IST ALPHA project: Architectures for flexible Photonic Home and Access networks

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Abstract

The ALPHA project addresses the challenges of building the future access and all types of in-building networks for home and office environments. The project investigates innovative dynamic architectural and transmission solutions based on the different optical fibres (single-, multi-mode and plastic) as well as wireless technology to support both wired and wireless services in a converged network infrastructure. The focus is on using the newest physical layer achievements and adequate management and control algorithms to reach a yet unprecedented end-to-end provisioned capacity for access and in-building networks at a fraction of the price of today's technologies and to simultaneously include the transport of existing 2G/3G and Beyond 3G (B3G) signals whether they are Internet Protocol (IP) or non-IP-based.

Keywords. Access networks, Optical fibres, Broadband services, Converged networks, Network Architectures, Transmission techniques.

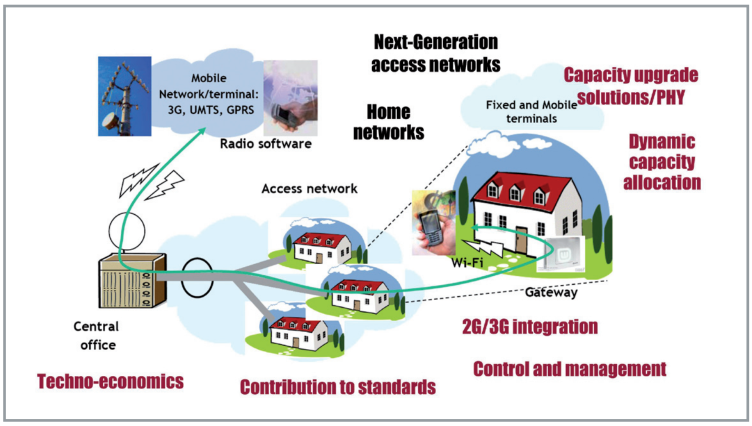
1. Introduction

The network of the future can be envisaged as a ubiquitous web allowing us to "stay connected" anywhere and anytime in the best possible way. The future networks will be expected to support state-of-the-art multi-media, storage and computational user services distributed over the network. These envisaged user-oriented services will likely include the Super Hi-Vision/Ultra High Definition (HD) Video, local and global Storage Area Networks, HD Video-on-Demand, Grid Computing services, High-Quality Video Conferencing, Very High-Speed File Transfer/Peering, Next-Generation Gaming as well as remote medical diagnostics and elderly care. It is also likely that the future network will encompass and support the mobile communication services by providing transport to 2G/3G and Beyond 3G (3G/B3G) signals. Therefore, the requirements of the future network will be extremely stringent: these will require well above 1 Gb/s and Quality-of-Service provisioned connectivity per end-user with corresponding capacities at the aggregation points and larger networks.

A key issue in developing very high bit-rate access and in-building networks is the availability of low cost high-speed networking and transmission technologies. Nowadays, typical proposed network solutions are often based on the available Ethernet (MAC) layer with the inclusion of the IP (Internet Protocol) layer and with a static physical layer based on copper (typically, CAT-5/6/7 cables) and optical single- or multi-mode fibres. With such solutions, the new applications demanding much higher bandwidth than those of today will cause network overload and unacceptable delays in the traffic delivery for, e.g., multi-media data streams. Furthermore, the mere bandwidth availability might not be the only problem, important aspects need to be considered in devising the network of the future will concern the support of adequate application-related quality levels (i.e. low latency and jitter, good resilience etc).

The IST ALPHA project was granted under the EC Framework Programme 7 with starting date of 1st January 2008 and a duration of 3 years with a main goal to devise innovative architectural and transmission solutions for access and in-building integrated multi-service Internet/Intranet and 3G/B3G networks with adequate management and control (se e fig. 1). The ALPHA consortium is coordinated by ACREO (Sweden) and formed by 3 system vendors, 3 operators, 6 universities, 3 small/medium enterprises and 2 research institutes. The Universidad Politécnica de Valencia has a significant role in the project since leads the area "Next generation PHY technologies" and carries several research activities such as MMF transmission (modulation and multiplexing solutions), RoF signal transmission in access networks (penalties, modulation and multiplexing techniques) to push further the current limitations and develop reconfigurable optical networks (dynamics in optical layer) for outdoor and in-building networks.

This paper is structured following the work plan of the project, which Scientific and Technical activities can be split in different workpackages (WP). Section II will summarize the "Future services and networks specification" (WP1), sections III and IV will be dedicated to "Access network architectures" (WP2), and "In-building network architectures" (WP3), respectively. Section V will present last results achieved by the Optical Communications Group in the UPV in the area "Next generation PHY technologies" (WP4), and section VI will present the "Demonstrations and field trials" (WP5) which are planned to do throughout the project. Finally, section VII will summarize the main conclusions we can present at this stage of the project.



■ **Figure 1**. *Key issues of ALPHA project*

2. Future services and networks specification

The future services that will be considered can be cast into two categories: The first one being the classical services already available or emerging such as mobile coverage, web-browsing, file sharing/peering, video and audio broadcasting and –on-demand (e.g. Video-over-IP, IPTV, Voice-over-IP) which must be transmitted over a converged fixed/mobile network. The second category of services is foreseen for a longer scope of five or more years owing to the expected increased capacity available to the end-user. The envisaged future services will include, for instance, Super Hi-Vision/Ultra High Definition Video, local and global Storage Area Networks, HD Video-on-Demand, Grid Computing services, High-Quality Video Conferencing, Very High-Speed File Transfer/Peering, Next-Generation Gaming, indoor delivery of high speed mobile data connectivity through femto-nodes, as well as remote medical diagnostics and elderly care.

However, in order to be able to compare the requirements of these services, a common metric to evaluate their needs is defined based on the following parameters: Bit-rate/Throughput, Tolerable Delay, Tolerable Jitter, Tolerable Packet loss, Mobility, Traffic Priority, and required degree of Security. The first four parameters are measurable quantities that can translate directly into network requirements and specifications while the last three are non-measurable and serve at defining the context of the specific service usage. Attending to the usage group and similar types requirements, six service classes are identified as following:

- Basic communication such as instant messaging, e-mail, and telephony.
- Internet-related services such as general browsing, e-banking, e-shopping and similar (including file sharing using peer-to-peer).
- Video-related services such as Video on Demand, IPTV and video conferencing.
- Online Virtual Environments such as a social network or gaming.
- Remote Technical services such as the ability to remotely control/survey your home
- Remote Health services such as remote health monitoring. The health related services that can be brought to the end user via the broadband access and mobile networks. These services are described as e-health services which are defined as covering all interactions and exchange of data via Information Communication Technologies (ICT) between patients and health service providers or between health institutions covering the access to health information records, telemedicine services and personal connected wearable devices for monitoring and/or supporting patients.

Tables 1, 2, 3 and 4 summarices the specifications required by the first four service classes [1]. The main conclusion from this service grouping is that the different networks will transport services that have an ever increasing need for bandwidth and more and more stringent requirements in terms of delay as services become more and more interactive and video based.

Service	Bit rate	Delay	Jitter	Packet Loss	Mobility	Traffic Priority	Security
IP telephony	12 – 96 kbps	< 400 ms, 200 ms recommended	< 50 ms	< 3% < 0.1% recommended	Yes	High	No
E-mail	1 Mbps/ 50 kbps (mobile)	Relaxed specification (seconds)	Relaxed specification	None (BER < 10^{-6})	Yes	Low	No
SMS and Messaging	Low (10 kbps)	Relaxed	Relaxed specification	None (BER < 10^{-6})	Yes	Low	No

■ **Table 1**. *Specifications of basic telecommunications services*

Service	Bit rate	Delay	Jitter	Packet Loss	Mobility	Traffic Priority	Security
Internet	1 - 100 Mbps	Relaxed specification	< 10 ms	None (BER<10^{-8})	Yes	Low	No
Music	5 – 128 kbps	Buffer dependent	Buffer dependent	< 1%	Yes	High	No
File sharing (peer-to-peer)	1 Mbps - 100 Mbps	Relaxed specification	< 10 ms	None (BER<10^{-8})	Yes	Low	No
Web3D (future)	10 Mbps to 1 Gbps	Relaxed specification	< 10 ms	None (BER<10^{-8})	Yes	Low	No

