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Abstract:

This public deliverable addresses Physical Layer Awareness aspects in 4WARD.

The main objective is to identify how different wireline and wireless channel impairments influence network parameters/characteristics and how this information is being accounted for, therefore, providing the basis for the Physical Layer virtualisation development and implementation related issues.

Wireless channel impairments are explained, being shown how they influence system/network parameters from System, Radio and User perspectives. Wireless Channel Requirements and higher layers features, e.g., Radio Resource Management and scheduling, are also addressed.

Overall this deliverable is intended to provide an inside view of different Physical Layer Awareness perspectives in 4WARD.

Keywords:

Physical Layer Impairments, Wireline, Wireless, Virtualisation.

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Terminology

ABC	Always Best Connected
ADSL	Asymmetric Digital Subscriber Line
ANCP	Access Node Control Protocol
AP	Access Point
ASE	Amplified Spontaneous Emission
ATR	Available Transfer Rate
BS	Base Station
BSS	Basic Service Set
CAPEX	Capital Expenditure
CB-RWA	Constraint Based Routing and Wavelength Assignment
CD	Chromatic Dispersion
CPU	Central Processing Unit
CS	Circuit Switch
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CVRRM	Cooperative Virtual Radio Resource Management
DCF	Dispersion Compensating Fibre
DGD	Differential Group Delay
DL	Downlink
DSL	Digital Subscriber Line
EDGE	Enhanced Data rates for GSM Evolution
EIGRP	Enhanced Interior Gateway Routing Protocol
EPON	Ethernet Passive Optical Network
ESS	Extended Service Set
FDD	Frequency Division Duplex
FEC	Forward Error Correction Codes
FFTC	Fibre-to-the-Curb
ForMux	Forwarding and Multiplexing
FTTH	Fibre-To-The-Home
FWA	Fixed Wireless Access
FWM	Four Wave Mixing
GDR	Group Delay Ripple
GMPLS	Generalised Multi-Protocol Label Switching
GP	Generic Path

GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
HDTV	High Definition Television
HFC	Hybrid Fibre Coaxial
HSDPA	High Speed Downlink Packet Access
HSUPA	High Speed Uplink Packet Access
IBSS	Independent Basic Service Set
INM	In-Network Management
InP	Infrastructure Provider
IP	Internet Protocol
ISI	Inter Symbol Interference
ISP	Internet Service Provider
LASER	Light Amplification by Stimulated Emission of Radiation
L2CP	Level 2 Control Protocol
LAN	Local Area Network
LCAS	Link Capacity Adjustment Scheme
LMP	Link Management Protocol
LoS	Line-of-Sight
LTE	Long Term Evolution
MAC	Medium Access Control
MAP	Mesh Access Points
MBS	Mobile Broadband System
MIMO	Multiple-Input Multiple-Output
MP	Mesh Point
MPP	Mesh Point Portal
MT	Mobile Terminal
NetInf	Network of Information
NLoS	Non-Line-of-Sight
NM	Network Management
OBS	Optical Burst Switching
OCS	Optical Circuit Switching
O-E-O	Optical-Electrical-Optical
OFDM	Orthogonal Frequency Division Multiplexing
ONU	Optical Network Unit
OOK	On-Off Keying

OPEX	Operational Expenditure
OPS	Optical Packet Switching
OSNR	Optical Signal to Noise Ratio
OTN	Optical Transport Network
OWD	One-Way Delay
PDL	Polarisation Dependent Loss
PER	Packet Error Rate
PHY	Physical Layer
PMD	Polarisation Mode Dispersion
PON	Passive Optical Network
POTS	Plain Old Telephone Services
PS	Packet Switch
PSP	Principal State of Polarisation
PTP	Point-To-Point
QoS	Quality-of-Service
RAN	Radio Access Network
RBN	Radio Backhaul Network
RF	Radio Frequency
RTW	Reaction Time Window
RWA	Routing and Wavelength Assignment
SAN	Storage Area Network
SBS	Stimulated Brillouin Scattering
SDH	Synchronous Digital Hierarchy
SGP	Stratum Gatewaying Point
SLA	Service Level Agreement
SMF	Single Mode Fibre
SONET	Synchronous Optical Network
SPM	Self Phase Modulation
SRS	Stimulated Raman Scattering
SSP	Stratum Service Point
TD-CDMA	Time Division-Code Division Multiple Access
TDD	Time Division Duplex
TV	Television
UL	Uplink
UMTS	Universal Mobile Telecommunications System

VCAT	Virtual Concatenation
VCG	Virtual Concatenation Group
VDSL	Very-high-bit-rate Digital Subscriber Line
VHO	Vertical Handover
VNet	Virtual Network
VNO	Virtual Network Operator
VNode	Virtual Node
VNP	Virtual Network Provider
VoIP	Voice over Internet Protocol
WCDMA	Wideband Code Division Multiple Access
WDM	Wavelength Division Multiplexing
WDM	Wavelength Division Multiplexing (or multiplexer)
WEP	Wired Equivalent Privacy
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WMAN	Wireless Metropolitan Area Network
WMN	Wireless Mesh Network
WPAN	Wireless Personal Area Network
XPM	Cross-Phase Modulation

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1. General considerations

New network architectures that allow the co-existence of multiple networks on common platforms through virtualisation of networking resources, while enhancing the utility of networks by making them self-managing, are proposed in 4WARD. These solutions embrace a full range of technologies, from fibre backbones to wireless networks.

The virtualisation of physical network resources enhances the possibility of handling different profiles in parallel with the impression of mutual isolation.

This simple abstraction has well-known limitations with respect to both performance and security. It also implies the use of complex and cumbersome mechanisms in order to deal with mobility in wireless environments.

4WARD has investigated multiple ways of constituting a generic path, that adapt transport functions to the capabilities of the underlying network, and evaluate how it can be implemented taking into account underlying physical and technological constraints. These generic paths represent the abstraction of all possible communication relationships between endpoints, irrespective of their physical realisation across wireless and wireline technologies, making the physical characteristics of paths available to higher layers, leading to enhanced reliability.

The focus is on the specificities of different types of paths, on how they could be abstracted by the resource interface and instantiated using the underlying resources (routers, switches, etc.). Means to allow the composition of a generic path to take the current load conditions and availability into account was also investigated, particularly in the case of intermittent wireless connectivity. Various alternatives for distributing data flow over the multiple paths have been evaluated. Evaluation criteria include the resulting performance and reliability characteristics of the generic path, and the way security with respect to potential misuse is enhanced or compromised in each case.

Another area of application for the generic path concept is mobility. 4WARD's view of a generic path extends the scope of 802.21 [IEEE10] to include wireline techniques, as well as more general topologies in addition to wireless handover. 4WARD designs will also be more comprehensive and be applied to an entire path and not just to a single wireless link.

4WARD aims at the seamless integration of wireless resource management into the future Internet by means of innovative cross-layer techniques that try to hide specific wireless characteristics from the overall transport system. In order to accomplish this, a framework has been developed to handle the radio resources of the wireless interface that is independent of the existing or future technology used. More generally, the control functionality allows integrating the new possibilities offered by future optical and wireless technology (optical burst switching, optical circuit switching, ubiquitous mobility, etc.). While these new technologies will provide powerful tools for establishing generic paths, it is necessary to account for physical layer impairments.

This document is structured as follows. A brief survey of wireline technologies is provided in Chapter 2. In Chapter 3, optical channel impairments are presented and discussed. A survey of wireless technologies is provided in Chapter 4. In Chapter 5, wireless channel impairments are explained, being shown how they influence system/network parameters from System, Radio and User perspectives. Wireless Channel Requirements and higher layers features, e.g., Radio Resource Management (RRM) and scheduling, are also presented. Different perspectives of Physical Layer Awareness, according to different Work Package views on the Theme, are presented in Chapter 6. The way that different issues were addressed in different deliverables is detailed in Chapter 7. Finally, Conclusions are drawn in Chapter 8.

2. Wireline technologies

This section gives an overview of wireline technologies, focusing on optical technologies, and transport networks.

2.1. Convergence to a unified transport network

The evolution of telecommunication networks has seen a shift from “one network one service” paradigm to a situation where many services are delivered over the same network. This trend is the result of a considerable effort made by operators, equipment manufacturers and standardisation bodies in order to bridge and unify previously dedicated core networks and indicates that, in the near future, probably all the major communications domains, like Plain Old Telephone Services (POTS), mobile, Internet, and home entertainment, will use the same underlying core, or transport network, as depicted in Figure 1.

