eMobility Technology Platform

Expert Working Group EWG-4

"Optical Fibre Technologies and Radio over Fibre Strategic Research for Future Networks"

White Paper

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Chair: Professor Hamed Al-Raweshidy

Hamed.al-rawhidy@brunel.ac.uk

eMobility
(Connect to the network community)

Contributors	Company /Institute	Email address
Nicola Ciulli	Nextworks	n.ciulli@nextworks.it
Enrique Areizaga	Tecnalia-telecom (Robotiker)	Enrique@robotiker.es
Andrea Blanco	Tecnalia-telecom (Robotiker)	ablanco@robotiker.es
Richard Penty	Cambridge University	rvp11@cam.ac.uk
Jim Everett	Ericsson Limited	Jim.everett@ericsson.com
S.Lowe	BT openworld	stephen.j.lowe@btopenworld.com
Moshe Ran	H.I.T Holon Institute of Technology	mran@hit.ac.il
Yosef Ben Ezra	H.I.T Holon Institute of Technology	benezra@hit.ac.il
B. Lembrikov	H.I.T Holon Institute of Technology	borisle@hit.ac.il
Hamed Al-Raweshidy	Brunel University, West London	Hamed.al-raweshidy@brunel.ac.uk
Sahibzada Ali Mahmud	Brunel University, West London	Sahibzada.mahmud@brunel.ac.uk
Bill Headley	University of Surrey	W.Headley@surrey.ac.uk
E. Tangdiongga	Eindhoven University of Technology	E.Tangdiongga@tue.nl

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1. Introduction

Wireless communication is entering a new phase where the focus is shifting from voice to multimedia services. Present consumers are no longer interested in the underlying technology; they simply need reliable and cost effective communication systems that can support anytime, anywhere, any device (ATAWAD). Globally, mobile data traffic will double every year, and reaching over 2 Exabyte's per month by 2013. Furthermore, mobile data traffic will grow from 1 petabyte per month to 1 Exabyte per month in half the time it took fixed data traffic to do so. In the 7 years from 2005 to 2012, it will have increased a thousand-fold. In addition, the Internet traffic grew from 1 petabyte per month to 1 Exabyte per month in 14 years.

As shown in figure 1, there will be three waves of Internet video. The first phase is experiencing a growth of Internet video as viewed on the PC, the second phase will see a rise in Internet delivery of video to the TV, and the third phase will involve a surge in video communications. Each phase will impact a different aspect of the network. The first two phases will be felt primarily in the metro and access networks, while the third will impact the core. In addition to Internet video, there is very high growth in the IP transport of cable and IPTV video on-demand services. Only the virtually unlimited bandwidth of optical fibre access network can provide such capability both for wired and wireless connectivity. Radio-over-Fibre has been addressing how to distribute broadband wireless signals in access networks, including dynamic allocation of resources.

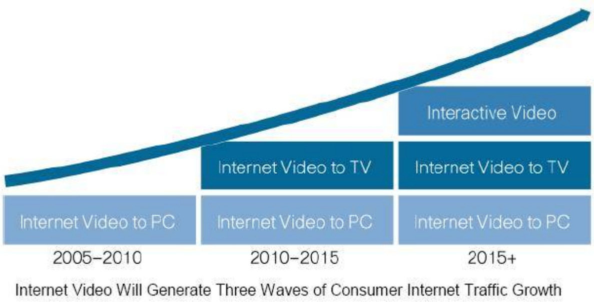

Figure 1. Internet traffic growth.

Driven by ever-increasing users' demands for broadband services, worldwide fibre-to-the-home (FTTH) rollout has recently surpassed thirty million users and is continuing to grow at a rapid rate. To realize various FTTx solutions, passive optical networks (PONs) have been considered as the most promising technology. Next-generation PONs are expected to deliver new and legacy services, both analogue and digital, in a single converged conduit. One such example is the radio-over-fibre (RoF) technology which makes use of an unspecified spectrum to backhaul wireless signals from multiple remote antenna ports via one trunk fibre.

The rapid and global spread of the internet is accelerating the growth of optical communication networks and the demand for more bandwidth has driven the use of photonic technology in telecommunication and computer networks. The diversity of future services will require high-capacity optical networks featuring dynamic and high-speed routing and switching of data packets. The new generation very high-bit rate optical packet switched networks require a potentially faster approach to decode the header bits optically so that a given routing decision can be made on-the-fly.

Internet traffic has been increasing at an annual growth rate of around 40%, and it will reach 1 Terabit/s in the core optical network according to figure 2. as the bandwidth demand increases in the future network.

