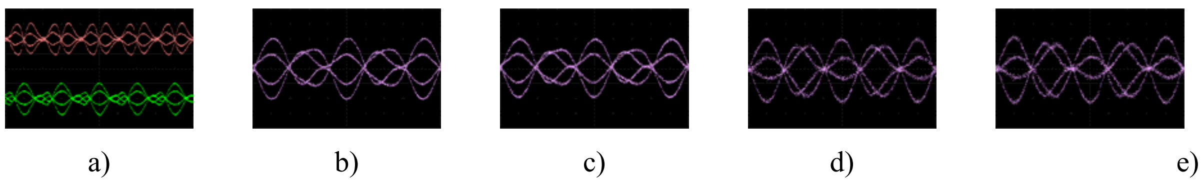

Fig. 39 (a) CAP16 eye diagrams for 10 Gb/s aggregate transmission: in-phase channel (top) and quadrature channel (bottom) (200 ps/div); (b) decoded in-phase channel after back-to-back optical transmission (100 ps/div); (c) decoded in-phase channel after 10 km optical transmission (100 ps/div); (d) decoded quadrature channel after back-to-back optical transmission (100 ps/div); (e) decoded quadrature channel after 10 km optical transmission (100 ps/div)

In summary, UCAM has proposed the application of carrierless amplitude and phase modulation as a route to the high aggregate data rates, e.g. 40 Gb/s, required by current and future optical data communication standards. For the first time, this shows how the use of simple and low-cost transversal filter architectures may allow flexible generation of channels with high spectral efficiency, allowing single-wavelength links with the current generation of optical components.

4.9.4 Launches for multimode-fibre links [UCAM]

Multimode fibre (MMF) is limited in use for high data rate transmission due to its low operating bandwidth mainly caused by inter-modal dispersion. Approaches to overcome this limitation have been investigated intensively in recent decades and have explored different launch schemes to achieve restricted mode excitation and hence allow increased link bandwidth. In the 10 Gigabit Ethernet standard, for example, a dual launch scheme was adopted, this involving the use of either centre or offset launch depending which performed better with the given installed fibre. Most recently, a novel Hermite-Gaussian (Fig. 40) line launch scheme was proposed and shown to provide potential fibre bandwidth enhancement. This is achieved through creating a near single-mode operation by exciting only a single mid-order mode group.

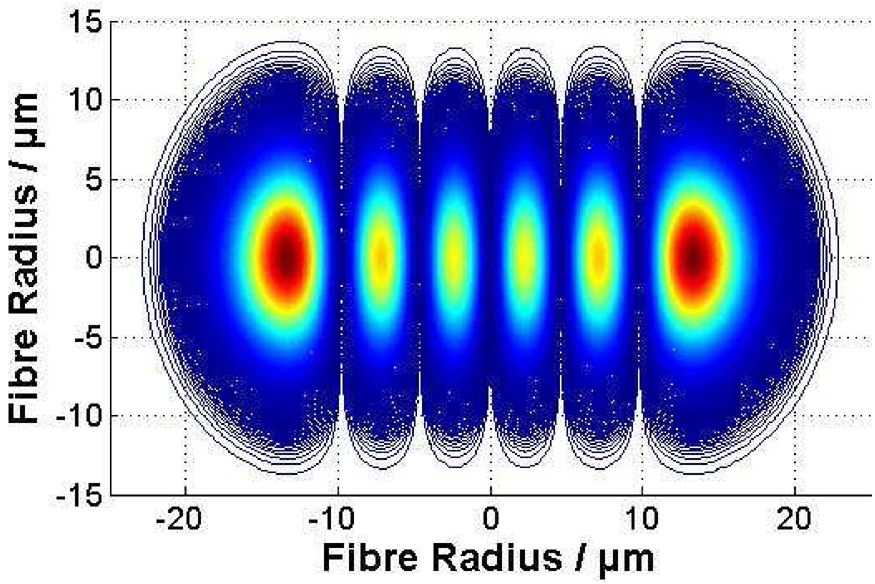

Fig. 40 Intensity profile of 5th-order Hermite-Gaussian beam

UCAM has recently investigated an elliptical Gaussian beam together with a 5th-order Hermite-Gaussian beam shaping mask to achieve an efficient and robust line launch (Fig. 41). This launch, implemented in a system, outperforms dual launch over a wide offset range (±6 µm) with reduced penalty and does not require manual testing at installation.

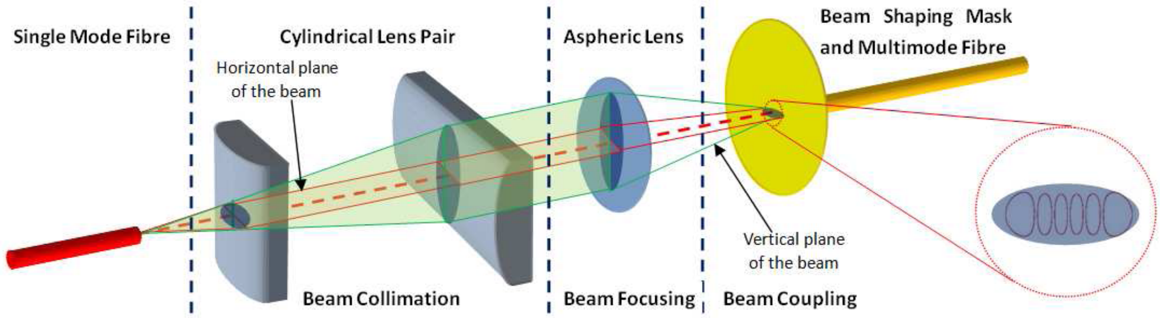

Fig. 41 Elliptical beam generation from a single-mode fibre and coupling through 5th-order Hermite-Gaussian beam shaping mask