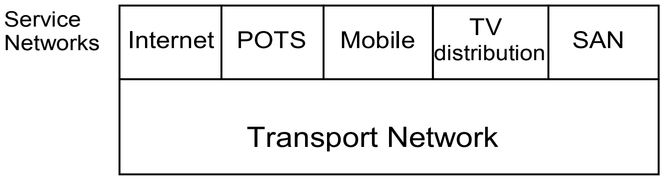

Figure 1 − Network architecture based on a converged transport network.

This unified transport network can even be used to support other service networks that carry particularly sensitive data, as it is the case of Storage Area Networks (SANs). SANs, whose importance has been growing since the 9/11 terrorist attacks, allow customers to periodically backup large databases to remote sites in order to prevent loss of information due to failures or catastrophes in the primary data centre. The transport network must be able to provide high capacity information pipes (paths), as transparently as possible, to the operators of the different service networks. Although, for these operators the primary concern is to guarantee a path with adequate Quality of Service (QoS) at the lowest cost, there are also other features that are expected from the transport network as:

- Excellent flexibility to adjust quickly to changes in the traffic or service patterns and modifications in the physical infrastructures;
- High availability to minimise the effects of node or transmission disruptions, emphasising the importance of using appropriate protection or restoration techniques at the network transport layer;

- High security levels;
- Increased automatisation in establishing and terminating circuits in response to requests from the service networks.

The high capacity requirements of the information pipes supported by transport networks and the big increase in traffic foreseen for the next years, justify that optical technologies, especially fibre optics, are the only possibility to carry traffic in these networks. A number of technologies can be used to construct optical transport networks, detailed in the next section.

2.2. Technologies and paradigms for transport networks

Optical transport networks can be classified into three categories: opaque, transparent and translucent. In opaque networks, the transmission of information is carried out in the optical domain, but all the other networking functions take place in the electrical one. This type of network requires a great number of optical-electrical-optical (O-E-O) conversions, since the optical data is converted into electrical signals at the node input and reversed again for optical at the node output. O-E-O conversions allow handling fine granularity data streams (≥VC-3) while regenerating degraded optical signals. These aspects are still interesting regarding current traffic characteristics. Nevertheless, these conversions represent one of the main costs in high capacity transport networks and, at the same time, a critical bottleneck to achieve faster data transport. The solution is to design all-optical networks, by guaranteeing that functionalities like multiplexing, switching, routing, and protection, are implemented in the optical domain. These networks are also known as transparent optical networks, because the information transmitted in the optical paths traverse the nodes transparently without any O-E-O conversion. In transparent optical networks, in general, the transmission reach of optical signals is limited due to the accumulation of physical layer impairments. Translucent networks emerge as a response to this constrain by using a set of sparsely but adequately distributed regenerators acting in the electrical domain.

Usually, opaque transport networks are based on SDH (Synchronous Digital Hierarchy), or SONET (Synchronous Optical Network) in the USA, in this way requiring a great number of O-E-O conversions along the network. SDH was introduced in early 1990s as a way to provide semi-permanent paths in the core of telephony networks. This technology has led to a significant increase in the capacity of the information pipes available to network operators, Table 1, and, at the same time, enabled a revolution in operation, administration and maintenance functionalities, through the development of powerful management systems.

Table 1 − SDH and OTN signal rates.

SDH		OTN	
Signal	Line Rates [Mb/s]	Signal	Line Rates [Mb/s]
STM-1	150.52	OTU-1	2 666.057
STM-4	622.08	OTU-2	10 709.225
STM-16	2488.32	OTU-3	43 018.413
STM-64	9953.28	OTU-4	≤ 130 000.
STM-256	39813.12		
STM: Synchronous Transfer Module		OTU: Optical transport unit	

Legacy SDH was developed aiming telephony applications and, in that way, it is not efficient in supporting data traffic, especially Ethernet traffic. In order to respond to these limitations, the SDH community has up-graded de SDH standard, introducing new technologies as Virtual Concatenation (VCAT) [ITUT07], [ITUT09a], Link Capacity Adjustment Scheme (LCAS) [ITUT06a] and Generic Framing procedure (GFP) [ITUT08a], leading to the so-called Next Generation SDH [Kart04]. GFP provides a generic mechanism to adapt traffic from higher layer client signals (e.g., Ethernet) to lower layer server signals (e.g., SDH and OTN), VCAT allows to virtually concatenate SDH/OTN containers in a virtual concatenation group (VCG), in order to easily adapt the capacity of semi-permanent paths to the line rates of Ethernet, and supports new routing paradigms, such as multipath routing. LCAS, which acts on VCGs, allows automatically modifying the members of VCG (via the Network Management System) making it possible to dynamically change the capacity of a connection and increases the network flexibility. At the same time, if used in conjunction with multipath routing, it opens new ways to design reliable transport networks, allowing, for example, to implement protection schemes that respond to failures with service degradation [AGRS04].

The development of optical technologies make possible to increase the amount of traffic sent over an optical fibre by sending multiple signals, each one on its own wavelength. This technique, referred to as Wavelength Division Multiplexing (WDM), has allowed achieving huge transmission capacities over optical fibres. Point-to-point WDM systems with capacities of the order of Terabit per second are now commercially available from many vendors, as shown in Table 2.

Table 2 − Capacity of commercially available point-to-point WDM systems.

Vendor	Equipment	Capacity [Tb/s]	Number of wavelengths × line rate [Gb/s]
Ciena	CoreStream	1.9	192 × 10
Alcatel-Lucent	1625 Lambda Extreme Transp.	2.56 1.28	64 × 40 128 × 10
Nortel	Optical Long Haul 1600	0.8	80 × 10 320 × 2.5
Ericsson	Marconi MHL 3000 Core	3.2	80 × 40

Besides the huge increase of capacity, the development of WDM technologies also held the promise of a true all-optical network. This new scenario required new transport overhead not provided by SDH, as well as extended error correction capabilities in order to increase the transmission distance, which explains why recently ITU published a new standard designated as Optical Transport Network (OTN) [ITUT03]. The line rates corresponding to the first three OTN hierarchies are presented in Table 1, while the line rates corresponding to the fourth one are currently under specification, and are expected to be between 112 and 130 Gb/s, aiming to be used as an appropriate container to transport the future 100 Gb/s Ethernet signals.

A number of paradigms have been proposed to design transparent optical transport networks, such as Optical Circuit Switching (OCS), Optical Packet Switching (OPS) and Optical Burst Switching (OBS) [Bona07]. The first paradigm allows establishing end-to-end optical connections, designated as lightpaths, and it is easily implemented using current technologies. However, OCS lacks flexibility in dealing with abrupt changes in traffic patterns and it is very inefficient in supporting bursty traffic, due to its coarse wavelengths granularity. In OBS/OPS networks, several IP datagrams are aggregated, at the edge of the network, in the same optical burst/packet, which is then routed to the destination, in optical domain, using a proper wavelength. OPS provides statistical multiplexing at the packet level, offering, in that way, a large bandwidth utilisation efficiency. However, OPS technology requirements regarding aspects like optical buffering, optical synchronisation, etc., are still too immature for a near term deployment. OBS technological requirements are less stringent, avoiding, for example, the use of optical buffering, by reserving in advance capacity in the network, using out-of-band signalling, since one of the promises of this technology is the separation of the data plane and the control plane [PeMP07]. The fact that the burst duration can be fairly longer compared with the packet duration in OPS, also favours OBS, permitting to use slower components. OBS also supports statistical multiplexing within the individual wavelengths, allowing traffic engineering in the optical domain with finer granularity than OCS.

2.3. The concept of optical Internet

The concept of optical Internet has been around for some time and, fundamentally, enables the possibility of transmitting IP traffic in optical format through transparent optical networks [LiES00], [Wein01]. This concept can be now implemented using the OCS paradigm, while OBS and OPS are seen as medium and long terms solutions, respectively.