■ **Table 2**. *Specifications of internet based services*

Service	Bit rate	Delay	Jitter	Packet Loss	Mobility	Traffic Priority	Security
IPTV	2 – 20 Mbps (for HD)	< 400 ms; 200 ms recommended	< 50 ms	< 1% < 0.1% recommended	Yes	high	no
VoD	Min. 2 Mbps Future: 1 Gbps	< 400 ms; 200 ms recommended	< 50 ms	< 1% < 0.1% recommended	Yes	high	no
Videoconference	128 kbps to 4 Mbps	< 400 ms 200 ms recommended	< 50 ms	< 1% < 0.1% recommended	Yes	high	no
Video Streaming (uncompressed)	Min. 128 Mbps. Recommended: 1 Gbps Future: 10 Gbps	< 400 ms 200 ms recommended	< 50 ms	< 1% < 0.1% recommended	No	high	no
TV broadcast (DVB-IP)	96 kbps to 45 Mbps (HD)	< 400 ms	< 20 ms	None (or use FEC)	Yes	high	no
TV broadcast (DVB-x / non IP based)	N/A rather BW occupied up to 8 MHz	< 400 ms	< 20 ms	None (or use FEC)	Yes	high	no
Immersive TV (future; using UHDTV)	24 Gbps uncompressed. < 640 Mbps compressed	< 400 ms; < 150 ms recommended	< 20 ms	< 0.4%	No	high	no
Immersive Videoconference (future; using UHDTV)	< 640 Mbps compressed	< 400 ms; < 150 ms recommended	< 20 ms	< 0.2%	No	high	no
Stereoscopic TV (future)	Min. 62.5 Mbps, up to 320 Mbps	< 400 ms; < 150 ms recommended	< 20 ms	< 0.4%	No	high	no
Free Viewpoint TV (future)	937.5Mbps	< 400 ms; < 150 ms recommended	< 20 ms	< 0.4%	No	high	no

Table 3. *Specifications of video based services*

Service	Bit rate	Delay	Jitter	Packet Loss	Mobility	Traffic Priority	Security
MMOG	Relaxed, 56 kbps	< 100 ms (best quality), up to 1s	<10 ms	Highly dependent on the engine from 3% to 35%	No	High	No
Online Distributed Environments	Up to 400 kbps, more in the future	< 100 ms (best quality), up to 1s Future: < 50 ms	<10 ms	Highly dependent on the engine from 3% to 35%	Yes	High	No
Interactive games (mobile)	1 kbps	250 ms	<10 ms	None	Yes	Low	No

Table 4. *Specifications of Online virtual environments*

3. Access networks

With the massive introduction of the FTTH technology in the access part of network, it becomes important to identify the different deployment scenarios and possible architecture alternatives to optimise the bandwidth utilisation at a lowest cost. In ALPHA project, innovative architectures and technical solutions will be analysed in the domain of access networks to define promising integrated access network solutions supporting both broadband and mobile (2G/3G and B3G) traffic transport. The delivery of this high bandwidth must be compliant with cellular communications or wireless local area networks. Fibre access networks are very attractive to accommodate this bandwidth demand growth, as it has been demonstrated in different scientific papers [2-3]. The optical fibre is used to transport and distribute multi-service signals while offering transparency and flexibility.

Passive Optical Networks (PON) topologies have been the basic architectures emerging as low cost solutions for optical communication systems. However, significant fluctuations in the traffic load due to the mobility of the users in the radio cells require dynamic allocated capacity solutions to avoid any waste of capacity and keep reduced costs.

Recent technological advances such as wavelength division multiplexing, dynamic wavelength assignment [4-5], development of agile optical component modules and survivable networking have extended the capabilities of the basic Broadband Passive Optical Network (B-PON) described in ITU-T standard G.983.1 in order to provide dynamic capacity allocation in the optical network. The use of flexible wavelength routers to assign different number of wavelengths to each base station (BS) depending on the actual demand has been previously proposed but using a large number of components with associated costs (see fig.2).

As a significant background for ALPHA project, the project AC349 PRISMA (Photonic Routing of Interactive Services for Mobile Applications) [4], which was part of the European ACTS (Advanced Communications Technologies and Services) pre-competitive R&D program, had as a goal the deployment of flexible wavelength routing techniques. In this approach, the desired wavelength channel reaches the ONU by being previously tuned in a wavelength router inside the network.

The reallocation of wavelength channels was performed by a flexible wavelength router based on Thermo-optic Mach-Zehnder switches, and an increase of the capacity and performance of the network was demonstrated without extending the fibre plant, offering solutions to a wide range of wireless services and capacity demands emerging in the mobile communications market provided a reasonable compromise between costs and reconfiguration flexibility. Since there was no broadcast and the wavelength channel was tuned inside the network, no problems of wasting of power and data capacity resources either problems of privacy were identified.

The PRISMA system was validated to support the evolution from GSM to UMTS, and also, new services such as fast Internet access and electronic mail, fast file transfer and video conferencing. At the local exchange, four 622 Mb/s bidirectional OLTs were used and the radio access points operated with up to five microwave carriers in the 5-GHz region, each carrying up to 20 Mb/s ATM wireless LAN data in orthogonal frequency division multiplexing (OFDM) and other nomadic computing applications such as web access, file transfer, etc.

Other contributions in the literature report on an automatic gain-controlled bidirectional add-drop amplifier [5], using an AWG (Arrayed Wavelength Grating) and a number of switches. A huge noise suppression capability, reduced complexity and misalignment of signals between the multiplexer and demultiplexer, and also, a reduced number of fibres are required to implement the dynamically reconfigurable WDM network. Also, a bidirectional wavelength add-drop multiplexer with a survivable function in the backbone ring network was proposed in [6]. The ring utilized a single fibre to connect each remote node that employs tuneable fibre Bragg gratings, and a few optical devices to provide the self-protected function when links fail.

Dynamic wavelength allocation (DWA) has been also demonstrated to provide bandwidth sharing across multiple physical PONs [7] in the SUCCESS-DWA PON. Tuneable lasers, an AWG and coarse/fine filtering in the downstream, and several distributed and centralized solutions for the upstream make an architecture good to upgrade existing PONs with an excellent scalability which can bridge the gap between TDM and WDM PONs.

More recently, dynamic reconfigurable WDM in the millimetre-waveband radio-over-fibre has been demonstrated for access networks [8] using a super-continuum light source and an architecture based on a reconfigurable OXC and AWGs in the remote nodes. High degree of scalability and successful transmission supporting nomadic users are some of the main advantages.

Finally, we recently published a reduced costs centralized architecture based on a single optically switched AWG [9] to achieve symmetrically variable capacity allocation in bidirectional access networks showing good performance for present and future services in the access network (see fig. 3).

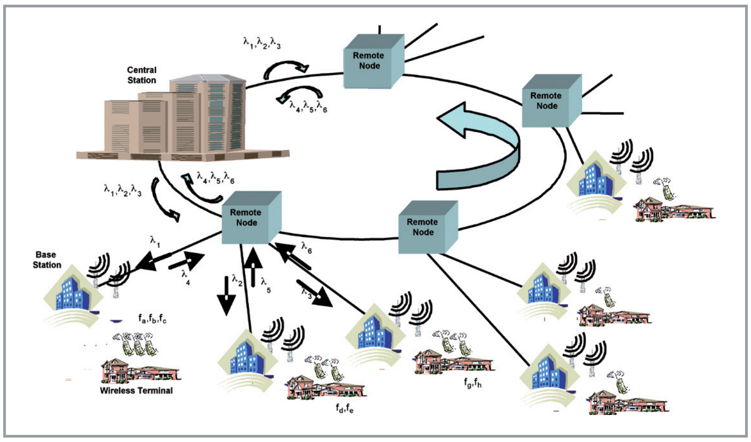


Figure 2. *General schematic of a reconfigurable fiber access network*

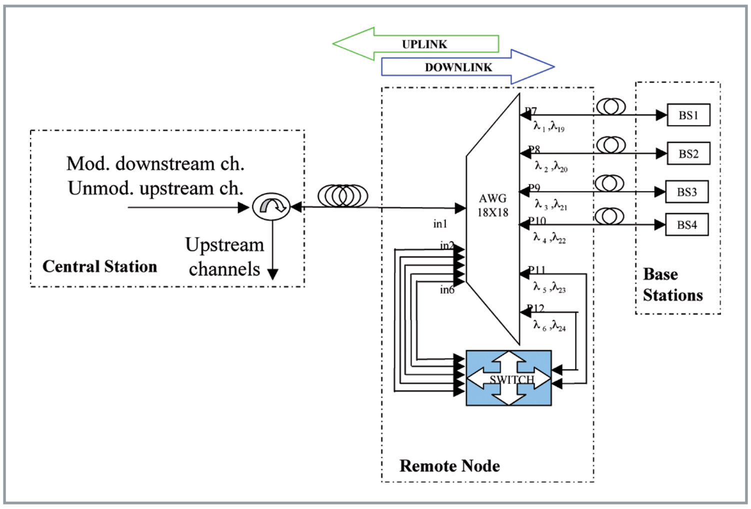


Figure 3. *Reconfigurable fiber access network based on an optically switched AWG*

4. In-building networks

The in-building networks are understood as various environments in which short-range networks are needed: residential houses (see fig.4) office buildings, hospitals, conference centres, airport lounges and others with a wide range of wired and wireless services to a wide range of end-user terminals.