The frequency response result in Fig. 42 clearly show that the elliptical Gaussian beam line launch achieves a high EMB improvement. For fibre A, which is illustrated in Fig. 42(a), the measured line launch –3 dB bandwidth is 8.2 GHz (2050 MHz·km EMB), where the centre launch and offset launch achieve 5.7 GHz (1425 MHz·km EMB) and 2.2 GHz (550 MHz·km EMB) respectively. This is a near 1.5 fold bandwidth improvement over centre launch and 4 fold improvement over offset launch. A misalignment tolerance test is carried out in terms of bandwidth measurement by manually misaligning the line launch beam against the cleaved MMF along both vertical and horizontal axes of the 5th-order Hermite-Gaussian beam pattern respectively. Fig. 42(b) shows that the peak bandwidth is reduced by less than 1 GHz with a misalignment of ±3 μm on either axis. The elliptical beam line launch thus maintains high bandwidth of above 7 GHz (1750 MHz·km EMB) within the ±3 μm launch offset assumed by the 10GBASE-LRM committee. The elliptical Gaussian beam line launch is shown to be a stable approach with an acceptable tolerance to launch misalignment. Meanwhile, the elliptical Gaussian beam line launch keeps outperforming the dual launch on fibre A even with a misalignment of ±6 μm.

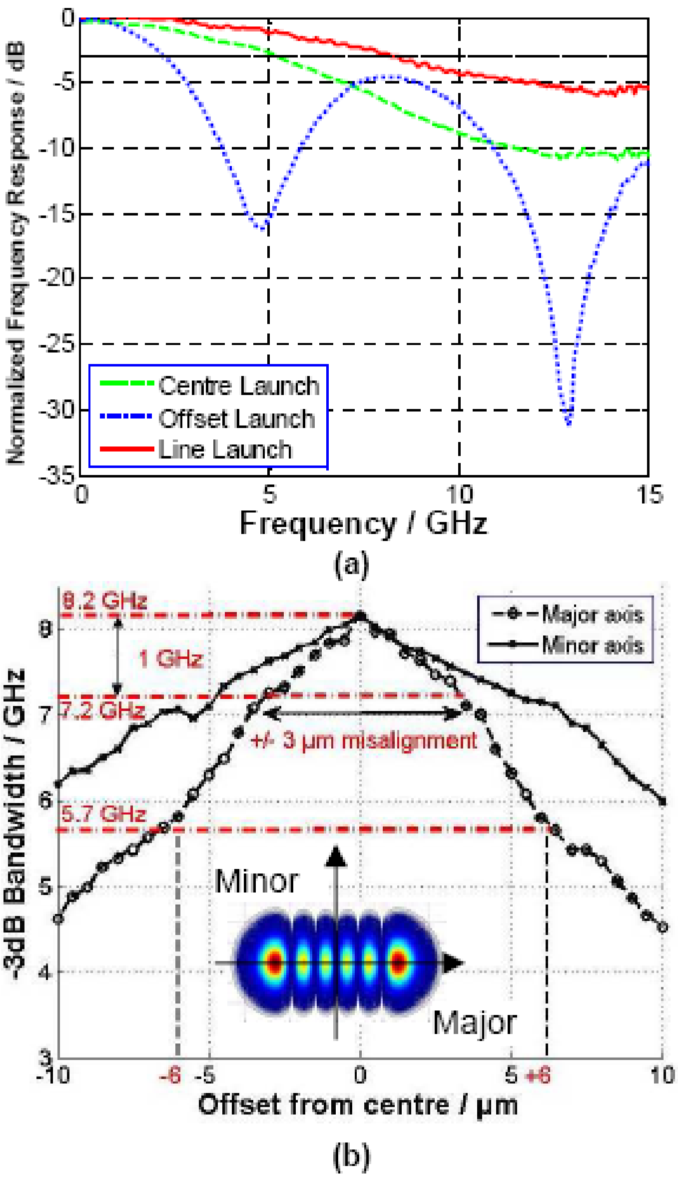

Fig. 42 (a) Plot of frequency response of fibre A, (b) bandwidth as a function of offset of elliptical Gaussian beam line launch along both axes

In summary, UCAM has demonstrated a novel efficient line launch with high system capacity improvement. The total insertion loss of a fibre to fibre link under this line launch scheme is less than 3.8 dB. Bandwidth measurements are carried out by using two fibres which favour centre or offset launches respectively and the elliptical Gaussian beam line launch outperforms the dual launch scheme in both cases. A misalignment tolerance experiment also shows that this launch can provide a stable bandwidth performance even with misalignments of ±6 µm, in excess of the ±3 µm tolerance required by data-communications standards. Finally, a data transmission test has shown that the elliptical Gaussian beam line launch has a very low power penalty of only 1.7 dB against back-to-back, 0.9 dB lower than the centre launch power penalty. Therefore, we believe that the novel elliptical Gaussian beam line launch scheme is a robust solution for high data rate MMF links, despite not requiring manual testing in installation.

4.9.5 *Improvement of the performance of a large core Plastic Optical Fiber link using an optical mode filtering technique [UoA]*

An investigation of the influence of the geometric properties of the interface between the fiber end and the photo-receiver on the performance of a large core SI-POF link was performed. It was proved numerically and confirmed experimentally that despite the common sense according to which a photodiode with a small active area (smaller than the fiber core cross-section) would negatively affect the link performance due to worse coupling with the fiber, the actual obtained bandwidth can be much higher due to higher-order mode optical filtering. Moreover, it was shown that this improvement can over-compensate the degradation due to decreased power incident to the receiver. Key-points for the numerical investigation are the explicit calculation of all modes supported by the fiber, their corresponding effective refractive index and their spatial distribution over the fiber end facet. The experimental confirmation relied on the fact that a small axial offset between the fiber-end facet and the receiver results in an effective reduction of the receiver's active region. This is equivalent to a higher order mode filtering as these modes reach the receiver's plane outside its active area.