The advent of optical Internet will change the way how networks are designed, because aspects such as routing and QoS no longer can be decoupled from the physical layer, a panorama that is quite different from the current IP networks, where such decoupling is taken for granted. In transparent optical networks, optical signals suffer from physical layer impairments, including attenuation, chromatic dispersion, polarisation mode dispersion, amplified spontaneous emission noise, crosstalk and various non-linearities [RaSi02]. These impairments must be taken into account when designing routing algorithms and may prevent using a simple shortest-path-first algorithm, like Dijkstra´s algorithm [Dijk59], to compute light paths within transparent optical networks. Furthermore, these impairments can also have an effect on QoS, because they affect, for example, the blocking properties, since packets for which it cannot be guaranteed a minimum signal quality are disregarded [VCPP07]. The interaction of the physical layer with high order layers even deepens, when using OBS or OPS, since these advanced network paradigms introduce at the optical domain a new level of random behaviour. This behaviour is due, namely, to the additional delays introduced by optical memories required by those technologies, which affects the latency and jitter of the optical packet-switching traffic, and to the impairments introduced by the optical switches that can contribute to increase the packet losses.

Future Internet solutions must rely deeply on optical technologies. Therefore, the challenges faced by Optical Internet must be not ignored when conceiving new paradigms as it is, for example, the concept of generic paths.

2.4. Limitations of the copper based access and the role of optics

The access part of the future networks will work as an aggregation platform that collects traffic from different sources based on different technologies and transfers it to the optical transport layer.

In the current wireline access networks, the term Digital Subscriber Line (DSL) denotes a family of technologies that enables high-speed data transmission over existing copper wires. The most common forms of DSL are Asymmetric DSL (ADSL) and high-speed DSL (VDSL), where the last form is the one that reaches the highest speed. A notable feature of all these technologies is that the line rates decrease significantly as the distance from the customer premises to the local exchange increases, only allowing one to achieve high bit rates for short distances. This trend is clearly shown in Table 3, which gives the theoretical maximum distances corresponding to the maximum line rates obtained with various DSL technologies The actual distances are even lower, because factors such as the quality of the copper wire pairs, electrical interference from outside sources and from other pairs, etc., highly condition the system performance. As a result, DSL solutions are not capable of providing the line rates of several 100 Mb/s foreseen for the next decade, and the only alternative is to introduce optical fibre into the access plant. There are different solutions to achieve this goal, depending on how closer the fibre is from the user. For example, in the Fibre-to-the Home (FTTH) solution, the fibre reaches the users premises, while in the Fibre-to-the-Curb (FFTC) alternative the fibre runs to a platform that serves many users. Each of these users has a connection to this platform using copper wires.

The deployment of optical fibre in the access plant can be done using Point-to-Point (PTP) or point-to-multipoint architectures. In the former architecture, there is one optical fibre running from the local exchange up to every user, while the latter one, designated as Passive Optical Network (PON), uses an unpowered optical splitter to enable a partly shared fibre architecture to serve multiple premises, typically 32. There are two main PON standards: IEEE 802.3ah Ethernet PON (EPON) [IEEE04b] and ITU-T G.984 Gigabit PON (GPON) [ITUT08c]. Both standards support a maximum transmission distance of 20 km, but GPON supports an aggregated bit rate that doubles the value of EPON, Table 3. A new standard that up-grades the EPON to bit rates to 10 Gb/s is now under specification [IEEE07a]. PON solutions are more cost effective than PTP ones, but the latter are more future-proof, because they can easily evolve from the current data rates of 100 Mb/s per user to 1 Gb/s per user. This is due to the fact that in PTP the line rates are dedicated to each user, while in PONs the line rates are shared by the multiple users, served by the network. As a consequence, in a scenario shaped by demands of several 100 Mb/s per user, new PON standards based on an aggregate bit rate of 10 Gb/s are required. These standards involve, namely, the use of 10 Gb/s electronics per user, and put much more pressure on optics than PTP solutions, which can be easily implemented using 1 Gb/s Ethernet technology. The shared nature of the PON structure also poses some security issues and requires, for example, the use of strong encryption techniques to prevent eavesdropping. Furthermore, jamming becomes possible, and the transmission of continuous light by a user, due to, for example, a damaged Optical Network Unit (ONU), is enough to block all the others from accessing the network.

Table 3 − Characteristics of DSL and optical access technologies.

DSL			Optical Access			
Technology	**Maximum distances at the maximum line rates**		**Technology**	**Line rates [Mb/s] Upstream /Downstream**	**Maximum reach [km]**	**Typical splits**
ADSL	2 km @ 8 Mbps		EPON	1250/1250	20	16
ADSL2+	0.9 km @ 24 Mbps		GPON	2488/2488	20	32
VDSL	0.3 km @ 55 Mbps		100BASE-BX	125 (per user)	10	PTP
VDSL2	0.2 km @ 100 Mbps		1000BASE-BX	1250 (per user)	10	PTP

The optical access solutions are now gaining momentum around the world, with many operators implementing these solutions as a way to respond to the broadband requirements imposed by bandwidth intensive services like, for example, IP TV/HDTV. The changing of the regulation panorama, as occurred, for example, in USA, where the Federal Communications Commission made an important policy decision in 2003 to free fibre-based solutions from unbundling regulations, as well as the fierce competition between incumbents, alternative operators and cable operators, are also other driving factors for the fibre based access networks. PONs are the preferred solutions for the operators involved in the deployment of fibre in the access, because they are the most cost-effective solution, due in part, to the fibre savings and to port savings obtained in the optical distribution frames in the central offices.

3. Optical Channel

This section describes the main impairments that occur in a long haul transmission on optical fibre (typically in the context of core optical networks). Many reference documents on optical fibre transmission can be found in the literature and in standardisation bodies. The description of impairments is intentionally simplified, and the reader may consult references for more detailed descriptions.

3.1. Optical channel impairments

Degradations that affect signal propagation can be classified as linear and non-linear [JoJo96], [Agra89]. Linear degradations do not depend on signal power. Non-linear degradation is more complex, depend on channel power and induce interaction between channels.

3.1.1. Linear effects

The main linear effects are:

- Amplified Spontaneous Emission (ASE);
- Polarisation Mode Dispersion (PMD);
- Chromatic Dispersion (CD);
- (linear) Crosstalk;
- Filtering.

Amplifiers are periodically placed in a fibre link in order to compensate for fibre loss α (in dB/km), and to maintain sufficient signal power at receiver side. During the amplification phase, spontaneous emission of decorrelated photons generates "noise". Noise is also amplified along successive amplifier stages. Noise contributes to the degradation of the Optical Signal to Noise Ratio (OSNR), which represents the ratio between useful signal power and noise. Receivers are characterised by the minimum level of OSNR they can accept for successful detection. This minimum value depends on many parameters, such as received power, modulation format, bit rate, and FEC (Forward Error Correction) codes use [ZBPC02].

So-called penalty in terms of OSNR is the amount of additional OSNR required for having "good performance". One usually reserves a "margin" on the OSNR minimum value in order to take into account different penalties due to other effects (e.g., CD).

PMD comes from a non-perfect isotropic medium that causes variable birefringence along the fibre. It is usually modelled as a concatenation of small birefringent sections with variable coupling conditions between each other. This results in the creation of two principal states of polarisation that fluctuate in time and along which the signal is decomposed. As a result, the two components of the signal propagate with different speeds and create Inter-Symbol Interference (ISI) at the receiver, Figure 2. Time delay between both orthogonal components is referred to as DGD (Differential Group Delay) and its mean value is called PMD (expressed in ps/km$^{1/2}$).

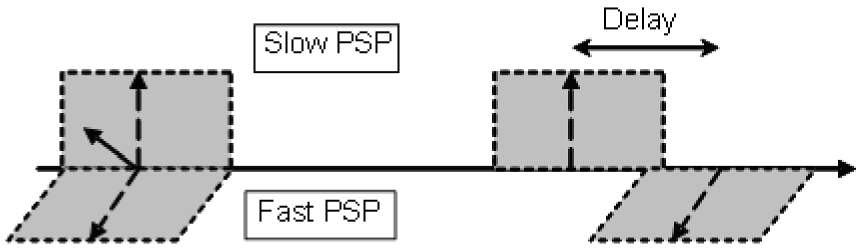

Figure 2 − Schematic of signal decomposition along both slow and fast Principal States of Polarisation (PSP).

Time delay has a random behaviour depending on polarisation state in the fibre and varies with frequency and time [KoJo02]; such behaviour is modelled by a Maxwellian distribution. From the system view point, mean DGD (i.e., PMD) should remain below a fraction “*a*” of bit duration in order to guarantee good performance; the value of “*a*” depends on the dedicated margin reserved for PMD, required outage probability and receiver sensitivity to PMD. A typical value for “*a*” is 10% [ITUT06b].