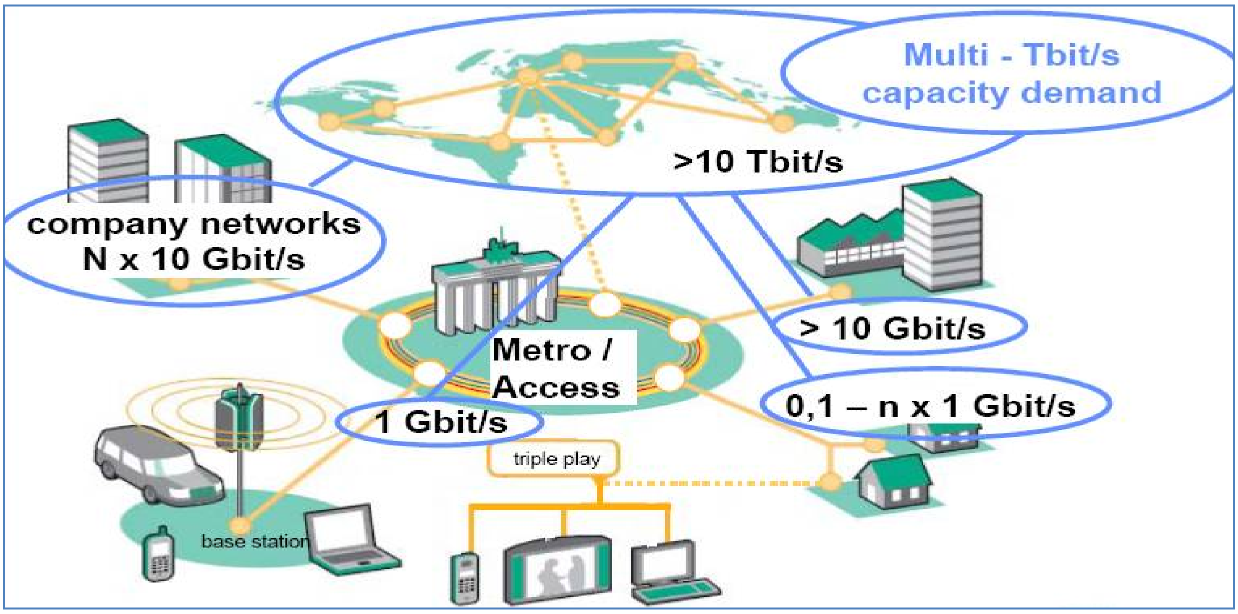

Figure 2. Bandwidth demand in future network

With the constant evolution and innovations in the processing capabilities of consumer devices capable of handling rich multi-media content, the current available bandwidth and the capacity of last mile wireless networks proves to be a major bottleneck. Provision of higher bandwidths to the end users thus becomes mandatory in order to streamline with the evolving multi-media applications and higher demand. Having a wired network although can provide higher bandwidths; it limits the overall convenience, mobility and has a significant impact on the cost. On the other hand, an end to end wireless solution does not serve the purpose because of capacity constraints at the access domain. An integrated approach as shown in figure

3, however, becomes an attractive alternative and with suitable planning, an acceptable compromise can be achieved between providing high bandwidth to the end users as well as being cost effective and convenient. To augment the bandwidth of the network, Radio over Fibre (RoF) Access points can be used at suitable locations throughout the network along with mesh routers to provide a low cost and high bandwidth solution. Optical Routers and switches can be used in the back end to aggregate the traffic and route it to the appropriate destination. Therefore, a high bandwidth and low cost solution can thus become feasible as well as scalable to cope with the future demands of increased bandwidth and high traffic volumes.

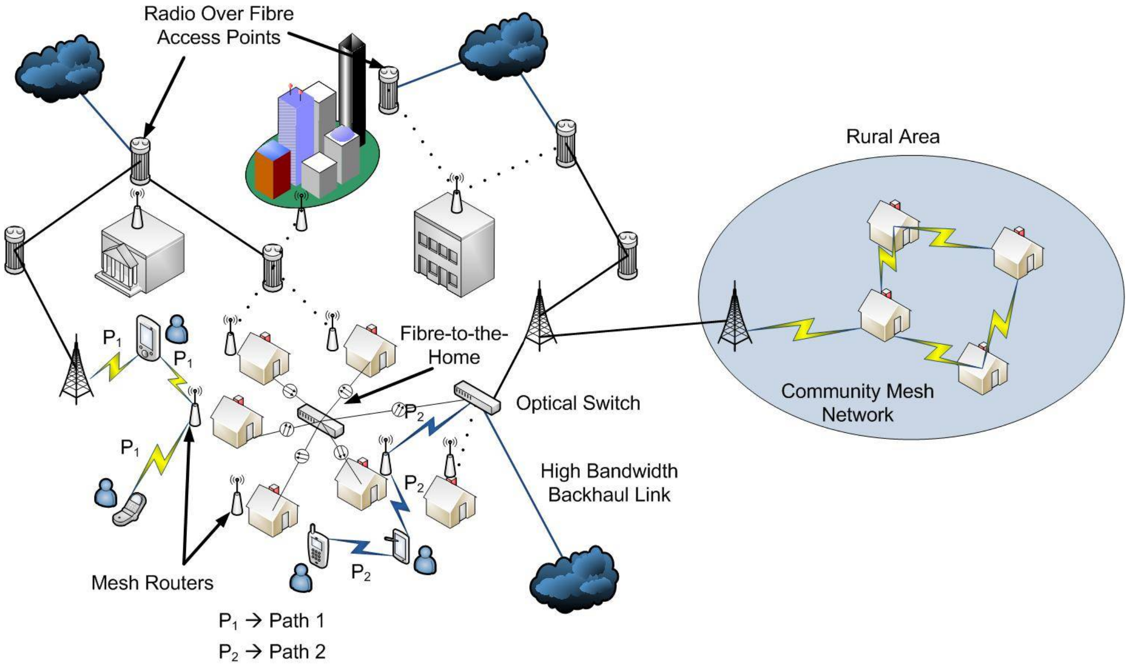

Figure 3. An Example of Integrated Wired-Wireless Network

With current technologies, however, networks will frequently suffer from bottlenecks in the face of rapidly increasing traffic, meaning traffic congestion caused by the insufficient processing speed of the electronic circuits inside the routers. In addition, the overall scale of electrical router node facilities, including switching bays and OE/EO line card bays, will become increasingly larger and will require ever higher power consumption. To solve these problems, node technologies based on ultra-fast optical packet switching have been intensively developed to replace conventional electrical router nodes, with the goal of eliminating unnecessary O/E and E/O conversions in the data plane, even in packet header recognition.