Numerical Investigation

According to the traditional approach, the modes supported by a multimode fiber can be divided into groups of modes, which experience approximately the same effective refractive index. This approximation gives accurate results for Differential Mode Delay (DMD) calculations, while it significantly relaxes the processing requirements. However, all modes that belong to a certain mode group have different spatial power distributions, the calculation of which requires mode solutions for all supported modes. From these solutions, the spatial power distribution of every mode can be calculated – using the well known Bessel functions –, while the DMD can be computed from the Neff (Fig. 43(left)) of each mode that is also easily derived from these solutions. The optical power of the modes incident to a receiver with dimensions smaller than the fiber cross-section can then be estimated (Fig. 43(right) and Fig. 44(left)), along with the corresponding DMD of these modes. The mean DMD/l as a function of the induced power loss is shown in Fig. 44(right). A 30% reduction of the mean DMD/l value is achieved having an additional optical power loss of 3.2dB [1].

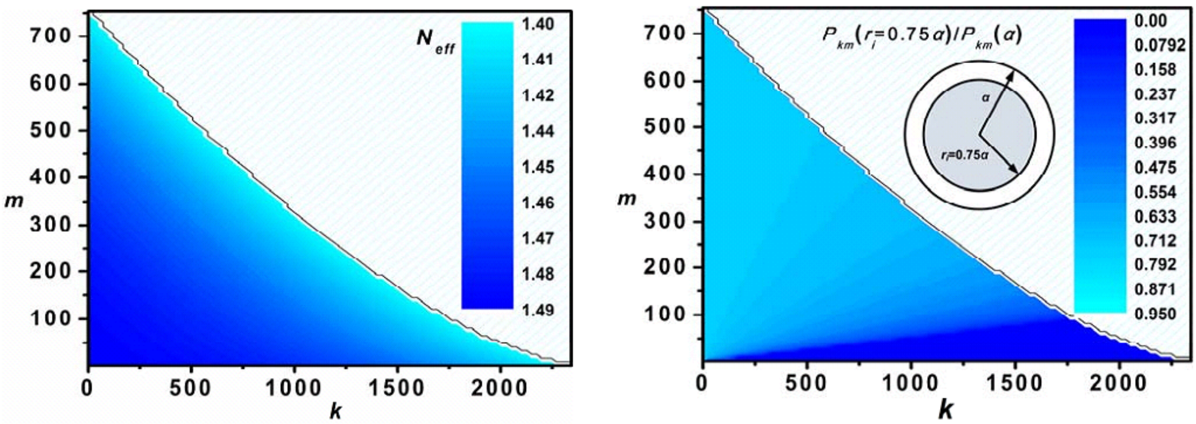

Fig. 43 Calculated effective refractive index (Neff) for all LPkm modes, supported by a SI-POF (left). Contour plot of the power ratio of each LPkm mode included in a circle on the surface of the fiber with ri=0.75a (right)

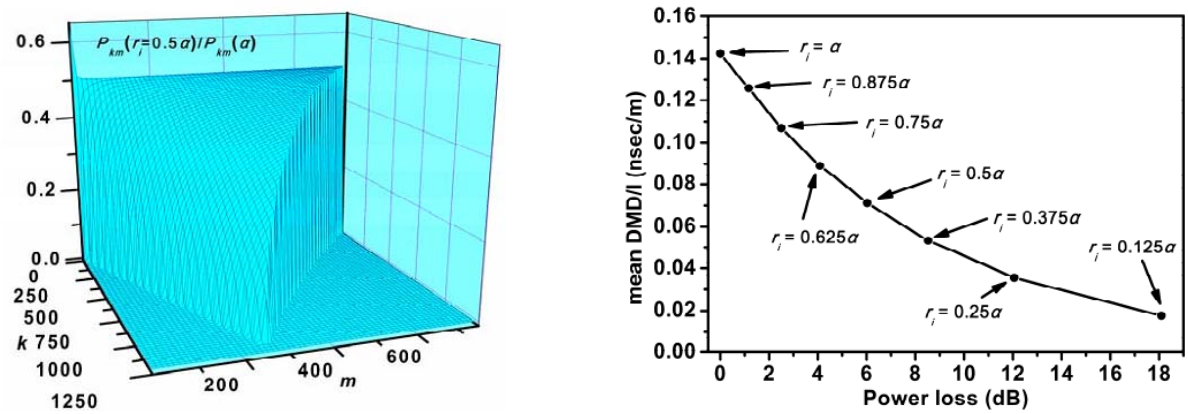

Fig. 44 3-D plot of the power ratio of each LPkm mode included in a circle on the surface of the fiber with ri=0.5a (left). Mean Differential Mode Delay per unit length (DMD/l) as a function of the power loss induced by the optical mode filtering method (right)

Experimental Confirmation

A schematic of the testbed used to evaluate this optical method for higher order mode filtering is shown in Fig. 45 (left). A Fabry-Perot (FP) laser (LDM-650-10-R-ST) emitting at 650nm was used as the optical source. The spectral width of the laser emission was 5nm. A photo-receiver with an effective active diameter of 0.8mm (HSA-X-S-1G4-SI) was placed on an in-house developed positioning system that allowed the introduction of air gap between the fiber end and the receiver, with micrometric accuracy. Typical SI-POF spans with a core diameter of 980um and a NA of 0.5 were used as the optical medium. Bit Error Rate (BER) measurements were performed for two different configurations regarding the bit rate and link length i.e. Setup I: 622.08Mbps (OC-12) at 62.5m, and Setup II: 1.25Gbps (Gigabit Ethernet) at 37.5m. In all cases a plain NRZ-OOK modulation format was employed, while a Pseudo-Random Bit Sequence (PRBS) with a length of 2^{11}-1.