Second order PMD due to frequency has to be considered when group delay is greater than 15% of bit duration.

CD is due to fibre index and filter phase dependence on the wavelength, resulting in group velocity dependence on wavelength. As modulated signals have extended spectra, CD tends to speed up spectral components of the pulses with higher wavelength while slowing down components of the pulses with lower wavelength (with positive CD; the effect is inversed if CD is negative). This results in a widening of the pulses in time domain (no effect on the optical intensity spectrum). CD is expressed in ps/nm/km, which refers to this group velocity delay for 1 nm space after 1 km propagation.

CD cumulates linearly with fibre length and may eventually result in ISI. In order to reduce its effect at the receiver, negative dispersion fibres (Dispersion Compensating Fibres - DCF) are periodically placed along the transmission line. The use of inline DCF leads to an increase in transmission attenuation and thus an increase of noise level of amplifiers to compensate for additional loss. DCF are usually placed in the interstage of amplifiers. Dispersion management consists of optimising inline dispersion in order to keep residual dispersion within receiver tolerance while keeping the amount of extra noise and non-linear effects at an acceptable level. Dispersion maps represent the evolution of cumulated dispersion in the line as a function of distance, Figure 3.

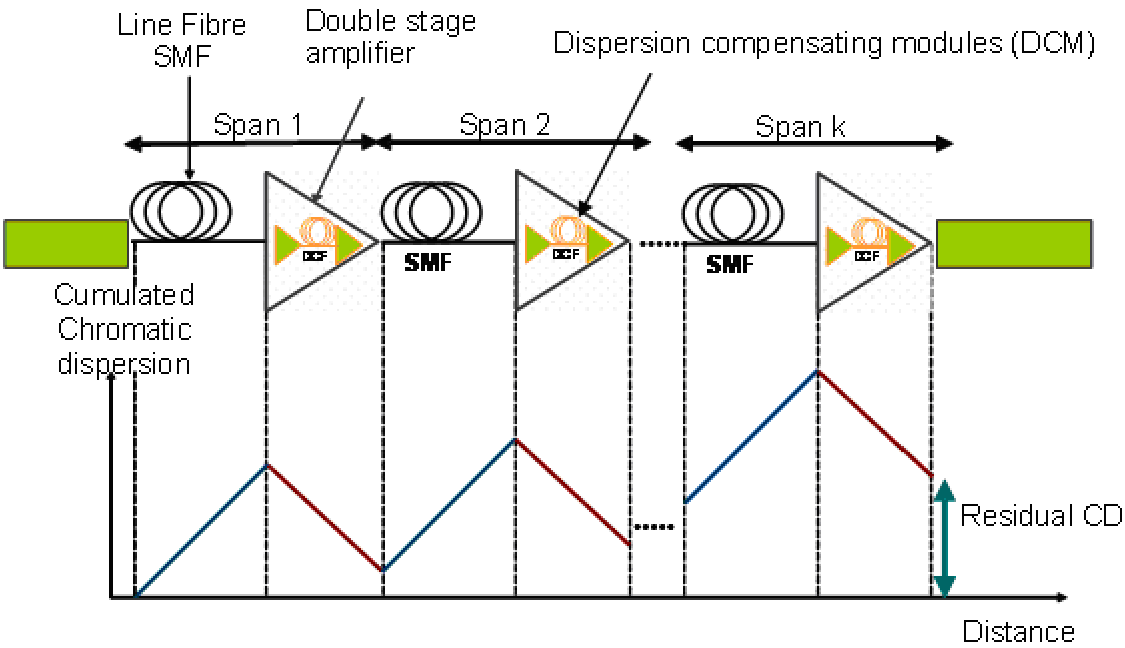

Figure 3 − Schematic evolution of CD in a link: fibre and DCF.

Receivers usually accept a certain amount of distortion (related to residual CD) depending on parameters such as bit rate and modulation format. Receiver sensitivity is usually defined as a penalty function of residual dispersion.

Polarisation Dependent Losses (PDLs) [ZBPC02] are due to devices such as filters, isolators, optical amplifiers that have different losses (or gain) as a function of polarisation state. PDL increases with the number of devices in a statistical manner. In order to limit the impact of PDL in system transmission, PDL values should be small (typically below 0.3 dB).

Crosstalk is of two natures: coherent or non-coherent depending on the unwanted source that interacts with useful signal [JoJo96]. Coherent crosstalk is due to a parasitic signal on the same wavelength as the useful signal. Non-coherent crosstalk is due to power contribution of channels at different wavelengths. This effect appears when filtering or switching functions do not isolate enough channels [ShGu99].

Filtering affects signal intensity because it narrows the useful optical bandwidth and this can affect side bands. This effect increases with the number of cascaded filters. Filtering degradation on intensity cannot be compensated for. Filtering effect on signal phase is an addition of phase ripples (Group Delay Ripple - GDR) producing locally an uncertainty on CD within signal bandwidth, resulting in ISI that cannot be compensated for [RhMK03]. This effect is enhanced if the ripple frequency is of the same magnitude as the signal bit rate, and if the centre of the filter is detuned compared to the signal wavelength.

The filtering effect can be included as a constraint on wavelength stability of LASERs, filters recommendation on centre frequency and bandwidth accuracy and on a maximum number of (different) filters that can be cascaded.

Some other effects exist that can be neglected in the context of classical 10 Gb/s long haul DWDM transmission compared to that presented above: extinction ratio of modulators, frequency response of receivers, slow detuning of filters, etc.

3.1.2. Non-linear effects

Non-linear effects are due to material intrinsic properties that depend on power (refractive index, loss, etc.) [EsRM02]. This dependence leads to inter-channel and intra-channel interactions that are enhanced with signal peak power, propagation distance, type of fibre, wavelength, and channel spacing. One can classify main non-linear effects that impair standard 10 Gb/s long haul transmissions as:

- Kerr effects due to refractive index power dependence. They are Self Phase Modulation SPM, Cross-Phase Modulation, XPM and four wave mixing (FWM);
- Scattering effects such as SRS, (Stimulated Raman Scattering) and SBS, (Stimulated Brillouin Scattering), [Agra97]. SRS and SBS effects are negligible compared to SPM, XPM and FWM at 10 Gb/s bit rate.

Self phase modulation tends to broaden signal spectrum. In the presence of CD this leads to the broadening of pulses that is comparable to CD but cannot be compensated for. This broadening results in ISI. SPM is the most important non-linear effect in 10 Gb/s On-Off Keying (OOK) transmissions when channel spacing is greater than 100 GHz.

Cross phase modulation occurs due to the index modification caused by neighbouring channels. XPM is all the more important as channel spacing is small and contributing channel wavelengths are close. The effect is enhanced when channels propagate with the same group velocity and when peak power of pulses is big (i.e., for low values of CD). With 50 GHz spacing, XPM is viewed as an important contribution to performances degradation).

Four wave mixing results in the creation of parasitic pulses due to power exchange between channels. It affects neighbouring channels due to power fluctuation of peak signal pulses and creation of ghost pulses. Compared to SPM and XPM this effect is not dependant on channel bit rate, and only depends on channel spacing and power.

Correct estimation of system performance requires that performance should be guaranteed until the end of life (knowing that usual system exploitation time is estimated around 10 to 12 years). End of life condition is usually included as an OSNR margin.

3.2. Conclusion on effects and impact on network design

An important conclusion on the description of the different effects affecting optical transmission is that they are very dependent on system parameters, such as bit rate and modulation format. The way impairments are compensated for is also very dependent on system vendors' technological choices.

A second important point to note is that these different effects are also very dependent on the fibre infrastructure quality: one should first note that there are different standards for fibres (e.g., [ITUT09b], [ITUT09c], [ITUT06c]), and that although standards give ranges and nominal values for fibre characteristics, fibres of a given standard deployed in the field usually present variable physical characteristics [BTGF03]. This resulting diversity forces operators to build huge databases with span and trunk characteristics, and it also forces system makers to adapt their transmission systems to each particular link to be deployed. One typical example is the diversity of amplification span loss to be handled within one transmission link that ranges from several dB to more than 30 dB.

Finally, one should remember that the cost for deploying new cables is prohibitive (from several k€/km to several 10 k€/km depending on deployment conditions) and that operators prefer to exploit their installed infrastructure.