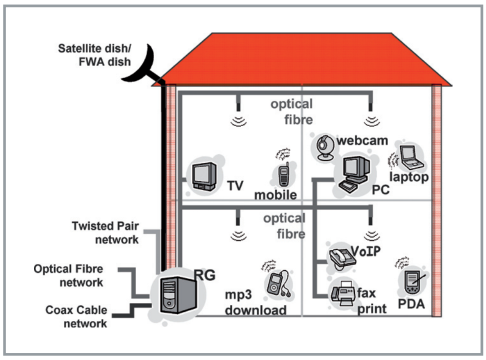


Figure 4. *Residential house with a ubiquitous home network*

In today's in-building networks, the various sets of services have their own dedicated network: the CATV and radio broadcast runs over coaxial cables, telephony over a twisted pair of cables, and data runs over CAT cables and/or via wireless IEEE 802.11 LANs. With the evolution of multimedia services, this separation of networks hampers the interworking between the services, and the introduction of new ones. It also makes it difficult to upgrade and maintain the overall infrastructure. Future broadband wireless networks may deploy higher carrier frequencies, implying radio pico-cells, and multiple antenna system concepts (MIMO). In many cases, Radio-over-Fibre solutions can help to consolidate signal processing at a central station (CS) and reduce antenna site costs. Also, most likely, next-generation user terminals will require multiple-Gbit/s data interfaces for fast and reliable data transfers.

The aim of ALPHA project is to get a unified and converged in-building infrastructure, which offers a common platform for all existing and foreseeable future services. Such infrastructure should be broadband and offer the opportunity to transport services of widely varying signal characteristics and QoS.

Low cost solutions are the cornerstone for deploying the future access and in-building networks.

In parallel with the architecture work, adequate network management and control functions will be studied for handling intra- and inter-domain traffic, i.e. for connecting the in-building network terminals to each other and to the access network.

4.1. Low cost solutions based on broadband sources

In this context, ITEAM contributes to this area the development of interesting low-cost solutions based on optical broadband sources for current subcarrier multiplexed (SCM)-based transmission systems employing multimode fibre (MMF) for short distance links, also avoiding the well known carrier supression effect (CSE) induced by fiber dispersion in double sideband (DSB) conventional modulated signals. In order to overcome the optical broadband sources frequency limitations over MMF transmission systems, the incorporation of a Mach-Zehnder Interferometer (MZI) structure (fig. 5) is proposed to generate a tunable transmission window free from limiting dispersion effects in a 20 GHz frequency range by using DSB modulation.

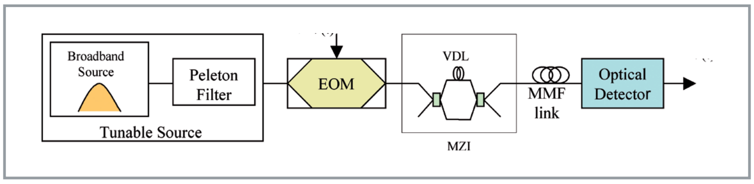


Figure 5. *Schematic diagram of the system setup with a broadband tunable optical source and the MZI.*

Figure 6 plots the experimental 5 km long MMF transmission system response for a 12 nm-width broadband source. The amplitude response presents a transmission window at baseband and an additional transmission window corresponding to the modulated optical signal transmitted through the MZI. This transmission window is tunable and placed at $\Omega_0=2\pi f_0$ which is found to be related only to MZI and fiber parameters as follows:

$$\Omega_0=\frac{\Delta\tau}{\beta_2 L} \qquad (1)$$

where L is the fiber length, $\Delta\tau$ is the delay difference between MZI arms and β_2 is the parameter dispersion. Therefore, by varying , the transmission window can be tuned and the impact of the CSE is minimized even if a DSB is used.

4.2. CWDM optical MMF transmission based on broadband sources

Also, the viability of coarse WDM (CWDM) optical MMF transmission systems using broadband optical sources is studied within the project. Figure 7 shows the experimental setup using the optical signal emitted by a broadband ASE source as optical carrier which is externally amplitude modulated. After transmission over 1 km MMF link, the modulated optical signal is filtered by a 16 nm width 4-channels CWDM centered at 1531, 1551, 1571 y 1591 nm, respectively in order to be routed to different Base Stations. The inclusion of a MZI including a variable tunable delay at each output of the CWDM filter allows a frequency slicing of each channel with a tunable periodicity related to the inverse of the tuned optical delay, and as explained above, a new transmission window appears at different electrical frequencies given by eq. (1) for each CWDM channel.

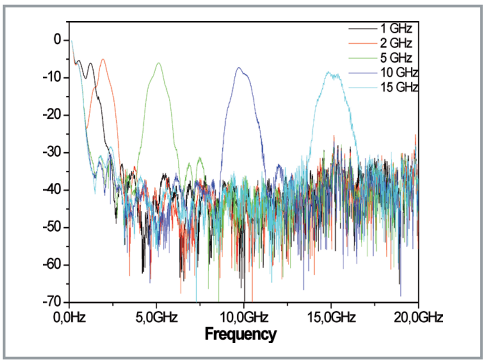


Figure 6. *Experimental MMF transfer functions for a Gaussian optical source profile at 5 Km with a transmission window tuning from 1 to 15 GHz*

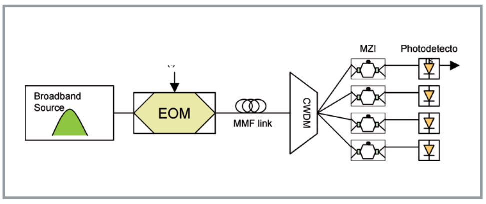


Figure 7. *Scheme of transmission system over MMF using ASE source and CWDM technology and interferometric structures.*

The quality of the QPSK signals transmitted by the CWDM channels when the MZI is employed is given by EVM of 6.20, 11.02, 12.00 and 9.50 % for 1531, 1551, 1571 and 1591 nm, respectively. Figure 8 shows the constellation diagrams corresponding each optical channel. Although a significant degradation is measured, different QPSK symbols can be easily distinguished and can be furtherly improved by increasing the total optical power per channel.

5. Next-generation PHY technologies

The development and integration of next generation technologies is required in the physical layer of access and in-building networks in order to support a wide range of wired and wireless services bringing them to a wide range of end users. At the core of this main objective resides the research on the potential bandwidth expansion

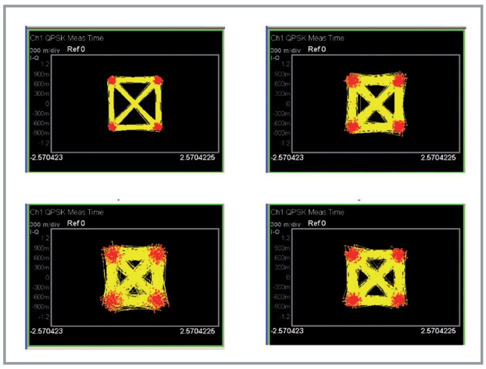


Figure 8. *Constellation diagram for the CWDM channels when the MZI is used in the transmission system: (a) 1531 nm, (b) 1571 nm and (d) 1591 nm.*

of current available MMF links and the development and implementation of novel transmission and multiplexing strategies applicable to existing fibre optic physical media (single-, multi-mode and plastic) that can integrate the transport of wired and wireless services. ALPHA target in this area will be to implement the transmission solutions that can guarantee the required bit-rate regardless the available physical media.

Efforts are now being made to extend access networks to higher bit-rates, such as aggregate 10 Gb/s. The optical fibre is a recognised choice for access networks, and increasing the upstream capacity favours the fibre-based access even more, compared to other competing technologies, such as copper twisted pair or coaxial-based networks. For in-building networks, and especially for home networks, using multi-mode and plastic optical fibre gives a substantial bandwidth (tens of Gb/s for multi-mode over hundreds of meters and up to 1 Gb/s for 1 mm-thick core plastic optical fibres over 100 metres) and savings on the equipment compared to single-mode fibre solutions. Using the plastic fibre for in-building networks makes possible to use the "do-it-yourself" approach since no special equipment is required in order to connect those fibres to the equipment.