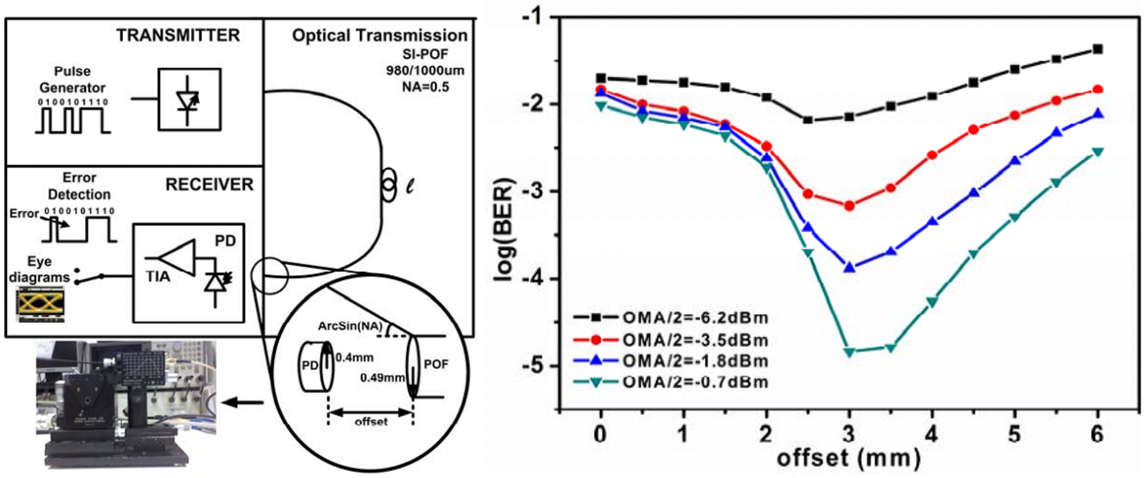

Fig. 45 Experimental setup schematic (left). BER for a bit rate of 622.08Mbps at 62.5m of SI-POF as a function of the offset value introduced (right)

The BER curves for Setup I and for different Optical Modulation Amplitudes (OMA) incident to the receiver are shown in Fig. 45(right). Due to the interplay between modal dispersion relaxation and power incident to the receiver, the BER value decreases with the offset (performance enhancement) as long as the former term's contribution is the dominant performance factor. After reaching a minimum, BER increases with further offset increase, since now the optical power reduction dominates and determines the performance of the system. It is worth mentioning that at zero offset an increase of OMA/2 by 5.5dB, results in a BER improvement of less than half an order of magnitude, meaning that the transmission impairments of the link are dominated by modal dispersion. On the other hand, an offset of 3mm improves the BER by up to 3 orders of magnitude despite the fact that it introduces an additional 3dB power loss. Such a native BER performance combined with a Forward Error Correction (FEC) leads to an error free operation (BER<10^{-12}).

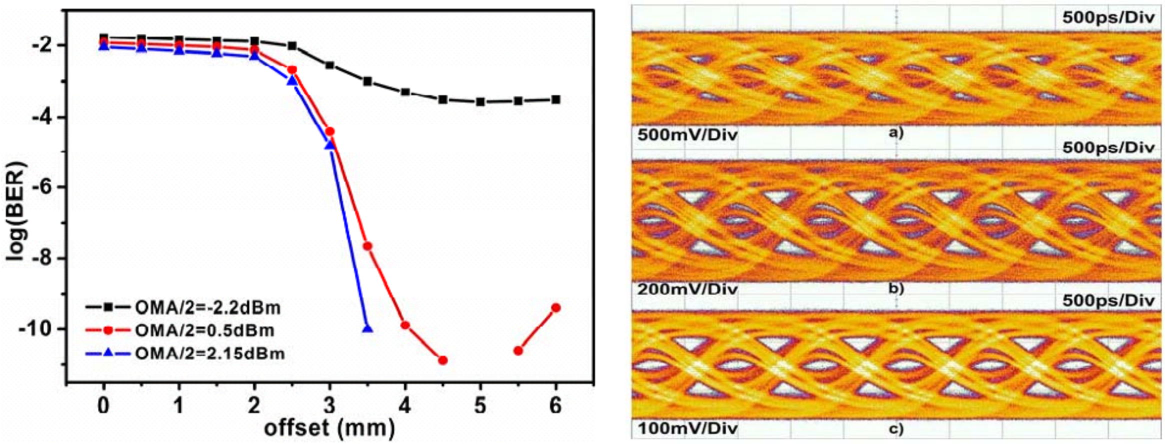

Fig. 46 BER for a bit rate of 1.25Gbps at 37.5m of SI-POF as a function of the offset value introduced (left). Eye diagrams for the same setup for a) no offset, b) 3mm offset, and c) 5mm offset. OMA/2 is equal to 0.5dBm for this instance (right)

In Fig. 46, the BER is shown for Setup II as a function of the applied offset for three different OMA values. This setup experiences even stronger Inter-Symbol Interference (ISI) – caused by modal dispersion – due to the higher bit rate. The small performance enhancement for low offset values (less than 2.5mm) in this case is attributed to the fact that the link length is comparable with the coupling length (Lc), which lies between 25m and 37.5m for this type of fiber, meaning that the highest order modes have been excited at a position close to the fiber end and have small contribution to DMD. As the optical power incident to the receiver is higher in this case, the optimum trade-off is achieved at higher offset values compared to the respective ones of Fig. 45. In this case, a BER of less than 10^{-11} is achieved for a 5mm offset and for an OMA/2 equal to 0.5dB. For an OMA/2 of 2.15dB the minimum BER is achieved for offset values larger that 6mm. In this case, an error free operation (BER less than 10^{-10} for Gigabit Ethernet) is achieved for offset values greater that 3.5mm.

Conclusions

It has been shown numerically and confirmed experimentally that an offset between the fiber end and the photo-receiver could play the role of an effective higher order mode filter with beneficial impact on the performance of the link. The same effect can be achieved by using a photo-receiver with an active region smaller than the cross-section of the POF.

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4.10 Wireless optical communication

4.10.1 Ultra-high-speed wireless optical links [FHG]

Collaborative links have been established to a working group of the EU project MAGIC (MAskless lithoGraphy for IC manufacturing), which has as main focus ultra high-speed (100 Gb/s) optical links. As a result the joint journal paper [1] (together with A3PICs Electronics Development, Austria and TU

Vienna) has been published, in which an overview of the possibilities for optical free-space communication systems regarding especially industrial applications was given.