These general considerations lead to the conclusion that physical effects have a strong impact on network architecture:

- The possibility to deploy links depends on system performance and fibre characteristics, thus, forcing some particular routes inside the existing infrastructure, or forcing some sites to regenerate the signal;
- System performance and fibre characteristics may also force to reduce system capacity in use (e.g., use a reduced number of channels in order to provision extra OSNR margin for impairments);
- Current systems have low inter-working capabilities resulting in the definition of mono-vendor (and sometime mono-generation) zones;
- Increase of deployed system capacity through higher bit rate channels is restricted to eligible links with respect to performance and is also dependent on system channel

occupation (mixing bit rates in current systems imposes a spectral separation between different channels). In other words migration paths from current systems to next generation higher bit rates have to satisfy mixed impairment constraints;

- Physical effects impact on architecture is even more important with the introduction of transparent and translucent networks;
- Indeed the design of networks is highly dependent on physical performance (equipment and fibres) especially concerning the placement of regeneration points or the definition of transparent islands;
- Although transparent nodes are by definition transparent to bit rate and modulation formats (to a certain extent), one must keep in mind that system evolution comes with performance evolution and that network design should be adapted accordingly;
- Besides planning constraints, transparency at the optical layer introduces complexity in the management and operation of the network. Translucent or transparent networks operate lightpaths with a reduced access to digital information carried by channel overhead (such as trail trace identifier and checksum). Management functions such as performance management, fault management (detection and isolation), and configuration management (lightpath provisioning with impairment constraints) are expected to be impacted, and may require additional monitoring functions at the optical layer (e.g., discussions are in progress on this subject in ITU Question 6 Study Group 15, [ITUT04]).

3.3. Impact on network parameters

The main parameters characterising optical networks are availability and throughput, and, in the particular case of transparent or translucent networks, reach and transparency.

All presented effects have directly or indirectly an impact on the transmission system reach. This means that during network design, the length of deployed links has to be adapted to cope with identified impairments. Once the systems are deployed, and if the transmission systems are correctly designed, impairments have no or little visible effects, and system transmission is reputed to be "error free". Practically this means the bit error rate is far below 10^{-9}, (which means less than one error every 0.1 s at 10 Gb/s) [ITUT00]. However, due to the stochastic nature of some effects (e.g., PMD) this bit rate is only guaranteed for a limited period of the year, which is called system availability. Availability of terrestrial systems is recommended to be over 99.999% of the time (around 5 minutes unavailability in one year) [ITUT88].

It may happen that a deployed system cannot be exploited with their full capacity, which can be due to limited system performance or unexpected aging of the systems. Reducing the number of channels in service can lighten the constraints on the system to cope with this situation. In the context of transparent networks, mixing the channel bit rates or using transparent nodes with insufficient performances may also force to reduce the possible number of in-service channels.

In a deployed opaque network (with all nodes being opaque), the transmission reach is almost not limited thanks to the regeneration points at each hop. The case of transparent or translucent networks is different as the feasibility of a transparent lightpath may not be guaranteed. In this case, impairments have a strong impact on the length of feasible transparent paths. In the context of core networks, it may be desirable for CAPEX or OPEX reasons to reduce the amount of optical to electronic conversion for transit traffic. A high sensitivity to impairments will reduce the savings potential imposing numerous regeneration points for lightpaths. Table 4 summarises the relation between the presented impairment and network parameters in the context of a deployed network, with standard transmission systems. Note that the relations are very dependent on the context (systems, bit rate, modulation formats, fibres, switching technology of transparent nodes, etc.)

Table 4 − Relation between the impairments and network parameters.

	Availability	**Throughput**	**Reach**	**Transparency**
ASE			X	X
CD		X	X	X
PMD	X		X	X
PDL	X		X	X
Crosstalk		X	X	X
Filtering		X	X	X
SPM			X	X
XPM	X	X	X	X
FWM	X	X	X	X
Aging	X	X	X	X

3.4. Optical layer awareness

As explained in the previous section, there are two main situations where physical impairments should be taken into account: planning and network operation. One focuses here on the network operation situation. As opaque networks are especially designed to guarantee the quality of transmission link by link, physical layer awareness is usually reduced to a single parameter: loss of light. The knowledge of physical impairments is not required at higher levels to operate such networks. One thus focuses in this section on transparent and translucent networks for which physical layer awareness is seen as a major requirement particularly for control plane functions.

3.4.1. Quality of transmission

In transparent/translucent networks, the notion of neighbour is not only related to the existence of a physical medium between nodes, it also requires that the transmission between the nodes should be assured with the minimum required quality of transmission, that one calls "physical feasibility". This may not be granted for all transparent lightpaths. Although preliminary study shows that extension of existing protocols (such as LMP in the GMPLS protocol suite) may solve this issue there is still active work in this domain to automate processes [BeRS04].

Topology discovery and path computing should only include feasible paths also with respect to impairments. This point is closely related to quality of transmission estimation and the well known CB-RWA introduced by [RDFH99] and largely explored since then with various modelling methods [YaRa05], [CaCM05], [SLSD05], [APMS07], [PGWV06], [LLLB07] and [ITUT08b]. Still, the physical feasibility problem raises issues like the reliability of the estimation and the construction and update of the physical databases required for physical modelling.

An alternative to physical aware routing consist in introducing an extension to the signalling process in order to collect impairments along the path during the signalling process [CAVC04], [Mart08], [Bern08]. In this way it is possible to reduce the amount of data to be collected throughout the network (while maintaining a reduced local database), thereby solving the problem of scalability and database consistency of impairment aware routing [MPCW06]. This method however does not allow optimising path computation as paths are computed without taking into account impairment.

Last, one notes that quality of transmission estimation is not always taken as the physical criterion, and that test-traffic probing may also add reliability during the path selection process [PiLMo7].

3.4.2. Wavelength continuity

Besides the constraints due to impairments, setting up lightpaths in a transparent/ translucent network requires to take into account the continuity constraint. This means that, as no (or reduced) optical to electrical conversions and no (or reduced) wavelength conversion are allowed in such networks, any lightpath should use the same wavelength from source to destination. This problem is often referred to as the Routing and Wavelength Assignment (RWA) problem, [RaSi95]. This problem, which has been widely studied in the context of network planning [ZAPR04], now also gains interest for network operation, [SGCC07], [Bern08b], and WSON signalling Supplemental Information for Wavelength Assignment ([Bern08b]). Basic proposed solutions consist in extending signalling protocols, collecting all free wavelengths along the path and taking a decision on the wavelength to be reserved at the downstream end node. Routing solutions centralising or distributing information on wavelength occupation, may suffer from scalability issues as well as database inconsistency.

3.5. Conclusion

In conclusion, one would like to stress that although studies on impairment-aware network planning are quite old, only recent studies have focused on physical layer awareness in network operation. Recent publications in the literature as well as in standardisation bodies show that interest in this domain is growing mainly driven by the deployment (predicted or ongoing) of transparency in optical networks and on the maturity of control plane solutions.

4. Wireless technologies

In this section a description of current mobile wireless and cellular technologies is made, the radio interface being the main focus.

4.1. Introduction

As a result of technological developments in different domains, several physical media support nowadays telecommunication systems. The classical wireline media (copper, coaxial, fibre) have developed worldwide thanks to the telephony system (that consists in spreading copper wires along almost all households, which can be interconnected to enable a voice connection) and afterwards, to the Internet, that explored more performing media, such as fibre that also were spread worldwide. As a result from these developments, a consolidated network connects nowadays the whole world, providing fast connectivity to end users.

The radio frequency medium has also been intensely explored by several wireless technologies, Figure 4. Initially, it was used for long distance and satellite communications, providing an efficient wireless way to reach areas that otherwise would be difficult to. To satisfy this need of more easy access to services, wireless access technologies also evolved strongly, providing wireless, mobile and seamless communications to end users. In this direction evolved telephony, with cellular systems such as GSM (Global System for Mobile Communications) and UMTS (Universal Mobile Telecommunications System), and Internet access, with Wireless Local Area Networks (WLANs) and WiMAX. This has opened the market to innovative solutions, efficient and performing wireless access representing nowadays one of the key drivers of telecommunication research and development.