The development of new and improvement of existing modulation formats makes it possible to constantly increase the transmission rate as well as the reach of the multi-mode and plastic fibres. The limitations on the achievable bit rate and using specific modulation formats arise from different mechanisms of signal degradation observed in optical fibres such as the modal attenuation, mode coupling, intermodal and chromatic dispersion, modal noise, non-linear effects, intermodulation and source coherence. These limitations need to be overcome to push the limits further and find the real constraints of these systems. The limits will be found from the evaluation of different factors of degradation in a variety of signal transmission scenarios, and also from a research work on the efficient modulation techniques for each physical media.

5.1. Radio over fibre system limitations

To satisfy the increasing demand for multimedia interactive services and support higher data rates, wideband communication systems are necessary in both wired and wireless links. Since the optical medium provides low losses and large bandwidth and radio signals enable mobility and easy access, Radio-over-Fibre (RoF) architectures have been actively investigated and have become an attractive solutions for future broadband wireless networks in hotspots and suburban areas [10]-[12] In the typical configuration, the RoF system transmits an optically modulated radio frequency (RF) signal from a CS to several remote base stations (BS) via optical standard single mode fibre (SSMF) back-haul. From each BS, the RF photodetected signal propagates to the (mobile or fixed) user terminal (UT) through a wireless channel. A synoptic diagram is illustrated in Fig.9.

Radio over fibre techniques enable wired/wireless convergence, increased capacity and centralised upgrading.

In such architecture, the complexity associated with the radio signal processing and routing functions is located back at the CS. This approach leads to a simple compact and cost-effective BS which role is then limited only to RF amplification optical-to-electrical and electrical-to-optical conversions. Furthermore, because propagation loss limits the transmission distance of RF signals, optical transmission medium characteristics turn out to be an attractive option for their transparent transport.

Improved coverage, increased capacity, centralised upgrading and adaptation, higher reliability and lower maintenance costs are the most important advantages of RoF technology. Nowadays, the application of optical networking concepts

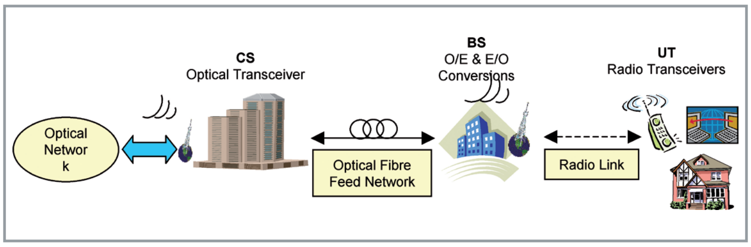


Figure 9. *Generic architecture of a Radio-over-Fibre system.*

to fibre-wireless systems has been also proposed in techniques such as dense wavelength division multiplexing (DWDM). Here, to simplify the network architecture, different wavelengths are employed to feed different antenna at the BS allowing multiple interactive services. A network upgrade and deployment of additional radio access points can be achieved easily by the introduction of new optical channels over the same fibre [13]-[17].

One of the major drawbacks in fibre optical transmission systems is chromatic dispersion whose primary effect is the intersymbol interference (ISI) [18]-[21]. In fact, since higher bit rates require smaller pulse widths, sources of wave distortion, such as chromatic dispersion and fibre nonlinear effects, become not negligible. The nonlinearity of an optical multichannel link also produces a large penalty in a long-haul transmission system when a high power signal is used. This limitation should be managed by selecting a suitable modulation format and controlling signal launched power levels.

In any fibre-radio WDM network, another cause of significant system impairments is the optical crosstalk. Two types, namely, in-band and out-of-band crosstalk can arise depending on whether the crosstalk channel is at the same wavelength as the signal. The entity of crosstalk depends on the filtering characteristics of any optical components (i.e. FBG, AWGM) employed in routing operations along the network.

Unlike the above system impairments, both phase and intensity noises from either optical source or signal oscillators are practical and decisive factors in high quality-of-service (QoS) applications that require a high signal-to-noise ratio (SNR). The resulting impact on the SNR of the received radio signals has led to a great deal of research activity developing noise and dispersion tolerant RoF transport schemes [22]-[25]. Laser phase noise has the most degrading effect on the performance of an optical-fibre communication link [22]. Because of it, the phases of both received and local oscillator (LO) signals fluctuates. Intensity noise coming from phase-to-intensity modulation conversion of a laser phase noise can be relevant in direct detection systems.

Signal waveform distortion can be generated by linear chromatic dispersion, fibre nonlinearity and their combination. In high-speed optical systems, because of the short optical pulses and wide optical spectrum, the effect of chromatic dispersion dominates the system performance. In DWDM optical systems with relatively low data rate per wavelength, inter-channel crosstalk originated by fibre nonlinearity, such as cross-phase modulation (XPM) and four-wave mixing (FWM) can become a limiting factor [18], [26], [27].

Crosstalk due to optical fibre nonlinearities in WDM lightwave systems incorporating optical add-and-drop multiplexers (OADM) is investigated in [26] and [27]. As previously mentioned in-band crosstalk is at the same wavelength as the signal and occurs either when the "add" wavelength or a reflected/delayed version of the dropped wavelength is present at the dropped channel. Meanwhile out-of-band crosstalk is by definition at a different wavelength and results from unwanted WDM channels arising from different optical sources being present at the receiver. In a single OADM the in-band crosstalk is in the order of -30 dBm and the power penalties arising from in-band crosstalk can vary depending on the RF phase difference between the crosstalk and desired signal.

One of the basic methods to enhance system performance is to increase the signal power to obtain higher values of SNR. However, this method contributes to problems that have the potential to degrade system performance. These problems include an increase in the nonlinearity of the optical fibre, and harmonics from a Mach-Zehnder modulator (MZM) [17], [28]-[32].

Until a few years ago, optical communication systems primarily employed conventional on-off keying (OOK). Recently, advanced optical modulation formats such as phase-shift keying (PSK) have attracted increased attention [33]. PSK formats has the advantage of requiring a 3dB lower optical signal-to-noise ratio (OSNR) than OOK to reach a given bit-error ratio (BER). The lower OSNR requirement of PSK can be used to extend transmission distance and reduce optical power requirements. Moreover PSK and its extensions to differential quadrature phase-shift keying (D-QPSK) and others, enables higher spectral efficiency and greater tolerance to chromatic dispersion, optical filtering and fibre nonlinear effects [34]. It is not surprising, then, that many of the recent long-haul WDM transmission records at rates of 10 and 40 GB/s per-channel are now held by systems based on PSK. Experiments have indicated the transmission capability of PSK, e.g., 64x42.7 Gb/s over 4000 Km, 80x42.7 Gb/s over 5200 Km, 40x42.8 Gb/s over 10.000 Km and 40x42.7 Gb/s over 8700 Km. At 10 Gb/s limitations from chromatic dispersion (CD) and polarization-mode dispersion (PMD) are similar for PSK and OOK. However, transmission performance in fibre is affected by the Kerr nonlinearity. This is exhibited as four-wave mixing (FWM), self-phase modulation (SPM) and cross-phase modulation (XPM). The extent of these effects depends on several system design factors, including average and peak optical power, modulation format, and the nonlinear interaction of signal with ASE noise. Dispersion management can be used in PSK systems to reduce the FWM efficiency among WDM channels to low levels. Therefore, interchannel FWM is generally not a concern. SPM and XPM affect PSK signals somewhat differently than OOK signals because for PSK signals an additional effect is important: noise-induced power fluctuations are converted into phase fluctuations by SPM, and become a source of transmission penalty. This nonlinear interaction of signal and noise is referred to as the Gordon-Mollenauer effect. At 40 GB/s, single-channel effects mainly limit signal transmission. In particular, intra-channel FWM transfers power between bit slots as pulses disperse into each other and mix due to fibre nonlinearity. In PSK systems, the phase fluctuations from this mixing are more dangerous than amplitude fluctuations. In intra-channel XPM intensity fluctuations of the dispersed and overlapped pulses, modulate the optical phase. The effect in OOK is time jitter when combined with dispersion, while in PSK, both time jitter and phase fluctuations are detrimental. As mentioned earlier, PSK has 3-dB lower peak power than OOK. Therefore, nonlinear PSK penalties can be reduced because of this more smoothly distributed power. Experimental results have consistently shown better performance for PSK than OOK in 40 Gb/s single-channel and WDM systems. In single-channel transmission through 1980 Km of standard single-mode fibre (SSMF) with 80-Km spans, PSK demonstrated that is not limited by FWM.