2. Rationale

Radio over Fibre is a rather ideal technology for the integration of wireless and wired networks. The main reason being is that it combines the best attributes of two common communication methodologies. A wireless network connection frees the end-user from the constraints of a physical link to a network which is a drawback of conventional fibre optic networks. Meanwhile optical networks have an almost limitless amount of bandwidth with which to satiate even the most bandwidth hungry customers where bandwidth for wireless networks can be a significant bottleneck. Thus RoF networks offer customers the best of worlds by allowing them to maintain their mobility while also providing them with the bandwidth necessary for both current and future communication/entertainment applications (i.e. HDTV, Video on Demand, 3DTV, video teleconferencing, etc.). Furthermore RoF networks also provide for greater geographical flexibility as compared to using either one or the other methodologies. Such network topologies could be useful in places such as large buildings, subways and tunnels where large amounts of people are mobile thereby making physical connections impossible and standalone wireless systems being faced with the difficulty of bandwidth limitations and handover issues.

While the concept of RoF networks has been around for several decades now, there is still a substantial amount of work that needs to be undertaken in order to improve their characteristics and capabilities. Several research priorities have been identified that should be addressed in order to improve not only the capabilities of RoF networks but also their cost effectiveness and robustness. The requirement to communicate a very high data rate such as rich multimedia with low power and low cost are the reason behind the integration between wireless and wired domains using RoF as this integration is the only way to allow high data rate with low power and low cost. The integration has the potential to make the networks more transparent, dynamic, faster and greener.

3. Research Priorities

3.1 Business Models and Network Architecture Design

The use of fibre technologies to distribute radio signals from a central office location into the access network has the potential to have a significant impact on power consumption. As part of the investigations into RoF technologies the reduction in power consumption compared with a more conventional approach using optical and radio backhaul networks with either SDH/SONET or Ethernet switching should be a key topic for research.

One of the most important advances in containing the overall power consumption of the Internet could be the efficient and innovative use of optical technologies in providing a converged access/metro network which is designed to carry all types of high speed traffic. This could include business and residential, and provide ultra-high speed broadband access to both domestic and business customers.

3.1.1 Support for on-Line Applications and Storage to Enable Fully Mobile Access to Business and Personal data

Business users have for some years needed access to their data while away from their operating base. They need access in two ways: while static in a remote office: while travelling to or from a remote office. The static connectivity may be provided by a wire connection but increasingly users assume that some form of wireless access will be available. The mobile access has to be provided by wireless but this may be a continuous high speed connection or a store and forward service such as is offered on trains and buses. In each of these business users scenarios the upstream data rate is as important as the downstream. In some cases there may be a requirement for a higher upstream than downstream, for instance when a field worker needs to upload photographic data.

This is a very different scenario than for the domestic user whose main requirement remains the desire to download music or to watch sports events while on the move. For sports events in particular the downstream data will far outweigh the upstream. However, it is likely that many users will be looking for the same data so a network with broadcast capability could improve the spectral efficiency of the air path considerably.

3.1.2 Network Costs Paid by Content and Service Providers but Free to End Users

States look to electronic systems to reduce their costs. They are under pressure to provide universal connectivity to match the other services such as water, gas, electricity and roads. In general users believe that these services are free to use. They overlook the costs they pay via their taxes. The networks are provided by commercial operators who must deliver a return to their shareholders. The challenge is to reduce the cost of the infrastructure to a point where services may be delivered to all member of the community. However, there could be an argument that people who choose to live in areas of low density population may be required to pay higher fees than those who live in dense urban areas.

It would be helpful if the various technologies harmonized standards to encourage reuses of components and thereby reduce the network costs. It would also be helpful for regulation to encourage infrastructure sharing. A prime example is the provision of 3G mobile services. Available spectrum would indicate that a single national wireless network makes most sense. But legislation required that each operator should provide their own access and trunk networks. Some progress towards sharing has been made with multiple operators on single masts. Greater efficiencies could be made if spectrum and access hardware was also harmonized.

3.2 Optical Network Switching for Hybrid Traffic

Efficient control plane architectures and routing algorithms are a key issue for building hybrid networks that integrate optical equipments and multi-technology wireless meshes. This scenario is particularly critical in the metro/access segment that can be characterized by different topologies of the optical domain, such as the tree, the ring, and the partial or full mesh. The topology layout often depends on the switching/transmission paradigm (e.g. PON or active optical switching) and the type of the switching nodes (e.g. a control station, a base station or an intermediate node in the fibre backbone). These optical switching elements should provide various functionalities to cope with the hybrid wired/wireless networking, such as advanced traffic mapping, services delivery, and dynamic traffic allocation, in order to support the demanding user driven applications in mobility scenarios covering a large set of wireless technologies, such as WiMAX, LTE, Wi-Fi, characterized by different QoS metrics and radio resource allocation mechanisms.