Wireless technologies are moving from access technologies to backbone ones, interconnecting nodes that originally were interconnected by wires or fibre, opening new challenges. Wireless technologies are not anymore only used as access technologies. Examples are, e.g., the current interconnection of UMTS base stations via point-to-point microwave links or with FWA (Fixed Wireless Access) systems. IEEE 802.16j [IEEE09] relay-based deployment concepts is also foreseen for UMTS Long Term Evolution (LTE). Additionally, there is a strong development of wireless mesh networks, an emerging two-tier architecture based on multi-hop transmission, with two fundamental objectives: to offer connectivity to end-users, and to form a self-organised wireless backbone.

Thanks to this development of different media for transmission of telecommunication systems, services have become world-wide available, reaching almost every person in the world. In the communications future, users will claim the availability of new and more services, neglecting the underlying systems in use [FeSC06]. Users simply aim to be always best connected. Research and development on wireless communications is evolving side by side with this idea, where integration, inter-working and convergence of systems are becoming a closer reality.

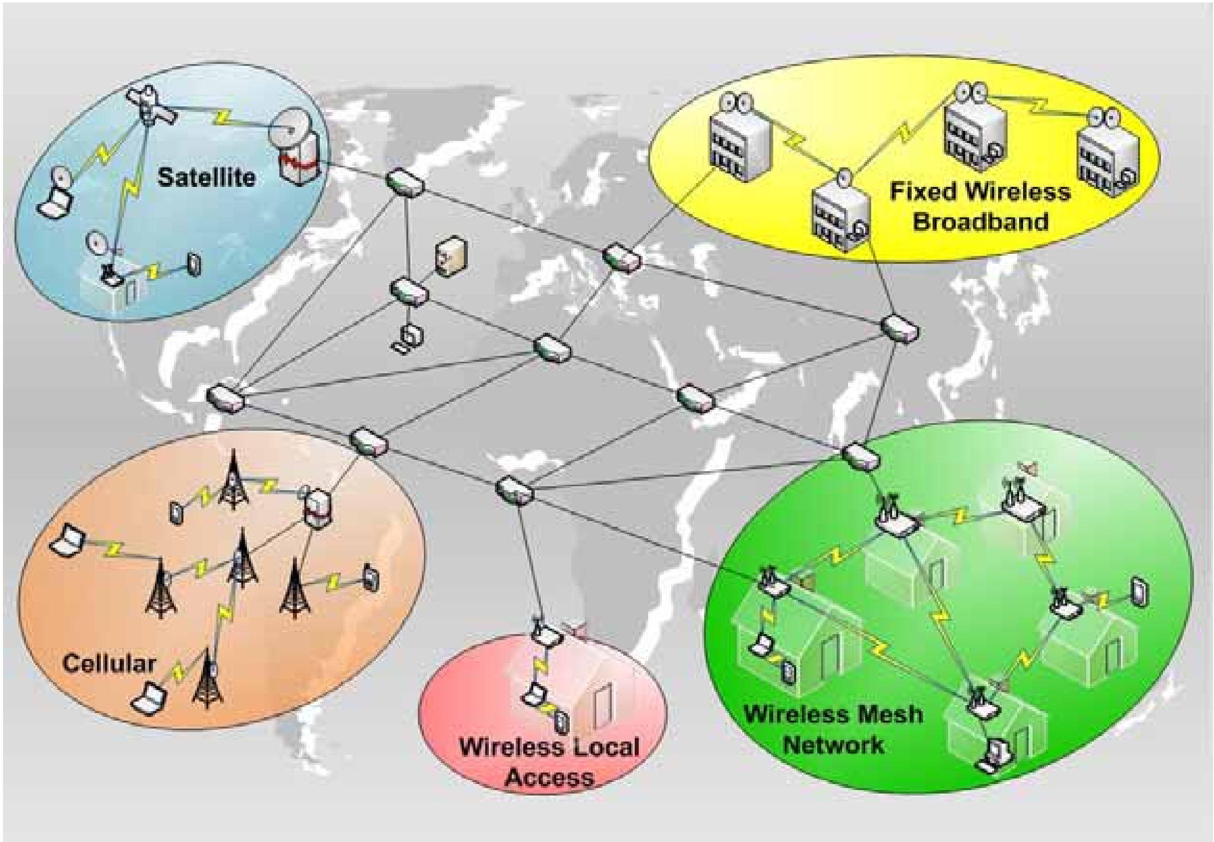

Figure 4 − Wired and Wireless Systems in telecommunication networks.

4.2. Wireless local area networks

WLANs were designed in order to be the wireless version of fixed computer networks, the so called Local Area Networks (LANs). WLANs architecture may be divided in two operating modes: infra-structured and ad-hoc.

Infrastructure, is the most popular and important mode, basically supporting a wireless Physical Layer (PHY) and a Medium Access Control (MAC) one, these two layers being transparent to the wired LAN upper layers, which enables access to the wired network and interfaces to the logical data link and management layers. Besides this, it can also provide additional functionalities, like terminals mobility among the different Access Points (APs).

The ad-hoc architecture allows terminals to establish direct links, transferring data without additional equipment, being useful for data transfer among closely located users, enabling many network applications. In this environment, an important feature can be established, coverage extension, which can be accomplished by having a terminal connected to the outside world (infrastructure), and at the same time being ad-hoc mode with other terminals. Thus, by combining these two modes, one ends up in fully multi-hoping environment networks, where, for example, a shadowed terminal may reach the “outside world” via a multi-hopping protocol network.

Primarily, in this type of networks, the bearer service was basically data, however, voice and video, generally real-time applications are also supported, due to the high capacity in data transmission, which reduces delay to a minimum, QoS being based typically on the throughput and packet delay. Issues like security, mobility management, channel access procedures, channel interference, network planning, network access control, and physical resources management, are different from the LAN wired world.

WLANs have a large capacity compared to others types of wireless networks; however, this characteristic is accomplished by sacrificing other aspects, like coverage, for instance. This high capacity is quite related to the channel throughput (on the order of 10 Mb/s), which is supported on a wideband channel (in the order of 10 MHz).

In order to guarantee users mobility, besides users in a WLAN environment usually operating their terminals in a quasi-stationary manner, the network coverage must be homogenous, therefore, in large networks frequency reuse factor techniques are applied. WLANs at their “natural environment” are currently the “best” Radio Access Networks (RANs) enabling all types of applications, which can be supported over the most common packet switching protocol, the Internet Protocol (IP).

A typical characteristic of a WLAN is that user throughput decreases when the distance between a user and an AP increases, leading to non-uniform throughput coverage. Therefore, WLANs deployment should be carefully designed, in order to maintain user satisfaction in all areas assumed to be covered.

WLANs have several advantages and disadvantages, some of them already mentioned; one that is probably the most interesting is the overall low cost, both at the operational/maintenance and deployment levels. The infrastructure equipment cost is very low compared to other wireless access networks, or even in some particular case to wired ones. Thus, a WLAN is an important competitive technology in low mobility hot spot areas.

In these networks, billing can have different strategies, depending on the network deployment entity, which can be private or public. In private WLANs, installed essentially in company’s buildings, university campus or similar, billing is usually absent, users’ authentication being the main concern. In public WLANs, installed mainly in hotspot areas (e.g., airports or shopping areas), users, when authenticated, are charged as a function of connection time or traffic volume, or more recently with a flat rate. In some cases, the user account is shared with other wireless networks.

The current state-of-the art in WLAN technology is based on the 802.11'x' family. There are currently three main physical layer specifications in the family: 802.11a, 802.11b and 802.11g, [IEEE99a], [IEEE99b] and [IEEE03a]. All of them are based on the use of the Ethernet protocol, and Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA), being upgraded versions of the former 802.11, with data rates of 1 and 2 Mb/s. Available data rates ranges from 11 Mb/s in 802.11b (with a fallback to 5.5, 2 and 1 Mb/s) to 54 Mb/s in 802.11a/g. The main parameters of the IEEE 802.11 WLAN family are presented in Table 5.

Table 5 − IEEE 802.11 WLAN physical layer family basic comparison.