The DWDM advent allowed a large number of channels on the same fibre. The advantages of this technology is the wavelength routing capability that it offers by using selective components like tunable filters, add-drop multiplexers etc. RoF technologies using SCM/WDM with dynamic wavelength routing for transmission of 60 GHz data modulated signals, in the fixed and mobile access networks are expected to be highly useful for future generation of RoF networks.

5.2. Advanced Modulation Formats

The intense investigation on modulation formats for the transmission of optical signals through optical fiber is a result of several benefits they can report. For example, some particular transformations of the signal before being fed into the fiber may give to the optical transmission more fiber dispersion, nonlinearities or noise robustness, besides of more capacity for information transmission given a limited frequency bandwidth or a relaxation on the transmitter and receiver requirements. In short, the optical signal shape which is transmitted is nowadays an intense field of study because of its beneficial interactions with fiber impairments and because of the less stringent requirements they may impose on the overall optical system.

An ideal modulation format is highly spectral efficient, that is, the optical signal is able to locate several bits of information per hertz, has a large dispersion tolerance, low susceptibility to fiber nonlinear effects and noise and is not severely affected by filter narrowing. The proposed advanced modulation formats are usually designed to meet some of these criteria and, thus, the choice for one of these formats is determined by the relative importance of each of these impairments in the context of use. For example, for very short reach, i.e., for distances below 2 km, aspects such as cost and power consumption also become important, and for metropolitan and regional optical systems where the resources must be dynamically allocated through the use of optical add-and-drop multiplexers (OADMs), resilience to filter narrowing is especially important.

Which technique has been used traditionally? The most widely deployed systems are wavelength division multiplexed (WDM) with wavelengths modulated at a bit rate of 10 Gb/s and employing nonreturn-to-zero (NRZ) modulation: the electrical data bit '0' is converted into a low optical intensity level and the electrical data bit '1' is converted into a higher optical level intensity. The reachable spectral density with this technique can be greatly surmounted by that reached with more advanced modulation formats: with a channel WDM spacing of 50 GHz, traditional formats achieve 0.2 b/s/Hz, whereas advanced modulation formats are able to reach bit rates of 40 Gb/s in such a narrow spacing and thus spectral densities of 0.8 b/s/Hz.

Three different attributes of an optical signal through the optical fiber allow us to transmit information in the optical domain: the intensity, the phase (including the frequency) and the polarization of the optical field, and, so, depending on which physical quantity we can distinguish intensity, phase, frequency and polarization modulated optical signals. Figure 10 shows schematically some modulation formats classified as just explained:

Those formats which employ M different levels of intensity are referred as M-amplitude shift keying (ASK) modulation formats. M different thresholds must be used at the receiver and the spectrum, optical as well as electrical, is reduced by a factor of log2(M). But, because of the fact that this technique falls into a sensitivity penalty due to a smaller difference between symbols for the same average symbol power than OOK, other multilevel modulations formats have attracted more attention.

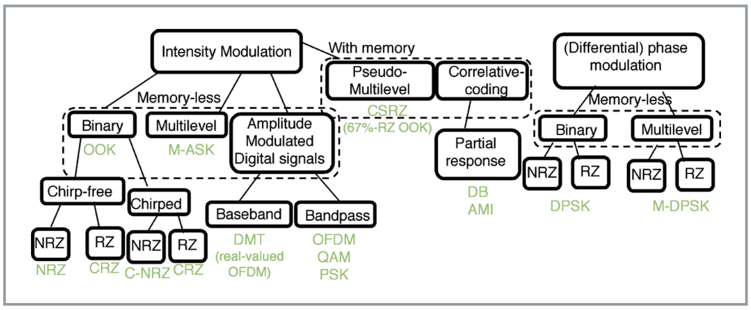


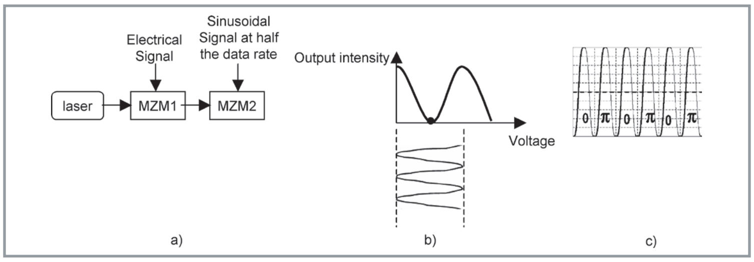
Figure 10. *Classification of modulation formats*

Another example of intensity modulated format is carrier-suppressed return-to-zero (CSRZ) – OOK, a pseudo-multilevel format. By sinusoidally driving a MZM pulse carver at half the data rate around its minimum intensity, the optical carrier is suppressed. As it can be seen in the next Figure, the sign of the optical field reverses at each bit transmission. It has compact spectrum a relatively better fiber nonlinearities tolerance than simple return-to-zero (RZ). Figure 11 shows its transmitter implementation:

Other approaches have been proposed, such as π/2-alternate phase return-to-zero (APRZ)-OOK, where the field phase alternates between 0 and π/2. π/2-APRZ has demonstrated to be more robust to fiber nonlinearities than CSRZ [35].
Duobinary (DB) and alternate mark inversion (AMI) are correlative coding formats, a subclass of partial response formats, where the actual transmitted symbol is correlated with the precedent symbols in such a way the transmission properties are improved. A spectrum narrowing

of the optical signal is achieved in DB format, what improves the resilience of optical signal to chromatic dispersion. Its resilience to narrowing filter has been also proved to be robust [36]. Typically it is implemented by precoding the data stream and, then, filtering with an electrical delay-and-add circuit. In the case of AMI format, its implementation is similar to DB and its RZ form (RZ AMI) is typically employed. RZ-AMI does not show a so high resilience to chromatic dispersion as DB, but RZ-AMI betters DB with respect to fiber nonlinearities resilience at 40 Gb/s [37].

Multilevel amplitude modulations, such as quadrature amplitude modulation (QAM) or phase shift keying (PSK) modulation, offer a promising alternative to increase the spectral efficiency by increasing the number of bits transmitted on each symbol, and so the bandwidth requirements can be reduced. These modulations formats facilitate the delivery of radio and wireless services and the transmission of broadband digital signals with suitable combination with SCM technique. The use of QAM and PSK radio signals has been an intense field of study for application to video transmission [38], [39] and it is receiving a deep interest in recent times to be used through MMFs [40], [41] and plastic optical fiber (POFs) [42].



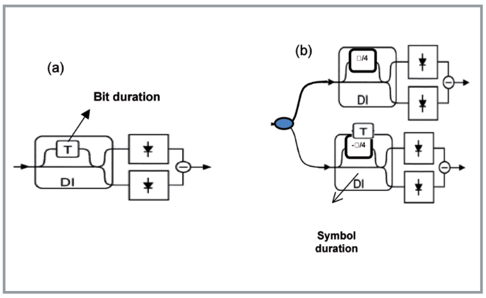
■ **Figure 11**. *a) Schematic of a CSRZ transmitter. b) sinusoidally driven MZM2 c) output intensity and phase field*

Another technique traditionally employed in wireless communications which has been investigated for optical communications is OFDM, a multicarrier modulation technique widely deployed in wireless communications. The information is carried in the frequency domain and the information complex values coming from a QAM or a PSK modulator are mapped onto a comb of subcarriers by means of an inverse discrete Fourier transform (IDFT). The real-valued signal after up-conversion intensity drives an optical modulator and then, the optical signal is transmitted. Fiber dispersion can be compensated for by using frequency domain equalization (FEQ) after passing to the frequency domain by means of a discrete Fourier transform (DFT). An intensive study on this modulation for optical transmission has been developed during the recent past years due to robustness to fiber dispersion [43]. When using discrete multi-tone (DMT) format, the values after the IDFT at the transmitter are real-valued, and so no inphase-quadrature modulator is needed. Research on DMT has concentrated on optical transmission through MMF due to the capacity of DMT (and OFDM) to combat frequency fading, and also because its simple way to adaptively modulate as the channel conditions when a feedback link to the transmitter is employed. Most of the research on DMT has focused on radio-over-fiber (RoF) systems, for application to local area networks (LANs) and for short distances through POF [44]-[46].

Owing to the fact that most of installed optical receivers employ square-law detection, the majority of optical phase modulated systems employ delay or differential modulation. By using a delay interferometer (DI) at the receiver, the delayed version of the transmitted signal acts as phase reference, and by a previously precoding at the transmitter, the signal is properly detected. DBPSK, or simply DPSK, is based on this method and its receiver requires a DI tuned with subwavelength accuracy for proper differential detection. Its main advantage is the 3-dB benefit on the receiver sensitivity when a balanced detector is used. Its performance against nonlinearities depends on the bit rate, being at 40 Gb/s than at 10 Gb/s. Differential quadrature PSK (DQPSK) reduces its bandwidth occupancy and so improves the spectral efficiency by using multilevel signalling. This also improves its resilience to fiber dispersion and polarization mode dispersion (PMD), but, at the expense of a more sophisticated and sensitive to frequency drifts receiver and a 2 dB poorer sensitivity than DPSK. Figure 12 shows their respective receiver implementations.