Block transmission with frequency-domain equalization (FDE) has proven to be an attractive alternative to orthogonal frequency division multiplex (OFDM) for radio frequency communication, especially at 60 GHz. In collaboration with TU Ilmenau it was shown, that FDE can be advantageously applied for optical transmission over dispersive channels as well, and in particular in direct-detection systems. Promising results for an illustrative visible-light communications link based on non-return-to-zero (NRZ) on-off keying (OOK) have peen published in a joint paper [2].

Moreover, a link has been established to the COST IC0802 group on “Propagation tools and data for integrated Telecommunication, Navigation and Earth Observation systems”. Optical wireless technologies are considered in a new recently proposed COST action. The proposal “Optical wireless communications - an emerging technology” was selected by the Domain Committee on Information and Communication Technologies for full proposal submission. The full proposal is currently in preparation and will be submitted by mid of January 2011.

The links established and/or strengthened by BONE are used and extended further, e.g. for preparation of new R&D proposals. As an example, proposals have been submitted in response to the PIANO+ call. The projects have been granted and will start in 2011.

Joint publications

[1] A. Paraskevopoulos, J. Vučić, S. Voß, R. Swoboda, K.-D. Langer, *Optical wireless communication systems in the Mbps to Gbps range, suitable for industrial applications*, IEEE/ASME Transactions on Mechatronics, Vol. 15, No. 4, pp. 541-547, August 2010.

[2] M. Wolf, L. Grobe, M.R. Rieche, A. Koher, J. Vučić, *Block Transmission with Linear Frequency Domain Equalization for Dispersive Optical Channels with Direct Detection*, International Conference on Transparent Optical Networks, pp. Th.A3.4, June 2010.

4.10.2 Radio over Free Space Optical Links [UCAM]

While radio over fibre DAS have many advantages, in some real world situations it won’t be practical to install fibre between the hub and RU. In such cases, a radio over free space optical link may be a solution.

Research carried out at UCAM using a high-power twin contact laser and moderate-power DFB laser have shown that such a system could be practical. Fig. 47 shows the experimental setup used to test the DFB on a free space link, and Fig. 48 the trade-off between the free-space losses and achievable SFDR.

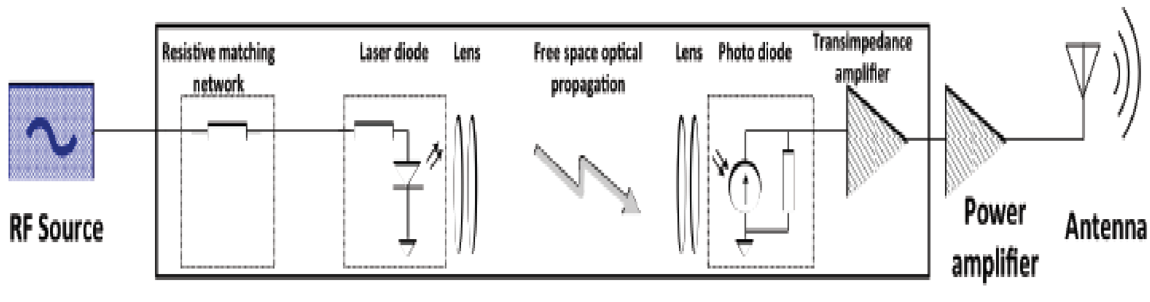

Fig. 47 Experimental setup for radio over free space optical link

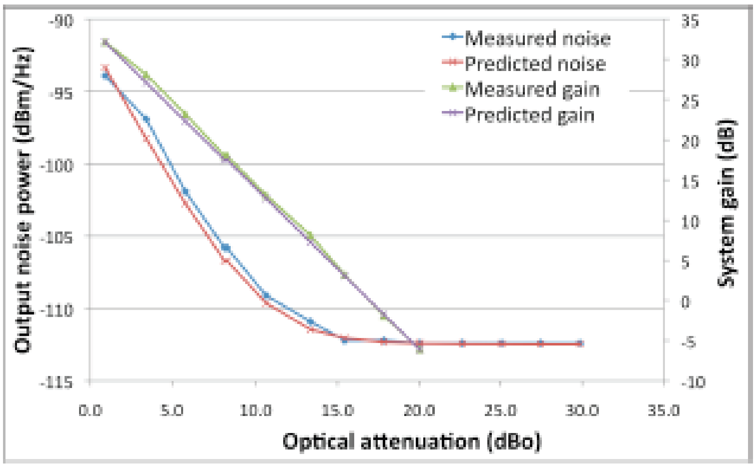

Fig. 48 Degradation of SFDR with optical attenuation (free-space loss)

4.11 Sensor applications

No activities of partners reported.

4.12 Techno-economic analysis

4.12.1 Cost analysis of in-building networks, comparing different architectures and transmission media [TUE, FT]

Fibre to the Home access networks are offering large access capacities of 100Mbit/s or even up to 1Gbit/s [1] . However, this capacity only goes as far as the doorstep of the user's home; reaching the user himself is hampered by shortcomings of today's in-building networks. Moreover, trends such as high-definition video streaming and fast exchange of huge data files to and from centralized terabyte-capacity servers imply that the capacity of the in-building network even needs to exceed the one of the access network connection [2] . In-building networks today typically are a mix of networks, each laid out for a particular set of services: coaxial cable networks for TV and radio broadcasting, twisted pair cables for telephony, Cat-5 cables and wireless LAN for data communication between desktop and laptop PC-s, servers, printers, etc. The variety of networks complicates maintenance, upgrading of services, and the introduction of new services. Combining the delivery of all services, wired and wireless, in a single converged in-building network can offer many improvements. Optical fibre is a powerful medium for this, thanks to its transparency for any signal format and its large bandwidth. Suitable candidates are bend-insensitive silica single-mode fibre (SMF), silica multimode fibre (MMF), and large-core plastic optical fibre (POF). A major competitor is the widely spread Cat-5E cabling. Next to the technical advantages [3] , the cost aspects of the fibre solutions are of major importance in deciding for a network solution.

In the following, we analyze the cost aspects regarding the installation and operation of the various in-building network solutions.