The IEFT GMPLS is one of the most promising control plane architectures to be evolved in support of the reservations and routing procedures in hybrid networks. GMPLS is natively designed to provide automatic provisioning of end-to-end connections with traffic engineering, traffic survivability (i.e. protections, restorations), automatic resource discovery and management. The core GMPLS specifications are fully agnostic of specific deployment models and transport environments: they are built upon the MPLS procedures and broaden the applicability of those mechanisms beyond the single data plane envisioned by the original MPLS specifications. However, due to the multiplicity of underlying Transport Plane technologies, some specific procedures and protocol extensions have just been defined in GMPLS to control transport networks as diverse as SDH/SONET, DWDM-based OTNs, OTNs with G.709 encapsulation, and Ethernet. This process of enhancement of the GMPLS protocols foundations is still active in IETF, because it needs to cope with new emerging transport technologies, such as the Carrier-grade Ethernet (i.e. PBB-TE) and the dynamically reconfigurable optical devices (ROADMs).

The natively generalized control approach enabled by GMPLS on the underlying Transport Plane allows a simplified handling of multiple switching technologies under a single Control Plane instance, like in the case of hybrid networks. This scenario is often referred to as Multi Region/Layer Networks (MRN/MLN), and it allows overcoming the traditional approach of overlaying specialized control instances, which is more and more inefficient. IETF CCAMP and MPLS WGs produced several solutions to handle the multiple switching technology issue in (G) MPLS. Among these, it is worth mentioning the LSP nesting [RFC 4206, RFC 5212] and the LSP stitching [RFC 5150]. With LSP nesting, multiple low-granularity LSPs can traverse a higher granularity H-LSP, which represents a Forwarding Adjacency in the Transport Plane. The H-LSP could be set up in a switching region and subsequently exported/used by other LSPs as a single hop. On the contrary, in LSP stitching a single end-to-end LSP is built by stitching a set of "LSP segments" (S-LSP) with the same switching granularity. The S-LSP could provide a solution for the control of multiple domains of bandwidth granularities under the same switching capability. An enhanced GMPLS Control Plane should be designed to support the high capacity and multi-granular switching in hybrid wired/wireless networks adopting DWDM or VHDWDM sub-systems as transport technology for the optical segment. These research tracks could produce innovations in terms of dynamic management of optical resources based on several criteria, such as service availability, user requirements, and traffic type. The main differentiating factor with respect to the GMPLS state of the art will be the nature and dynamics of the triggers for the Control Plane, which will mainly derive from the multi-technology wireless network. Therefore, new bandwidth specifications and possibly new tunnelling services may arise from these activities on Control Plane.

3.3 Design of the RoF Subsystems and Components, Including Link Budget Analysis

As the number of radio services becomes greater, and as their signal bandwidth and carrier frequency increases, there is a need to define the performance of the radio over fibre link which carries the signal. There is a range of techniques to do this, ranging from the simple design based on link gain (but ignoring noise and distortion) to sophisticated time domain system models based on physical model of individual devices. The former approach has the advantage of simplicity but does not give any insight into the ultimate limit of the RoF system. The latter approach is much more accurate but requires large amounts of computing resource and long computation time, making this approach an ungainly one when carrying out link optimization. A useful compromise, which has many attractions in terms of flexibility and speed of computation, is the link budget approach. Here components are parameterized in terms of their RF gain, noise and distortion, thus enabling simple, but still accurate, spreadsheet based models. The models can be used to identify the critical components in a link and thus the performance that they require to improve link performance. It is crucial to realize that the design of RoF links should address in many cases the hybrid fibre-wireless channel. Proper link budget design over the hybrid wireless (indoor) - wired (fibre) channel will enable overcoming the inherent tremendous wireless propagation loss by using wired segments

The choice of sub-systems for any given RoF link and the service(s) that it needs to carry depends on many variables. For instance optimization in terms of performance is likely to require very high performance (and therefore expensive) components and so there will be many trade offs (of which cost-performance is only one). Ongoing trends are (i) cost reduction – as telecom lasers become cheaper as a class (it is now possible to buy a 10 Gbs laser in bulk for <$1 compared to $1k five years ago), direct modulation analogue lasers are also reducing in price, (ii) higher bandwidths and carrier frequencies, (iii) higher power generation from source lasers and power handling from photodiodes, thus improving link gain and (iv) increased co-use of electronics and optics to improve overall link performance.

3.3.1 Implementation of Radio over Fibre Units

Most current RoF links that are available commercially have relatively limited frequency ranges. Firstly most commercial systems are narrowband and only carry a single (or at most a low numbers) of radio services. Consequently if a system is to carry a multiplicity of services, it will need multiple parallel RoF links. There should be a broadband solution which is attractive for providing a single infrastructure able to support multiple services. Secondly most services that are carried have relatively low carrier frequencies, with the majority of commercial services having a carrier at a frequency < 3GHz. Clearly as required data capacity rises, inevitably so must carrier frequencies.

There is consequently a great deal of room for development of components and systems that (a) operate at higher carrier frequencies (with all the issues that causes in terms of fibre dispersion, component cost etc), but perhaps more importantly in developing broadband networks able to support the multiplicity of services that are now required, mostly for commercial / enterprise environments, but increasingly even in the home. Whilst broadband optical transmitters and receivers are available, multi-octave RF components are not, at least at the commodity price points that are necessary.