The employment of field polarization has mainly attracted attention as a way to improve the transmission properties of pseudo-multilevel or correlative coding [47], and to polarize multiplex (POLMUX) different signals at the same wavelength, doubling in this way the spectral efficiency, or in order to reduce the linear WDM crosstalk by alternating the polarization between adjacent WDM channels [48]-[49].

Finally, it is worth to remark the re-born interest in coherent detection. This is mainly due to the progress of digital signal processing for high speed signal phase estimation and channel equalization. Coherent detection offers very interesting features, since the application to optical communications of traditional radio signals does not need of differential encoding or developing a single sideband modulation. For exam-



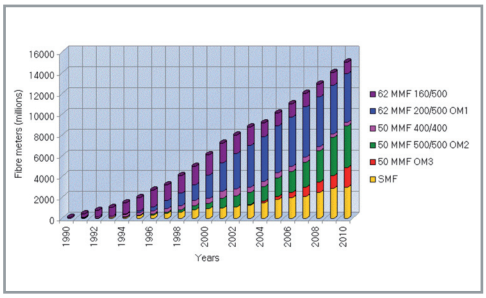
■ **Figure 12**. *DPSK balanced receiver, b) DQPSK balanced receiver.*

ple, besides the study on direct detected OFDM, the recent study on coherent detection of OFDM has proven to be more spectrally efficient and with reduced OSNR requirements [50],[51].

5.3. High capacity MMF links

MMF links are currently attracting much interest as the transmission medium for gigabit per second local area networks (LANs). Such high-speed links are particularly needed for backbone links, because of the increased LAN bandwidths following the 10-Gigabit Ethernet (10GbE) standard. The majority of installed in-building fibre (approximately between an 85% and a 90%) consists of 62.5/125 µm silica MMF [52,53] (see fig. 13). There is recently an important drive to utilize this existing infrastructure to support the ever increasing capacity demand because MMFs bring multiple advantages regarding to their ease of installation, maintenance and handling, which in turn implies an important cost reduction. However, the transmission capacity of these in-building networks is severely limited by intermodal dispersion. Despite of this disadvantage, recent efforts have pointed that MMFs can be employed to support high-speed digital connections such as those required by GbE applications for transmission speeds up to 10 Gb/s in short-reach distances. Furthermore, it has been demonstrated that the use of laser instead of LED based transmitters results in a considerable improvement of the MMF link transmission bandwidth.

Different novel techniques are now being developed to achieve this target such as mode group diversity multiplexing [54,55], optical frequency multiplication [54,56], the application of MIMO (Multiple Input Multiple Output) techniques [57], and SCM [58-62]. Among these approaches, the last one become especially interesting since it provides the potential for the delivery of radio and wireless services and also for broadband digital transmission by suitable combination of the traditional SCM with Orthogonal Frequency-Division Multiplexing (OFDM), [60]. Another important approach to force less intermodal dispersion consists in reducing the number of modes propagated through the fibre by means of practical mode-filtering implementations at the transmitter and/or receiver side, [63,64]. The transmitter side mode-filtering is performed by exciting a limited number of lower order modes in the MMF



■ **Figure 13**. *Installed Base: Worldwide Building Backbones*

and thus coupling only a small portion of the total power into the rest of the transmitted modes. The mode-filtering at the receiver side consist in recovering the lower order propagated modes which implies some signal energy loss.

It is also possible to increase even more the total transmission capacity of MMF links by combining wavelength division multiplexing (WDM) with some of the above proposed techniques, [58,65-67].

The potential of MMFs for broadband ROF transmission in the microwave region has been theoretically justified in [68] as a consequence of the nonideal behavior as a microwave transversal photonic filter of a MMF link. The search of increasing bandwidth solutions took us to achieve successful transmission of broadband signals by combining mode-filtering at the transmitter side (central launching) and low-linewidth lasers as well as performing SCM and WDM techniques through middle-reach MMF links, [61,62,67]. It must be noted that central launching the light from a SMF in turn entails two notable implications: it concentrates most of the energy in the axial core region and reduces the amount of energy in the higher order modes thus reducing the effect of modal dispersion from the coupling of the higher order modes to the lower ones.

Combined mode-filtering at the transmitter side and low-linewidth lasers along with SCM and WDM techniques enabled successful transmission of broadband signals in MMF.

We would like to emphasize on three important results that will be described in sections 5.3.1-5.3.3. The first one is related to the subcarrier transmission of RoF (Radio over Fibre) signals in a broad range of frequencies, ranking from 3 to 18 GHz, through a 5 Km MMF link, [61]. These values are the highest ones ever reported to our knowledge for MMF in terms of combined frequency and distance performance. The second one consists in the simultaneous SCM analogue and digital signals transmission through the 5 km MMF link, [62]. The originality of this work just lies in the simultaneous high-frequency analogue and baseband digital transmission, first one performed through MMF links. The last and more significant experimental demonstration is the successful transmission of 10x20Gb/s channels through the 5 km MMF link living a total aggregate bitrate per distance product of 1 Tb/s·km, the highest value ever reported to our knowledge in terms of MMF links, [67]. It must be taken into account that we have employed 62.5-µm core-diameter graded-index multimode silica fibre with a parabolic core grading.

5.3.1. High-frequency radio over fibre subcarrier transmission

In this first experimental demonstration we perform the delivery of Quadrature PSK (QPSK) modulated radio signals with subcarrier frequencies ranging from 3 to 18 GHz through MMF links of up to 5 km.

The scheme of the setup for the experimental demonstration of SCM signals is shown in Fig. 14.

Recent efforts have pointed that MMFs can support high-speed digital connections such as those required by GbE applications for transmission speeds up to 10 Gb/s in short-reach distances.

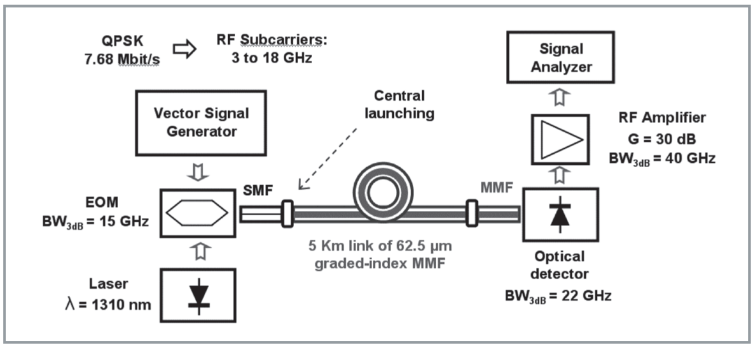
An Agilent E8267C vector signal generator generates the RF subcarriers, ranging from 3 to 18 GHz, which are modulated by a 7.68 Mbit/s QPSK data channel. The combined RF signal is used to externally modulate a CW optical signal generated by a Santec TSL-210V high performance tunable laser characterized by a low linewidth, $\Delta\nu < 1$ MHz, emitting at a wavelength of 1310 nm. After the modulator, the light was directly launched by means of an FC/PC connector into the 5 km MMF link. The applied central launching scheme involved a radial offset ranging from 0 to 2 μm. Thus the SM-MM launch scheme provides the initial spatial mode filtering effect by launching only a limited number of lower order modes into the MMF link. At the receiver end the electrical signal was detected using an MMF-pigtailed 22-GHz-bandwidth Discovery Semiconductors DSC30S PIN photodiode and a 30 dB RF amplifier with a 40 GHz bandwidth before being QPSK demodulated by the Agilent N9020A MXA Signal Analyzer.

We analyzed the QPSK signal space constellations of the measured In-phase/Quadrature polar vector for the cases corresponding to subcarrier frequency values of 3, 6, 9, 12, 15 and 18 GHz. Fig. 15 illustrates the measured constellations the 5 km link where one can easily see that each one of the illustrated measured polar vectors shows a very good location of the four points in the constellation. Only a slightly increase of the clusters is observed for the 5 km link in the cases relative to 15 and 18 GHz, fact that must be attributed to the external modulator frequency response.