In-building network architectures

A number of basic architectures are considered for the wired backbone network [4] : a point-to-point (P2P) architecture (Fig. 49.a) with individual cables running from the residential gateway (RG; connects the in-building network to the access network) to each room; a bus architecture (Fig. 49.b) with a cable to each floor which by means of a hub is tapped off to each room; and a tree architecture (Fig. 49.c) with a cable to each floor from where via a switch a cable runs to each room. The maximum link length depends on the cable type and the data speed; for Cat-5E it is 100 metres for

Fast Ethernet and Gigabit Ethernet, for MMF 550 metres, and for PMMA POF typically 70 metres for Fast Ethernet and up to 50 metres for Gigabit Ethernet (still in the research phase). With SMF, the maximum link length achievable exceeds any realistic building size. Given the limited reach of POF and Cat-5E links, a larger building is covered by putting the RG at a more centralized position, such as in the hybrid star-tree architecture (Fig. 49.d) or variants thereof (star-P2P, star-bus).

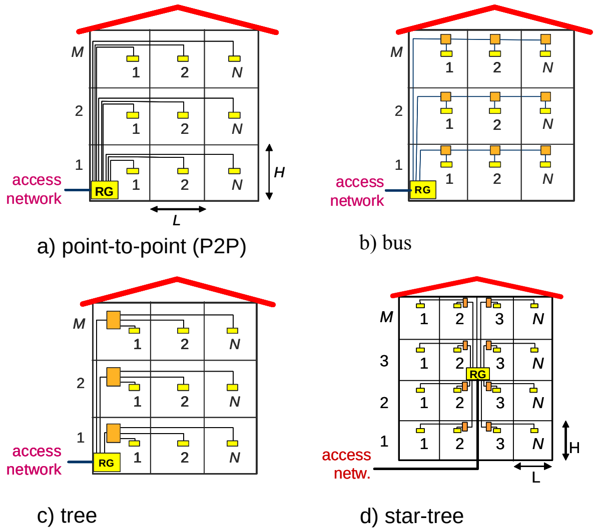

Fig. 49 In-building network architectures

Out of the multitude of building scenarios available, we selected three representative typical scenarios: residential home, office building, and multi-dwelling building. We analyzed the network cost aspects by using the analysis method we have developed earlier [4] .The building dimensions assumed are given in Table 1.

Table 1 Building dimensions

	No. of floors M	No. of rooms per floor N	Distance between floors H (in m)	Distance between wall outlets L (in m)
Residential home	3	4	3.3	8
Office building	10	50	3.8	10
Multi-dwelling bldg.	10	16	4	14

We have assumed that the nodes in the network (the hubs in the bus architecture, and the switches in the tree architecture) perform their routing functions in the electronic domain; hence there is opto-electronic conversion at their inlets and outlets. Typically, they can handle IP-based signals but no non-IP signals (such as analog video), and thus the network becomes opaque.

A fully transparent network, able to handle any signal format, is achieved in a P2P fibre-based architecture, and in all-optical bus or tree architectures where passive optical power splitters or passive wavelength routers are used in the nodes. As these passive optical devices are readily available for SMF but not commercially available (yet) for MMF and POF, a transparent network requires SMF.

For bidirectional links, duplex POF cables are assumed. Given the higher fibre losses which reduce the link budget, and the issues with coarse wavelength multiplexing, a bi-directional single-POF link is not readily feasible.

CAPEX analysis

The capital expenditure (CAPEX) costs to install the various network architectures using different media (SMF, MMF, POF, Cat-5E) have been calculated for the three building scenarios. The cost items taken into account are: cables, ducts, connectors, media converters (opto-electronic transceivers), hubs, and switches. For the various architectures, the costs of each category were expressed in the building dimensions given in Table 1. Based on prices obtained from various manufacturers, and typical labour costs for mounting and installation, the costs per item assumed in our analysis are given in Table 2. It should be noted that market prices vary considerably, depending on specific type and volume, and also the labour time involved for e.g. mounting different connector types varies widely. We assumed typical values here; e.g., we assumed 10 minutes labour time per field-mounted optical connector, which typically amounts to 10€. A major advantage of using large-core POF is its easy (do-it-yourself) mounting to devices, mostly not even requiring a connector but just plugging in the bare fibre; hence connection costs of POF can be much lower than those of SMF, MMF, and Cat-5E.

Furthermore, as fibre is not sensitive for electromagnetic interference (EMI), the fibre cables may share the ducts of the electrical power cables, thus avoiding the costs of separate ducts. This is not feasible for Cat-5E cables, for EMI and safety reasons.

Table 2 Network cost items and their power consumption

	Cat-5E	POF	SMF	MMF
Installed cable costs	1.8 €/m	1.7 €/m	1.74 €/m	1.95 €/m
Max. link length	100 m	70 m	1000 m	550 m
Mounted connector costs	13 €	3 €	15 €	14 €
Media converter costs; power consumption	(negligible); 0.65 W	30 €; 0,85 W	70 €; 1.15 W	40 €; 1.15 W
Hub/tap costs; power consumption	20 €; 0.2 W	20 €; 0.2 W	20€; 0.2 W	20€; 0.2 W
Switch costs, power consumption	10 €/port; 0.3 W/port	10€/port; 0.3 W/port	10 €/port; 0.3 W/port	10 €/port; 0.3 W/port