3.3.2 Digital Distribution

Currently most traffic which eventually ends up as a radio signal is carried digitally over an operator owned or public telecoms network and it is only at the base station or access point that the data is modulated onto a radio carrier. RoF systems usually take the analogue signal, either directly from the base station or via a repeater, and then transport it as transparently as possible to a remote antenna. The advantage is that distributed antenna systems can increase coverage and capacity without requiring a base station for each antenna, particularly important for in-building applications. The downside is that the RoF link inevitably adds noise and distortion to the analogue signal, thus limiting the dynamic range (and hence radio range) of the overall link.

As the performance of analogue to digital convertors (ADCs) and digital to analogue convertors (DACs) improves and their costs drop over time, it is now becoming possible to digitize the analogue signal for transmission over a digital link, followed by reconstruction of the original analogue signal at the receiver unit. Once the signal is in digital form, it can be transported and distributed without any loss of quality or information, unlike the analogue RoF signal, which is a key advantage.

This approach requires a high number of digitization bits (14 being the minimum for a usable, dynamic range with 16 or even 18 being preferable) though DACs/ADCs are now on the market which can achieve this resolution with bandwidths compatible with radio services. One issue is that the digitization of a relatively narrow radio bandwidth (e.g. 50MHz to enable WCDMA services to be digitized), would require 50 x 2 (for Nyquist sampling) x 16 (for number of digitization bits) = 1.6 Gbs digital transmission. However, this sort of data rate is now not expensive with Ethernet and the Fibre channel standard driving down the costs of optical data communications networks well below the costs of a narrowband RoF link.

Whilst this field is in its infancy, various feasibility papers have appeared in the literature and a growing number of groups are beginning to study this field. Important areas to study are (i) digital RoF system specification, (ii) trade-off between ADC/DAC resolution and system performance, (iii) transport protocols, including the transport of the necessary timing information, (iv) reconstruction of the analogue signal at the remote unit.

3.4 Meshing Fibre with Wireless:

Although an integrated wired-wireless approach can resolve most of the issues related to provision of high bandwidth to the access domain, there are some issues which need to be investigated and suitable algorithms and solutions need to be devised to eliminate or mitigate these issues.

3.4.1 Routing in a Heterogeneous Environment

In an environment with different available wireless Air Interfaces (AIs) and as well as wired interfaces, efficient routing becomes an important as well as a non-trivial issue. The operating range and attributes of available wireless AIs and the requirements of a particular flow for which the path need to be established are important factors which should be taken into account to discover an end-to-end path which is stable, robust and can satisfy the QoS of the flow between end devices. Similarly, depending on the type of the end devices, the feasibility of using a high bandwidth wired route in the middle to the destination wireless network also needs to be investigated.

3.4.2 Mobility Management

With the induction of RoF access points as well as high bandwidth optical switches in a wired-wireless network, the handling of flows from mobile devices and the respective mobility management becomes an important issue. The appropriate vertical and horizontal handover strategies and the effect of handover delays need to be taken into account while forming a path between end devices for a flow which has delay constraints. Furthermore, if the path consists of RoF access points, the processing delays also need to be taken into account while switching from wireless to wired domain and vice versa.

3.4.3 Resource Allocation Strategies

In a dynamic heterogeneous environment with a high demand imposed by user devices in congested urban areas, the efficient allocation of spectrum resources becomes mandatory. Appropriate resource allocation policies need to be defined which can allocate a fraction of spectrum based on the expected density of users that are going to use a particular AI at a particular time and hence utilize the part of the spectrum which deals with that AI. A history of previous allocations can be used and efficient spectrum usage estimation techniques need to be developed to aid the resource allocation algorithms.

3.4.4 Service Aware Network Connection

The main problem for the wireless and fibre networks would be to ensure minimum data rates for each service for the end to end connection. In order to optimize the data rates on the wireless links and on the wired links, a service aware Quality of Service could be used. Multi Services Level Agreements (SLA) has to be negotiated in order to guarantee QoS for the different applications (voice, video, data) while simultaneously optimizing the network resources.

3.4.5 Bridging Wireless Mesh and Fibre Protocols

Today most of the interconnections between wireless and wired equipments are performed at IP level. This allows simple architectures but implies processing delays between the lower layers in the protocol stack and the higher layers. This delay is not compatible with the Gigabit data rates. Furthermore, this solution cannot guarantee a global QoS from end to end as it does not take advantage from the medium access control mechanisms implemented on the wireless and wired networks. So, new approaches have to be taken into account especially at the lower level protocol stack in order to guarantee end to end QoS and smooth transitions between wireless and wired networks. One possibility would be to define at the MAC level the interoperability and cross layering between both wireless and wired networks.

As an example, using two radios for each radio relay on a wireless mesh network would allow with a TDMA protocol to provide end to end guaranteed data rates using appropriate time slots on each radio (with a TDMA protocol).

As described previously, the interoperability and cross layering between wireless and wired networks is of importance in order to provide efficient bridging between wireless mesh networks and fibre networks.