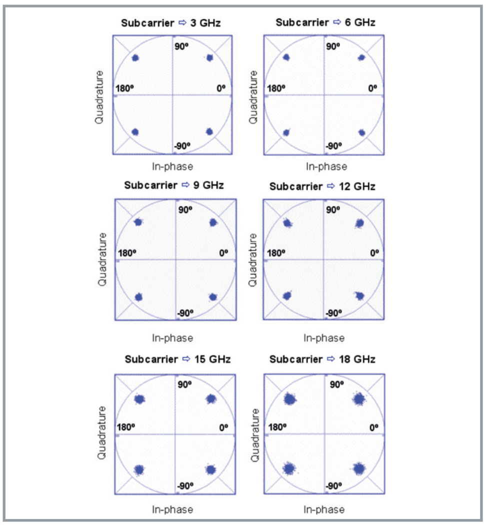
An error vector is a vector defined as the Euclidean distance in the I-Q plane between the ideal constellation point and the point received by the receiver. The Signal Analyzer provides the QPSK error vector magnitude (EVM), a common quality metric widely used in digital communication systems. For each of the modulating frequencies, the measured EVM values did not exceed 6.5%, percentages that are situated well below the maximum magnitude allowed by the 3GPP standard.

5.3.2. Simultaneous baseband and radio over fibre signal transmission

Previous results suggest the potential feasibility to transmit simultaneously combined di-



■ **Figure 14**. *Block diagram of the experimental setup for QPSK transmission over the 5 km MMF link*



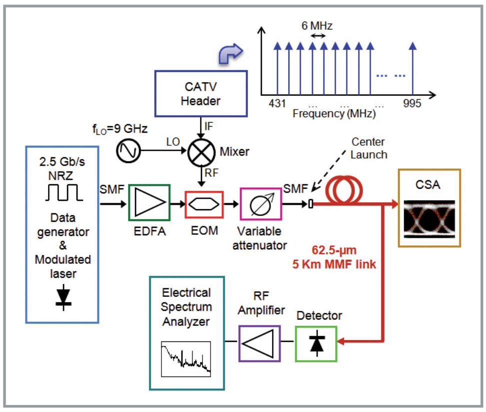
■ **Figure 15**. *I/Q measured polar vector diagrams for a 5 km multimode fiber link*

gital baseband and SCM signals within a given wavelength channel and open the possibility of improved spectral efficiency, multiformat signal transmission and also the implementation of SCM optical label swapping in MMF links.

The schematic of the setup for the experimental demonstration is shown in Fig. 16. The digital frame generator, Tektronix Optical Test System OTS9000, delivered an optical signal at 1550 nm modulated with a 2.5 Gb/s 2^{31}-1 pseudo-random bit sequence (PRBS) NRZ data stream. After being amplified by an erbium-doped fibre amplifier (EDFA) providing about 20 dB optical gain, the light was externally modulated by an analogue RF signal composed by 95 CATV SCM channels, 6 MHz spaced, upconverted to 9 GHz carrier frequency, ranging the upper band from 9.431 GHz to 9.995 GHz. The optical output of the EO modulator was passed through an optical variable attenuator before being central into the 5 km MMF link.

In order to characterize the eye diagrams of the 2.5 Gb/s digital baseband signal, the MMF output end was directly coupled to the 2.5-GHz bandwidth 62.5-µm core-diameter MMF input of the Communications Signal Analyzer (CSA). The electrical spectrum characterization required the optical output of the 5 km MMF link to be detected using the MMF-pigtailed photodiode.

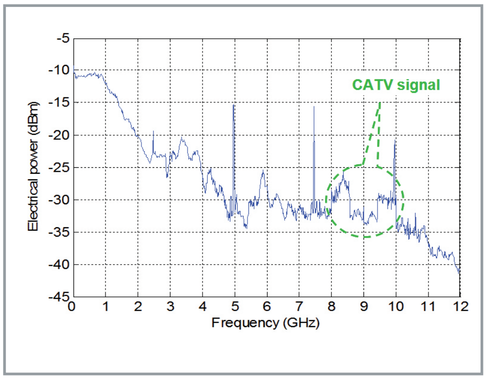
To test the performance of the analogue and digital simultaneous transmission proposed scheme, we measured in first place the received electrical spectrum at the output of the electrical amplifier. Fig. 17 shows the overall measured electrical spectrum from 0 to 12 GHz, where the 2.5 Gb/s digital baseband spectrum and the analogue high-frequency spectrum, allocated in the [8.005,8.569] GHz and [9.431,9.995] GHz bands, can be easily identified. The electrical spectrum of the 95 multiplexed subcarriers of the upper CATV band, where five 6 MHz-spaced channels



■ **Figure 16**. *Block diagram of the experimental setup for simultaneous transmisión*

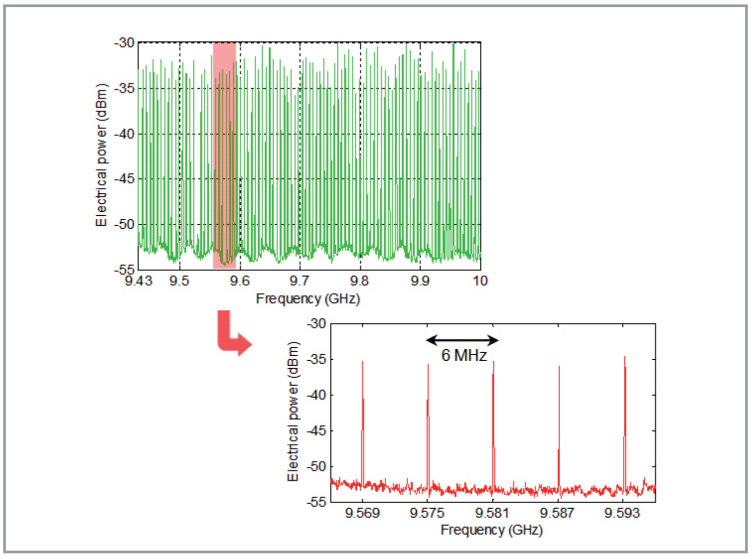
have been shown in detail, is plotted in Fig. 6 showing a signal to noise ratio (SNR) ranging from 25 to 17 dB.

For the evaluation of the impact of second and third order distortions, we will resort to a common measure often used in CATV and cellular telephone systems, the Composite Second Order (CSO) and the Composite Triple Beat (CTB) distortion parameters. The intermodulation distortion measured at the electrical output of the CATV header for the whole frequency plan transmission took values in the range of -69 to -65 dBc for the CSO as well as for the CTB parameter. When simultaneous transmitting analogue and digital data signals, the distortion values measured at the end of the MMF link were in the range of -41 to -39 dBc for the CSO parameter while -42 to -39 dBc for the CTB parameter. The power penalty caused by the RF mixer inclusion results in CSO and CTB degradation around 16 dB, while the degradation due to MMF transmission varies from 3 to 7 dB throughout the measured CATV frequency plan (see fig. 18).



■ **Figure 17**. *Overall measured received electrical spectrum*

To evaluate the performance of the 2.5 Gb/s digital transmission, the recovered eye diagram and the corresponding quality factor Q are shown in Fig. 19 at the optical output of the digital frame generator and at the end of the MMF link for the case of digital data signal independent transmission as well as analogue and digital data signal simultaneous transmission. It can be seen that open eye diagrams are observed for both transmission schemes at the MMF link output, resulting in a quality factor Q = 7.26 for independent digital transmission and Q = 7.05 for simultaneous transmission, what implies a Bit Error Rate (BER) < 10^{-12} for a received optical power of -3 dBm.



■ **Figure 18**. *Measured received electrical spectrum for the upper CATV band*

Comparing both results, we can affirm that the distortion produced for the analogue signal is practically negligible over the 2.5 Gb/s transmission.

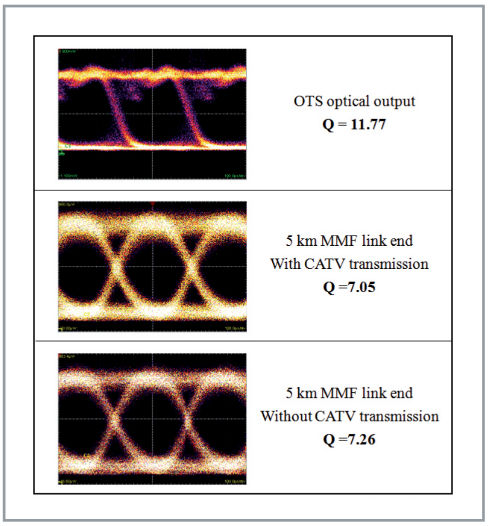
Higher transmission capacities could be achieved combining the proposed scheme with wavelength division multiplexing techniques, [67]

5.3.3. 1 Tb/s·km MMF link combining WDM transmission and low-linewidth lasers

Finally, we performed the experimental demonstration of 10x20 Gb/s data transmission channels using 10 dense WDM channels over the 200-GHz ITU grid's C-band through the 5 km MMF link.