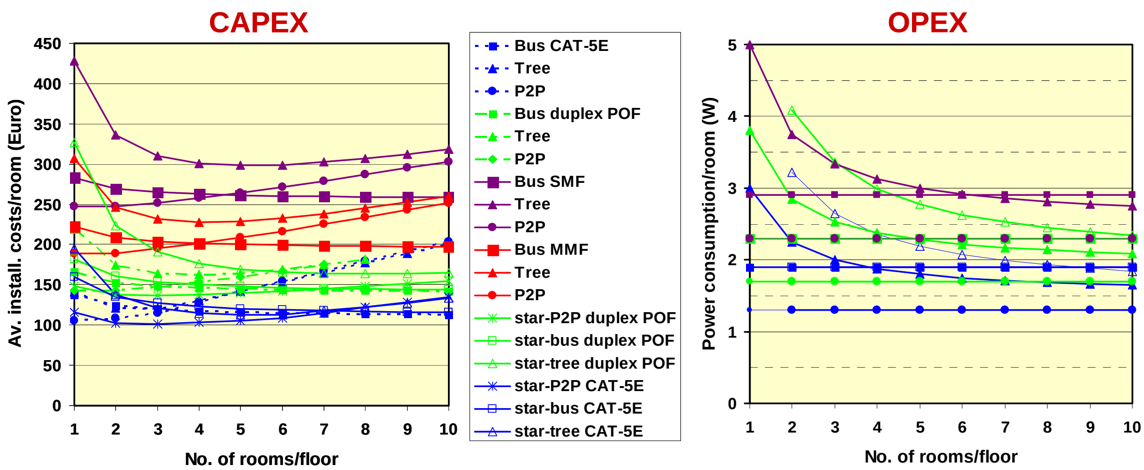

Fig. 50 Low-rise building with *M*=3 floors; left: network installation costs per room; right: power consumption per room

For a low-rise building (with *M*=3 floors), the average network installation costs per room versus the number of rooms per floor are given in Fig. 50 (left). These results have been calculated for buried ducts, as in green-field installation. The duct costs are lower for on-the-wall mounted ducts, as in brown-field installation (i.e. upgrading), but the total costs are then only marginally lower. As Fig. 50 shows, the costs are lowest for Cat-5E cabling, but for cabling with duplex POF cable the costs are only marginally higher. For smaller homes (low number of rooms per floor), the costs for the P2P architectures are lower than those for shared architectures (bus, tree). For larger homes, the costs of the shared architectures are lower, in particular for the bus architecture, as the costs of the common network parts are shared by more rooms and the average cable length per room in the P2P architecture gets considerably higher.

When sharing the ducts with the electrical power cabling, in the fibre solutions the duct costs are saved. As shown in Fig. 51, the POF solutions then become quite competitive with the Cat-5E solution. When the media converter costs will decrease further, POF can clearly become the cheapest solution.

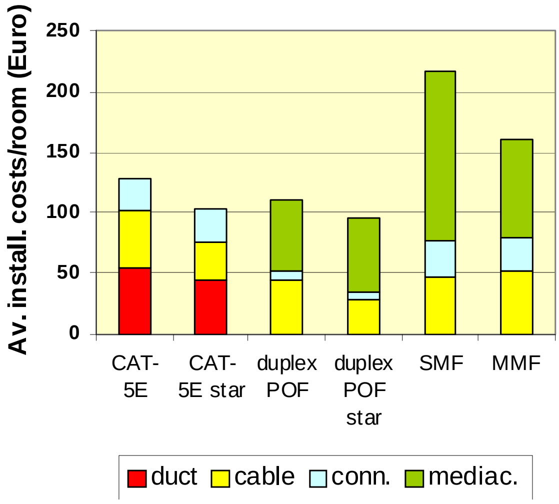

Fig. 51 Residential home with *M*=3 floors and *N*=4 rooms/floor; cost items for P2P architecture (with duct sharing for the fibre solutions)

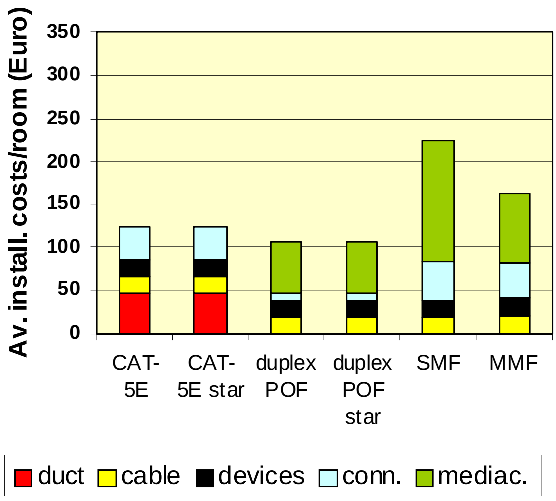

Fig. 52 Office building with *M*=10 floors and *N*=50 rooms/floor; cost items for bus architecture (with duct sharing for the fibre solutions)

For larger buildings, the cabling and ducting costs become dominant; hence the bus architecture, which offers the highest sharing factor of the cabling, is the cheapest. As illustrated in Fig. 52, in a bus with duct sharing the POF solutions outperform the Cat-5E solutions regarding network installation costs.

OPEX analysis

The operational expenses (OPEX) are largely due to the power consumption in the active network splitting devices and in the opto-electronic media converters for the fibre-based solutions; typical power consumption figures are listed in Table 2. As shown in Fig. 50 (right), for small buildings the P2P architectures consume the least power; for larger room numbers, the tree architectures are the most favourable. Cat-5E solutions consume the least, closely followed by the duplex POF solutions. To approach the power consumption of the Cat-5E line drivers, reducing the power consumption of the media converters is needed.

Concluding remarks

Minimizing the costs of in-building networks implies a joint minimization of CAPEX and OPEX. Regarding CAPEX, notwithstanding their early state on the market duplex POF solutions are already cost-competitive with Cat-5E, in particular when the POF shares the ducts of the electrical power cabling. In smaller buildings (residential homes), a P2P architecture with POF is preferred, and in larger buildings (office buildings), a star-bus architecture. Regarding OPEX, Cat-5E solutions consume a bit less power than POF solutions. For small buildings, a P2P architecture is preferred; for larger ones, a star-tree architecture.

In the longer term, when prices have come down further, all-optical bus architectures may be preferred, deploying bend-insensitive SMF. These solutions combine a reasonably low CAPEX with low OPEX (as they are passive), whereas they offer the highest functionality regarding service upgrading and traffic routing for the delivery of capacity on demand.