Standard	**IEEE 802.11**	**IEEE 802.11b**	**IEEE 802.11a**	**IEEE 802.11g**
Access	CSMA/CA			
Coding and Modulation Schemes	FHSS, DSSS BPSK and QPSK	CCK/DSSS QPSK	OFDM with [64, 16]QAM, QPSK and BPSK	CCK for DSSS with QPSK OFDM with [64, 16]QAM, QPSK e BPSK
Throughput [Mb/s]	1 and 2	1, 2, 5.5 and 11	6, 9, 12, 18, 24, 36, 48 and 54	1, 2, 5.5, 6, 9, 11, 12, 18, 24, 36, 48 and 54
Frequency Bands [GHz]	2.4 – 2.4835		5.150 – 5.250 5.250 – 5.350 5.725 – 5.825	2.4 – 2.4835
Channel Bands [MHz]	3×25	3×25	8×20	3×25
Power levels	1W, 100mW, 10mW/MHz	1W, 100mW, 10mW/MHz	1W, 50mW, 250mW	1W, 100mW, 10mW/MHz

Three basic topologies are supported in 802.11b WLANs, the Independent Basic Service Set (IBSS), the Basic Service Set (BSS), and the Extended Service Set (ESS):

- IBSS configurations are also referred to as an independent network. Logically, an IBSS configuration is analogous to a peer-to-peer office network in which no single node is required to function as a server. In IBSS, APs can communicate directly with one another, generally covering a limited area;
- BSS configurations rely on an AP that acts as the logical server for a single WLAN channel. While it may seem that the AP adds an unnecessary layer of complexity, it is actually necessary to perform the wired-to-wireless bridging function, and to connect multiple channels;

- ESS configurations consist precisely of multiple BSS cells that can be linked by either wired or wireless backbones; the wireless interconnection of BSS follows a mesh topology.

The 802.11b MAC layer defines both a frame format and a MAC scheme that differs from standard Ethernet. This frame format enables a number of features, such as fast acknowledgement, handling hidden stations, power management, and data security. Nevertheless, the access to the medium is based in contention (nodes compete for the access to the medium on a packet basis), not guaranteeing nor QoS nor fairness.

Besides the basic 802.11 standard, in its a, b and g versions, IEEE also defines other additional amendments/standards, as follows:

- IEEE 802.11d, dealing with information exchange between systems; local and metropolitan area networks, where specific requirements are defined at MAC and PHY layer specifications [IEEE01];
- IEEE 802.11f is a recommendation for multi-vendor AP interoperability [IEEE03b];
- IEEE 802.11h is an amendment to spectrum and transmitted power management extensions in the 5 GHz band, defining mechanisms that may be used to satisfy regulatory requirements for operation in Europe [IEEE03c];
- IEEE 802.11i includes a definition of Wired Equivalent Privacy (WEP) for backward compatibility with the original standard, which provides more robust data protection [IEEE04a];
- IEEE 802.11e is an amendment that defines a set of QoS enhancements for wireless LAN applications through modifications to the MAC layer. The standard is considered of critical importance for delay-sensitive applications, such as Voice over Wireless IP (VoIP) and Streaming Multimedia. The amendment has been incorporated into the published IEEE 802.11 standard [IEEE07b].

It should be noted that there is a significantly larger number of amendments that are not referenced herein. The ones presented herein are the ones being considered most relevant within the scope of this document.

Due to the current WLAN success, the future sounds very promising, since new incoming systems are already being developed.

The IEEE 802.20 Mobile Broadband Wireless Access, which is also known as Mobile-FI, aims at enabling high throughput data rate Non-Line-of-Sight (NLoS) links for vehicles and trains travelling up to 250 km/h in a metropolitan area network environment.

The 802.20 will support data rates of greater than 1 Mb/s at ranges of 15 km or more, operating in licensed bands below 3.5 GHz. It will incorporate global mobility and capability for roaming support, supporting real-time traffic with extremely low latency (20 ms or less), i.e., VoIP; the typical channel bandwidth will be less than 5 MHz. The 802.20 working group aims to provide spectral efficiencies, sustained user data rates, and numbers of active users that are all significantly higher than achieved by existing mobile systems. In support of these goals, the 802.20 will design new PHY Layer and MAC layers optimised for packet data and adaptive antennas.

Additionally, the IEEE 802.21 standard defines services in the 802 family that enable and enhance handover between heterogeneous systems. IEEE defines the 802.11n amendment based on previous 802.11 standards by adding Multiple-Input Multiple-Output (MIMO) and Orthogonal Frequency Division Multiplexing (OFDM). MIMO uses multiple transmitter and receiver antennas to allow increased data throughput through spatial multiplexing and increased range by exploiting the spatial diversity and the use of special coding techniques.

4.3. Cellular networks

The general cellular network architecture is basically characterised by the radio stations, the Mobile Terminal (MT) and the Base Station (BS), and the corresponding Base Station Controllers, the Mobile Switching Centre being the most important component where all communications are processed. The operator can manage the whole network via an Operation and Maintenance centre.

The allocated frequency bands depend on systems and countries; nevertheless, one can typically find cellular systems operating in frequency bands ranging from 0.4 up to 2.2 GHz. Additionally, spectrum usually is licensed and allocated to operators, being regulated by international or governmental regulators.

Formerly, the main service in these networks was voice, supported on a Circuit Switch (CS) technology, however, the Packet Switch (PS) world has converged to cellular networks, and currently cellular networks have a multitude of multimedia services, ranging from simple Machine-to-Machine messaging to video telephony or virtual reality communication. Other feature concerning services is roaming, enabling users to use a mobile device in virtually any country, this being an enormous success, thanks to a global networks standardisation.

Cellular networks are conceptually related with high coverage and mobility, meaning that these networks are oriented to provide high mobility without any noticed QoS degradation.

These networks have a huge importance, from the coverage point of view, typically characterised by a high percentage of geographical or population coverage.

It is expected that when these networks achieve complete maturity, it is almost virtually impossible to find a region that is not covered, practically at all speeds. Usually, the cellular concept is related to cellular terrestrial networks, however, it can be related with satellite systems, which can establish a cellular topology at the earth surface. Thus, it is possible to have coverage beyond the continental ground, and have it on high sea as well.

From the capacity point of view, cellular network operators can easily adapt their systems to the required capacity, being typically supported on a hierarchical cellular and layered structure, which can be adaptable to: hotspot areas, urban, suburban and rural areas, by using pico-, micro- and macro-cells, and in the near future femto ones. Cellular networks QoS may vary, depending on the geographical region and its traffic density, and of course on the network planning quality itself.

Due to the historical evolution and continuous innovation, billing in these networks is based on a very complex model, enabling a large number of user's billing profiles and services differentiation. Nevertheless, the most important are the time and information volume driven billing systems.

Currently, the most used cellular systems in Europe are GSM, primarily designed for voice, and UMTS, [HoTo00]. The General Packet Radio Service (GPRS) network is an "always on", for data, being based on the existing GSM network; using the existing GSM network to transmit and receive IP based data. GSM/GPRS has been updated to Enhanced Data rates for GSM Evolution (EDGE), being an upgrade to GPRS radio interface that increases data throughput, hence, being referred to as EGPRS, and reaching up to 384 kb/s.

Concerning UMTS, currently only the Frequency Division Duplex (FDD) mode is being used, the Time Division Duplex (TDD) one not being in commercial use, [3GPP00c], [3GPP00d]. This mode uses Wideband Code Division Multiple Access (WCDMA), the carried services being characterised by their symmetric traffic, like voice, and being deployed in every kind of environment, particularly in micro- and pico-cells.

As previously referred, capacity is a key issue in cellular systems. Capacity in UMTS depends mainly on transmitted power, users' behaviour (used services, bit rate), quality network targets (blocking and delay), multipath fading, signalling, and handover schemes.

More recent releases of UMTS, like HSDPA and HSUPA (High Speed Downlink and Uplink Packet Access), have extend the data rate up to 14.4 and 5.4 Mb/s, respectively, being expect that future releases, under LTE (Long Term Evolution), will further increase these values to the order of several 100 Mb/s).

The cellular future vision is currently divided in two perspectives. One expresses that the next generation will be a brand new radio interface, which leads to a standalone Mobile Broadband System (MBS); the other concerns the next generation network concept as a Radio Access Network integration vision, being assumed two main components, a common Core Network and a multi system MT. The main advantage of this latter concept is that it takes the best advantage of existing and available wireless networks, thus, a next generation MT must support multiple wireless systems, while implementing the existing wireless systems protocols and the new amendments, which allow seamless handover between different wireless systems.