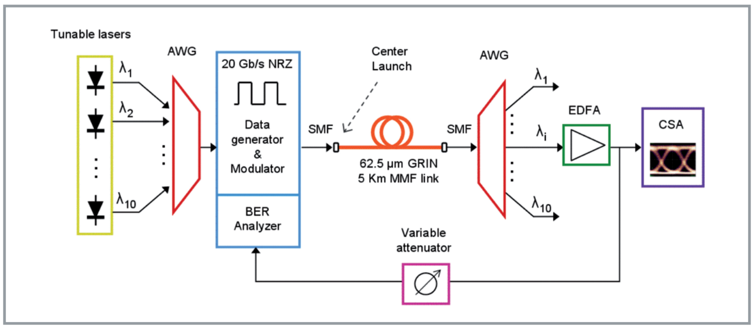
The scheme of the setup for the experimental demonstration is shown in Fig. 20. The 20 Gb/s NRZ signal was modulated onto 200-GHz (1.6 nm) spaced wavelengths over the ITU grid on the C-band resulting in a throughput of 200 Gb/s. Each of the 10 CW signals provided by the low-linewidth DFB lasers, characterized by a linewidth range of 1-10 MHz, delivered 8 dBm optical output power, wavelengths ranging from 1540.56 to 1554.94 nm were combined using a commercially available 40-channel AWG. Prior to their modulation by the Parallel Bit Error Ratio Tester (ParBERT) electro-optic modulator, each channel polarization state was conveniently controlled by a polarization controller. Following their modulation with a 20 Gb/s 2^{31}-1 PRBS NRZ

Three versatile testbeds will be used for testing the network approaches under investigation including physical and MAC solutions, control and management and services such as 2G/3G/B3G transport.



■ **Figure 19**. *Measured eye diagrams and quality factors Q*

data stream, the 10 optical channels were central launched into the 5 km MMF link with an standard first order chromatic dispersion parameter of D = 17 ps/(nm·km). The 5 km link propagation assured the properly time decorrelation of the PRBS sequence in adjacent channels which is in fact equivalent to having transmitted the channels previously modulated with different 2^{31}-1 PRBS patterns.



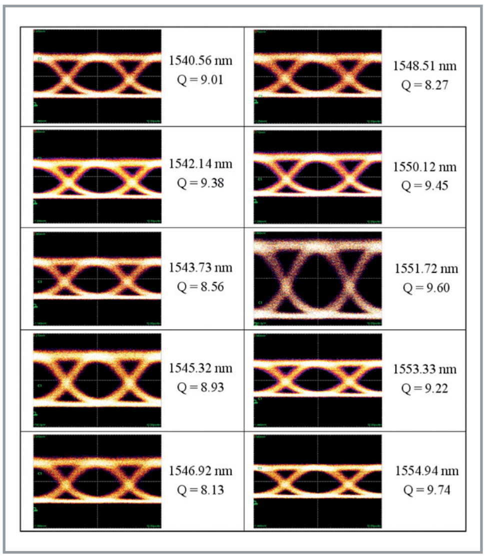
■ **Figure 20**. *Block diagram of the experimental setup for WDM transmission*

At the receiver end, each of the 10 possible channels were wavelength selected using another 40-channel AWG, the output of which was amplified by an EDFA before being properly detected and analyzed by the CSA and the 40 Gb/s ParBERT analyzer.

To evaluate the performance of this setup, fig. 21 shows the recovered eye diagrams and the corresponding quality factors Q after simultaneous transmission over the 5 km MMF link for every 20 Gb/s received WDM channel ranging from 1540.56 nm to 1554.94 nm. It can be seen that open eye diagrams are observed for every selected wavelength resulting in a high measured quality factor Q that ranges from 8.13 to a value of 9.74, what implies a BER < 10^{-15} for a received optical power of +1 dBm.

Fig. 22 shows the measured points for the BER for every one of the 10 received channels versus the optical receiver power. Despite the differences in the received optical power level between channels, due in part by the different attenuation suffered in the mux/demultiplexing process, one can affirm that all the wavelength selected channels follow a similar BER behaviour. For all channels error free transmission is achieved with received powers in the -7 to -4.5 dBm range. It must be noted that the SM-MM launching scheme causes a power penalty of 2 dB, which is in line with the results presented in [64] for the transmission of 10 Gb/s signal over 3.7 km MMF link for mode-field matched centre launching at the same BER.

Therefore, we have experimentally demonstrated that by combining central launching through a SMF and a low linewidth laser the transmission of broadband signals (from baseband to high-frequency radio regions) is feasible in a 5 km long 62.5-μm core-diameter graded-index multimode silica fibre link. A record aggregate bitrate per length product of 1 Tb/s·km has been achieved in a MMF link by combining the former capability with WDM transmission. This corresponds to the highest value ever reported to our knowledge for MMF links.



■ **Figure 21**. *Recovered eye diagrams and quality factors Q for every demultiplexed WDM channel*

6. Demonstrations and field trials

The goal of the ALPHA project will be pursued by creating a versatile development and complex test environment that will be used to assess the architectural and transmission solutions proposed in the other workpackages. This environment will be based on three project testbeds that will be used to assess the network solutions under investigation. These three testbeds include:

- A single-mode fibre- based Access-Home

testbed with Radio-over-fibre functionality at Alcatel-Lucent and France Telecom in France (*ALF-FT testbed*).
- An Access-Home testbed with the mixed fibre-based physical layer and independent test-pilots at Acreo in Sweden (*Acreo testbed*),
- A Home Network with Simulated Home Environment based on the ALPHA physical layer technologies and with support of femto-nodes at Telefonica in Spain (*TID testbed*).

The testbeds will be offered as an open test platform to the other project partners and, if necessary, to other European research projects. The testbeds will represent the various technologies and domains studied in the project as well as include interfaces between those technologies/domains. The testbeds will be used for testing the network solutions under investigation including the various physical and MAC layer solutions, control and management planes solutions, various services such as the 2G/3G/B3G transport, as well as for testing inter-domain interworking and compatibility.

7. Conclusions

This paper has presented the ALPHA project, as an Integrated Project in the VII Framework Programme, which main goal is to investigate new architectures and transmission solutions for future converged access and in-building networks providing support to both wired and wireless services and according to end-user future services requirements. In the scope of the project, the Optical Communications Group in the ITEAM-UPV collaboration has been presented mainly focused on reconfigurable optical access networks, low cost solutions for optical in-building networks, and significant contributions to the next generation physical layer technologies. In this area, the main contributions of our group have been the study of Radio over Fiber system limitations, the comparison of advanced modulation formats and the experimental demonstration of a record aggregate bitrate using WDM over MMF transmission link.

Acknowledgements

The authors wish to acknowledge the European Comission FP7 under project ALPHA (grant no. 212352) and the Ayuda Complementaria para el proyecto ALPHA TEC 2008-01408-E/TEC funded by the Ministerio de Ciencia e Innovación.

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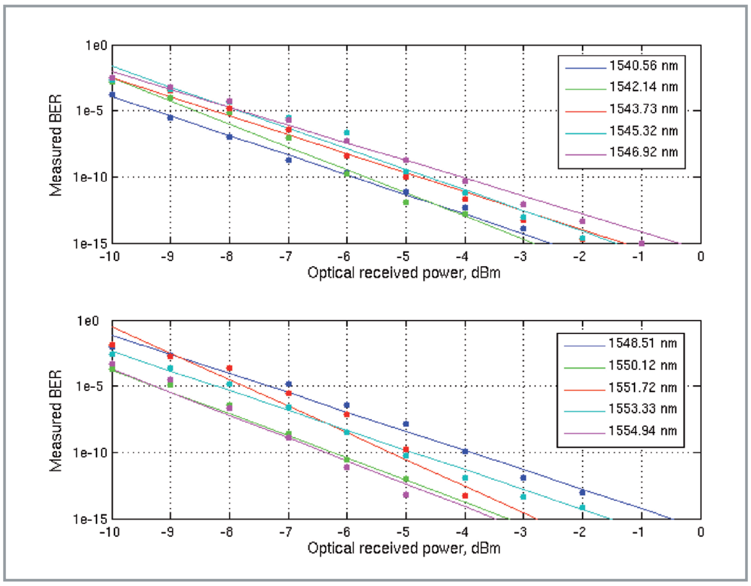

Figure 22. *Bit error rate versus optical received power for every WDM channel*

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