There is a big interest to combine wireless mesh networks and optical fibre. One application example would be the following one allowing Fibre to the Air transmissions for the last mile and optical fibre networks for the core network. Figure 4 shows an application example using wireless mesh networks and optical fibres. The wireless networks can be based on millimetres waveforms or on UWB waveforms or both combined. In this example, the services which are delivered are composed of broadcast of a large number of digital TV channels (HD included), collection of video streams for video-surveillance in addition to a large capacity for usual VoIP and data transmission.

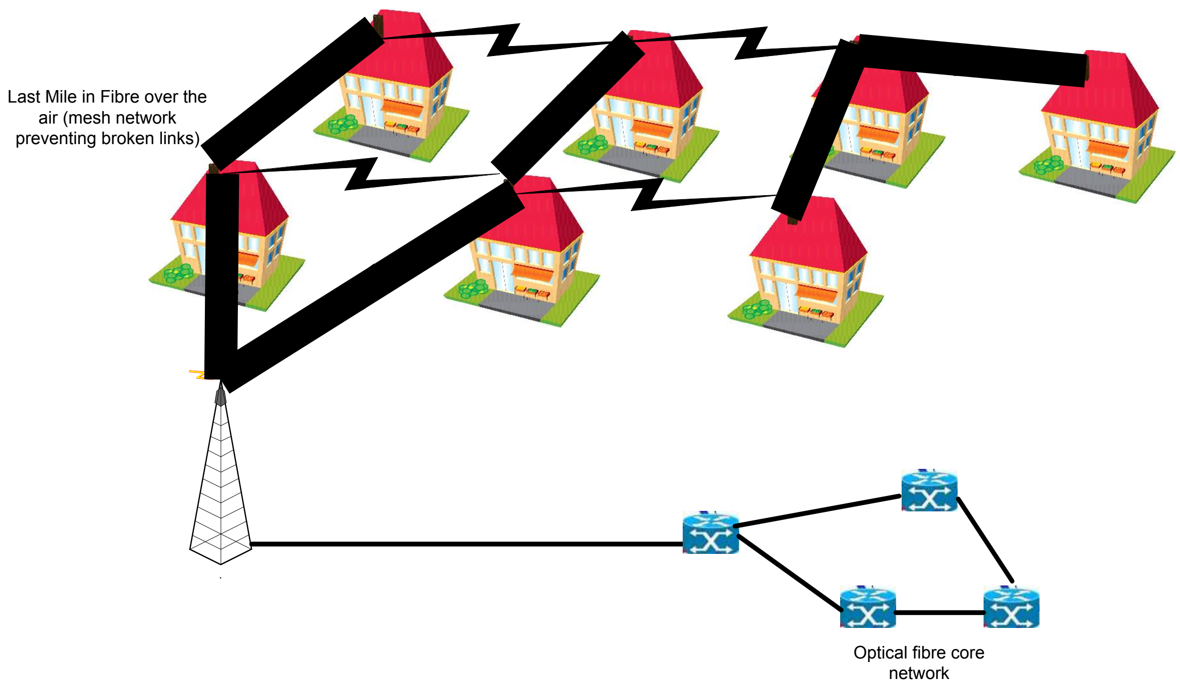

Figure 4. Meshing Fibre with wireless

3.4.6 Optical-Wireless Component Integration

Over the last thirty years the microelectronics industry has undergone a revolutionary transformation due to integrations. By combining discrete electronic components onto a single monolithic platform, microelectronic components have realized a dramatic increase in device performance while also providing a substantial reduction in cost. Currently the field of optoelectronics is undergoing the same sort of revolution as Optical Electronic Integrated Circuits (OEIC's) are a hot topic at the moment. The idea is to capitalize on the same cost and performance benefits that the microelectronics industry has reaped over the past few decades by combining electronic and optical components onto a single substrate.

It is believed that this integration could be taken one step further. By combining wireless, optical and electrical components monolithically, cost and performance improvements could also be had for RoF devices. Furthermore these devices could be developed so to address the deleterious problems such as latency due to data conversions between the various media types (i.e. wireless to electrical to optical). If some of the intermediate conversion steps could be eliminated through the use of direct media conversion components, issues such as latency, power consumption and cost could all be minimized thereby making RoF networks more efficient and cost effective.

3.5 Network Architecture

Another aspect of RoF networks that could benefit from further research is the architecture of the network. Ideally a high-speed fibre optic backbone connecting hundreds or thousands of remotely placed wireless/optical transceivers could provide the end-user with a nearly unlimited amount of bandwidth almost seamless connectivity no matter where they travelled; whether crossing a room in their home or crossing a large metropolitan area in their car. However such a network will inevitably be faced with several practical issues. The first is cost. While a large amount of interconnected transceivers would provide excellent mobile coverage for the end-user, these transceivers would also require power, even in standby mode. Thus as the number of transceivers increases, so too does the power consumption by the network and hence its operational cost. Thus in the absence of any sort of "green" transceivers, a network architecture that balances bandwidth and mobility while minimising power consumption should be investigated. This effort could be made in conjunction with the work done on integration as integrated components should not only be lower in cost but may also be more energy efficient and thus have a significant impact on optimal network architecture.

Installation costs are also an important consideration for RoF networks. One of the prohibiting factors of FTTx installations is the labour costs involved in installing the network. Hence it would be cost effective to minimise the amount of fibre installed in the network and instead make as many of the final connection to the end user using wireless. The drawback of this scenario is that the network bandwidth may suffer as potentially large amounts of users and their devices crowd the wireless link. Thus the tradeoffs between end-user bandwidth, including end-user future needs, and installation costs should be addressed so that high bandwidth data links can reach as many as end-users as possible at a cost that can be supported by the average telecommunication provider's business plan.