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[2] M. Popov, Proc. OFC 2010, paper OWQ6
[3] A.M.J. Koonen et al, Proc. IEEE Phot. Soc. Annual meeting 2009, paper ThC2
[4] A.M.J. Koonen et al, Proc. OFC 2010, paper JThA46

Joint papers

A.M.J. Koonen, H.P.A. van den Boom, H.-D. Jung , H. Yang, E. Ortego Martinez, P. Guignard, E. Tangdiongga, *Photonic In-Building Networks – Architectures and Advanced Techniques*, Proc. COIN 2010, pp. WeC1-2, Jeju Island, S. Korea, July 2010.

A.M.J. Koonen, H.P.A. Van den Boom, E. Ortego Martinez , P. Guignard, *Economics of in-building optical fiber networks*, Proc. ANIC 2010, Karlsruhe, June 2010.

A.M.J. Koonen, H.P.A. van den Boom, E. Tangdiongga, H.-D. Jung, P. Guignard, *Designing In-Building Optical Fiber Networks*, Proc. OFC/NFOEC 2010, pp. JThA46, San Diego, March 2010.

4.13 Safety and health aspects

No activities of partners reported.

5. Mobility actions

Several mobility actions were completed and/or started in 2010:

UC3M – GET

- Prof. C. Vázquez and B. Fracasso and B. Vinouze had discussions during a 2 days visit at Telecom Bretagne of C. Vázquez, in Feb. 2010, and 3 days visit at UC3M of B. Fracasso and K.Hegartty, in May 2010.
- A new mobility action by Prof. C. Vázquez to Telecom Bretagne will be done in Jan. 2011.

UniBo - TUE

- 2 bilateral Erasmus master graduation student projects exchanges have been done between UniBo and TUE during 2009-2010
- Mr. Davide Visani spent 11 months at TUE, from Feb. 1 to Dec. 22, 2010, working on high-speed data transmission over POF links, and radio-over-POF techniques.

Univ. of Valladolid – TUE

- Erasmus student master project exchanges between Univ. of Valladolid and TUE took place in 2008-2010.

6. Joint publications

In 2010, the WP16 partners have made 11 joint publications, and 19 single-institution papers.

Joint papers

[1] A. Paraskevopoulos (FHG), J. Vucic (FHG), S. Voß (FHG), R. Swoboda (A3PICs Electronics Development GmbH), K. Langer (FHG), *Optical wireless communication systems in the Mbps to Gbps range, suitable for industrial applications*, IEEE/ASME Transactions on Mechatronics, Vol. 15, No. 4, pp. 541-547, Aug. 2010

[2] A.M.J. Koonen (TUE), H.P.A. van den Boom (TUE), H. Jung (TUE), H. Yang (TUE), E. Ortego Martinez (TID), P. Guignard (FT), E. Tangdiongga (TUE), *Photonic In-Building Networks – Architectures and Advanced Techniques*, Proc. COIN 2010, pp. WeC1-2, Jeju Island, S. Korea, July 2010

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[10] D. Visani (UniBo), Y. Shi (TUE), C.M. Okonkwo (TUE), H. Yang (TUE), H.P.A. van den Boom (TUE), M.S.A.S. Al Fiad (TUE), G. Tartarini (UniBo), E. Tangdiongga (TUE), and A.M.J. Koonen (TUE), *Wired and Wireless Multi-Service Transmission over 1mm-Core GI-POF for In-home Networks*, accepted for publication in Electronics Letters, 2011

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7. Joint workshops

OpTech-Net Workshop on Dec. 13, 2010 (UDE, TUE)

Periodically OpTech-Net workshops take place to bring manufacturer, research institutes and user together to discuss actual topics with respect to POF based Fiber in The Home Networks.

In this context the focus of the workshop at the University Duisburg-Essen (UDE) on Dec. 13 was laid on European activities related to polymer optical fibers. New research results and future developments have been discussed; see Fig. 53.

Fig. 53 Prof. Koonen (TUE) presents actual research results at the OpTech-Net workshop in Duisburg, Dec. 13, 2010

Joint WP13/WP16 workshop

In order to establish the dissemination of knowledge built up in the joint activities, and to discuss new joint activities, a joint WP13/WP16 workshop has been held at ECOC 2010 in Torino, on Sep. 22.

Workshops at conferences

WP16 researchers have contributed to many other workshops and conferences by disseminating the jointly built knowledge. Amongst others, a Workshop was held at OFC 2010 in San Diego, and a Special Symposium inside ECOC 2010 in Torino:

- Workshop OMB, Monday March 22, 8.00-11.00 am, "Beyond the Doorstep - Can Fiber also invade the Home?", organizers: Ton (A.M.J.) Koonen, Eindhoven University of Technology, The Netherlands, and Dalma Novak, Pharad LLC, USA. Several contributions were given in this Workshop by BONE partners (FT, TUE, PoliTo, ACREO)
- Special Symposium Tu.4/5.G, Sep. 21, 14.30-18.30, High-speed short-range optical communications, organized by Roberto Gaudino (PoliTo) and Sebastian Randel (Siemens), with several contributions from BONE partners.

8. Joint projects

New FP7 projects related to WP16's area have been set up together by BONE partners:

- MODE-GAP (UCC, Univ. Southampton, TUE) ; about mode group multiplexing techniques and networks
- FIVER (Essex Univ., IT) ; about fibre-wireless networks

9. Concluding remarks

In the final year of BONE, joint activities of WP16 partners have taken place in many of the sub-areas of common interest. These activities resulted in 11 joint publications and 20 single-institution papers, in exchange of personnel by 5 mobility actions, and in 4 international workshops. Also some new projects have emerged from the interactions between WP16 partners.

Looking back over the WP16 activities since its start, it may be stated that the BONE project has provided valuable new opportunities for cooperation between research groups in Europe in the area of in-building optical networks, which has led to a remarkable increase in exchange of scientific personnel through mobility actions, in joint publications, and in jointly organized workshops. All this has strengthened the worldwide visibility of European research in the in-building networks area, comprising ‘hot’ areas such as high-capacity fibre-wireless networks, high-capacity (plastic) multimode fibre networks, and the convergence of wired and wireless services in a single optical in-building network infrastructure.

It is to be expected that these WP16 results have laid the basis for lasting research cooperation in future projects.

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