Another issue that needs to be addressed in an RoF network architecture is reliability. This aspect is especially true as personal health monitoring technologies become mainstream. If the fibre backbone were to be severed in an RoF network, hundreds or even thousands of end-users could suddenly find themselves isolated uncoupled from the network. This would be especially problematic for an end-user who required immediate assistance for a sudden health emergency. Thus some level of redundancy should be built into the network so that even a minimal amount of communication can be maintained at all times no matter what happens. Wireless mesh networks are a good example of providing redundancy to a network should one (or more) data paths become disrupted. The mesh could be used to reroute data to transceivers that still have a functional fibre connection thus improving the reliability of the network.

3.5.1 Coexistence of Digital and Analogue in Hybrid Fibre Wireless Systems

Passive optical Networks (PON) technologies such as EPON, GPON and APON realize sophisticated and economical optical access network for providing broadband access and also provide different multiple services such as CATV, telephony, as well as high speed Internet access. There will be growing demand for broadband wireless access and mobile communications. In particular, the hybrid broadband optical system and optical feeder architecture for wire line and wireless access nodes are promising. These hybrid optical platforms can simultaneously transmit digital baseband (for example 1Gbs or 10 Gbs Ethernet) and Radio Frequency (RF) signals. Therefore the issue of the coexistence of digital and analog transmission becomes very important. The technical challenges of implementing next generation PON technologies include new architectures to support migration path from already deployed 1 Gbs systems towards 10 Gbs along with analogue video overlay on the downstream. In these context requirements for coexistence between 1 Gbs-10 Gbs and analogue signals is mandatory to assure a smooth migration path. For example the wavelength allocation plan for 10 Gbs EPON must take into account the existence of 1Gbs equipment on the same PON plant. The downstream channels for two data rates will be WDM (Wavelength Division Multiplexing) multiplexed. The upstream channel coexistence most likely be resolved via Time Division Multiplexing (TDM).

Three wavelength channels are usually addressed to support digital upstream/downstream and an analogue video overlay on the downstream. Requirements place on the network such as optical loss budget, transmission distance, split ratio etc. Impose challenging problems to address as: potential conflict in wavelength allocation, non-linear crosstalk between high power PON and analogue video signals and challenging power budget requirements along with challenging implementation of a burst receiver design to support both legacy 1Gbs and 10Gbs.

3.6 Green Radio over Fibre

By "Green Radio" we mean technologies that can be considered safe in the sense that allow for the lowest possible consumption and radio operating power levels. Typical use cases for these technologies are "safe connected home" and "future hospital". In the first scenario a full range of short-range in-house emerging wireless standards are expected to coexist as 802.11n, WHDI along with new high data rate streaming audio& video, wireless sensor and remote control networks. Recently, femto-cell has emerged to drastically improve coverage and capacity of mobile communications indoor by communicating with the cellular network over broadband wired connection. With "always on" home networks people are possibly exposed to undesirable electro-magnetic (EM) radiation.

A similar consideration holds for hospital environments where weak vital signal functions have to be monitored and interchanged continuously over the radio channel in the presence of sick and therefore vulnerable people. At present some 8 – 10 functions per patient are monitored. These numbers are expected to grow rapidly in the coming years. Advanced in-body wireless systems (as Pillcam video capsule, see www.givenimaging.com) became available and provides patient-friendly with superior diagnostic efficiency alternative to other imaging technology.

In essence the use of "green radio" with very low EM radiation is of utmost importance.

That means reducing the EM radiation for indoor environment by two order of magnitudes to levels much below 1mW.

Reduction of the emitted radio power in-doors to minimum levels comparable to the levels of the parasitic emissions by using hybrid fibre – wireless technologies is a promising approach to realize green radio and implies series of challenges discussed below.

- Topologies and network concepts to support the delivery of Gbs radio signals over hybrid fibre/wireless channels
- Support the functionalities of multi-radio
- Multi standard ad-hoc networking and interworking of devices of different standards
- Versatile interconnection to the outer public access network

3.7 Optical Packet Switching

Optical switching removes the need of converting optical signals to the electronic domain in the intermediate nodes. This fact entails key advantages: The bottlenecks caused by the limited speed of electronics are avoided, costs and power consumption associated with the optoelectronic conversions are minimized, and latency is reduced due to the unreachable speed of photonics.

Three optical switching paradigms have been proposed: optical circuit switching (OCS), optical burst switching (OBS), and optical packet switching (OPS). From all of them OPS presents the highest degree of flexibility and bandwidth use, implying QoS capabilities and costs savings respectively. This technique relies on switching each packet independently in the optical domain, which is the optical counterpart of current electronic packet networks. The challenges hindering the implementation of optical packet networks are, however, significant.

Three strategic areas of research are identified to advance in OPS feasibility:

3.7.1 Optical Memories:

Photonic buffering mechanisms for storing optical packets, as electronic memories store optical packets in current routers. Currently, the only commercial solution has been employing coils of fiber for this purpose but this is not a desirable technique in terms of integration, access speed, or tenability.

3.7.2 Large, Ultra-Fast Optical Switching Fabrics:

Switching elements must have response times below 1ns for avoiding latency inefficiencies. The most extended and mature technology for optical switching is MEMS (Micro-Electro Mechanical Mirror Systems) that features switching times on the order of several microseconds. Other switching mechanisms, such as employing electro-optic materials or SOAs (Semiconductor Optical Amplifiers), present the adequate ns speeds. However, significant research must be performed in order to solve the issues hindering their scalability, such as losses, crosstalk, etc.

3.7.3 Control Mechanisms:

The implementation of a light, flexible and efficient control plane is required. A GMPLS (Generalized Multiprotocol Label Switching) control plane seems to be promising for the implementation of OPS. An important field of research is open regarding labeling coding/decoding and swapping techniques, routing algorithms for optical packet networks, and optical QoS matters.

3.8 FTTH and its Application at Home

To increase the network capacity for the in-home environment, RoF technology has the potential to support broadband access for personal area networks (PANs) and short range communications in Femto and picocell networks. Such a broadband infrastructure needs to be very cheap, both in itself but also crucially to install, and so large core diameter plastic optical fibre (POF) has been indentified to offer the advantages of "do-it-by-yourself" installation, easy maintenance and smaller bending radius (5 mm) over conventional silica single-mode or multimode fibres. Meanwhile, the recent commercialization of low power consumption and broadband transceivers at visible wavelengths also add to the potential for the use of POF RoF networks in the home.

The main issue is that the POF has a very low intrinsic bandwidth and so multi-carrier technologies are necessary to increase the data rate it can carry to useful values. For the POF PANs described above, wireless-USB has become a very attractive solution for short range high capacity in-building and in-home links, providing as high as 480 Mbs data rate for personal communication devices. The ECMA-368 alliance for physical and media-access-control layer, wireless-USB standard utilizes multi-band orthogonal frequency division multiplexing (MB-OFDM) to combat with multi-path fading effect in air interfaces, while providing high capacity at the same time. The required bandwidth for each sub-band of MB-OFDM UWB signal is 528 MHz using 122 sub-carriers. The 6 MB-OFDM sub-bands are centred at frequencies from 3.96 to 10.3 GHz.

As data rates delivered to the home rise beyond the Gbs rate, as is already happening in the far-east, it will be necessary to develop multi-tone sub-carrier multiplexing technologies to increase the UWB rates currently available. Cost reduction of the transceiver units will also be necessary in order to commoditize this.

3.8.1 Radio-over-POF for in-Home Networks

Fibre to the home will not be the end game. In order to enable true broadband service delivery up to the end users, fibre networks need to be extended into the user's home itself. Moreover, in order to improve the manageability and upgrading we foresee that the present diversity in in-building network infrastructures (twisted pair, coaxial, CAT5E) needs to be replaced by a single network capable of delivering all types of services. Due to its huge bandwidth, EMI immunity and signal format transparency, optical fibre is the preferred medium. Future research towards in-building networks should focus on finding optical fibre network technologies, which should be easy to install and to maintain. In particular, plastic optical fibre (POF) with large core and large numerical aperture is a very promising type of fibre for easy 'do-it-yourself' installation by unskilled (residential) users. Several flavours of POF can be found including single fibre step- and graded index and multi-fibre variants. The recent multi-core single POF is an interesting candidate, as it features reduced dispersion and increased tolerance to bending losses. These fibre types do have considerable modal dispersion and hence a quite limited bandwidth-distance product. Recent researches on POF is directed in one hand to achieve transmission capacities of multi-gigabit per second using advanced modulation formats and in the other hand to deliver transparently wireless signals over 1-mm core diameter 50-m long fibre. For wireless delivery of services over POF, the bandwidth limitation could be overcome by processing the radio signals at baseband in the optical domain and (down/up)converting them in the antenna sites. Other techniques such pre- and post equalizations could be employed to further increase the bandwidth. Since low-cost transceivers should be used to generate and receive the visible light signals, research on components should be directed to achieve large linear operations and high optical signal to noise ratio. Another aspect worth to consider is to consolidate all microwave radio signal generation and modulation at a central site. The challenge is to carry and route the microwave signals over the highly dispersive and lossy POF. Remote generation of microwave carriers for >60 GHz range could be a major step forward in reducing network costs in terms of installation and maintenance because maintenance and upgrading can be done from one central place. Beam shaping and steering by means of smart antennas and MIMO techniques in single- and multi-core POFs could lead to higher capacity and more robust radio-over-POF networks.

4. Recommendations

Based upon the research priorities discussed above, the following recommendations are put forth in order to address the identified priorities:

R1- Investigate methods to integrate wireless, optical and electronic components. This effort should result in lower cost, lower power consumption optical/wireless transceivers with significantly improved characteristics as compared to transceivers comprising discrete components.

R2- Investigate methods to allow for direct conversion of data signals from one media (i.e. wireless) to another (i.e. optical) without requiring intermediate conversion steps (i.e. electrical). This effort should minimize latency times and power as well as power consumption by the network.

R3- Investigate the tradeoffs between the financial and technical aspects of RoF networks. Some of these tradeoffs would be capital and operational expenses as functions of bandwidth, reach, mobility and repeatability. This effort would provide service providers a better understanding of the costs involved in rolling out and maintaining an RoF network as compared to using either all-optical or all-wireless networks.

R4- Reduce the operational and capital costs of ultra fast broadband using both wired and wireless technology.