4.4. Fixed wireless access

In order to offer end users a high speed broadband access in the called "last-mile" network part, several solutions were defined. These solutions include the Digital Subscriber Line (DSL) group of technologies that are generally referred to as xDSL, Hybrid Fibre Coaxial (HFC) network, which is a technology being developed by the cable TV industry to provide two-way, high-speed data access to the home using a combination of fibre optics and traditional coaxial cable, Fibre-To-The-Home (FTTH), which is basically offer optical fibre access to a subscriber, and a fixed broadband wireless access network (sometimes referred as wireless DSL). These networks differ from mobile wireless by the fact that the endpoints in fixed wireless solutions are stationary, and therefore much less susceptible to limitations imposed by radio propagation in wireless mobile environments.

A Fixed Wireless Access (FWA) network operator traditionally provides radio access to fixed users, like companies, being an alternative to wireline. In these networks, capacity can vary, due to link capacity sharing among end users. Moreover, coverage and capacity, like in cellular systems are related, meaning that, low traffic leads to bigger coverage than high traffic case.

A classical FWA system usually provides fixed services on non standard technologies; in fact, these broadband fixed wireless accesses were typically used for Line of Sight (LoS) and PTP communications. Do to these characteristics, and without been able of providing mobility to end users, these systems were always kept absent of the mobile and wireless world, but this is not true anymore, Worldwide Interoperability for Microwave Access (WiMAX) being a standards-based wireless technology that provides high-throughput broadband connections over long distances. WiMAX can be used for a number of applications, including "last mile" broadband connections, hotspot and cellular showing, and high-speed connectivity for companies.

An implementation of the IEEE 802.16 standard, WiMAX provides metropolitan area network connectivity at speeds of up to 75 Mb/s.

IEEE 802.16 has developed a Point to Multi-Point and mesh architecture broadband wireless access standard [WiMa05]; the standard covers both the MAC and the PHY layers. The spectrum allocation includes [10, 66] GHz for LoS, and a sub 11 GHz for NLoS more suitable for residential and small business users.

The 802.16 Wireless Metropolitan-Area Network, which is the wireless MAN standard, is followed by three amendments; 802.16a, 802.16b and 802.16c to address issues of radio spectrum, quality of service and inter-operability, respectively. The 802.16e mobile WiMax which aims to add mobility to the 802.16a standard and include services that supports low-latency data and real-time voice. The 802.16e is an extension to the 802.16a standard physical layer and media-access control link, hence, 802.16e mobile devices will be compatible with 802.16a fixed stations. The 802.16e has a target shared data rate of about 70 Mb/s, operating in the [2, 6] GHz licensed bands, with typical channel bandwidths ranging from 1.5 to 20 MHz.

4.5. Wireless mesh networks

Wireless technologies are moving from access technologies to backbone ones, interconnecting nodes that originally were interconnected by wires or fibre, opening new challenges. There is a strong development of wireless mesh networks, an emerging two-tier architecture based on multi-hop transmission, with two fundamental objectives: to offer connectivity to end-users, and to form a self-organised wireless backbone. WMNs may also be called infrastructured ad hoc networks, where Mesh Points (MPs) constitute an ad hoc network that provides infrastructured access to end-users. A WMN can be seen as a wireless concatenation of multiple hotspots, the WMN architecture is illustrated in Figure 5.

WMNs are comprised of two types of nodes: mesh routers and mesh clients. Mesh routers, also called Mesh Points (MPs), act as radio backhaul routers supporting mesh networking, able to discover their peers and associate with them, cooperating in a self-organised way to create a Radio Backhaul Network (RBN).

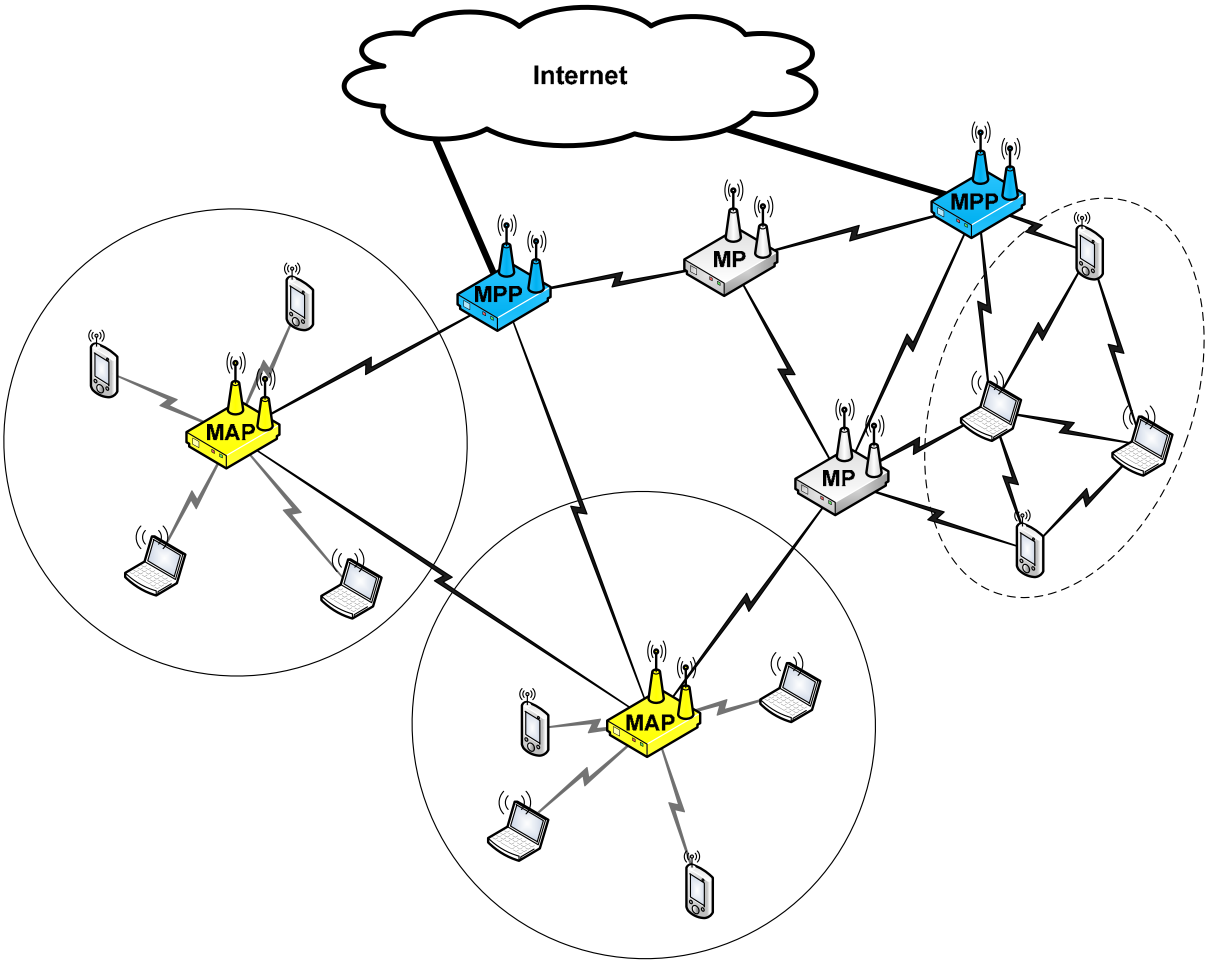

Figure 5 − Wireless Mesh Network architecture.

MPs are able to select an optimal path through the WMN to forward traffic. They are usually equipped with multiple wireless interfaces built on either the same or different wireless access technologies. Some MPs act as APs, so-called Mesh Access Points (MAPs), which cover a region where they offer connectivity, building Radio Access Networks (RANs) that provide access to mesh clients, the typical stations. Stations associate to MAPs, not requiring new functionalities, and communicate by means of the RBN. The RBN can be a self-standing network, simply offering inter-user connectivity. Otherwise, if connection is available through one or more MPs acting as IP gateways, so-called Mesh Point Portals (MPPs), the RBN might be considered as a local wireless extension of the Internet. Some mesh clients may also provide peer to peer communication among clients, where mesh clients forward traffic or even perform routing and self-configuration functionalities, like typical ad hoc networks.

WMNs support ad hoc networking, and have capability of self-forming, self-healing and self-organisation, enabling flexible integration, quick deployment, easy maintenance, robust, low cost, high scalability, and reliable services, as well as to enhance the network capacity, connectivity and throughput. Due to these inherent advantages, WMN is believed to be a highly promising technology converging the future generation wireless mobile networks.

WMNs may have different scopes. A mesh Wireless Personal Area Network (WPAN) may be based in technologies such as IEEE 802.15.3. A mesh WLAN may be based in technologies such as IEEE 802.11, as there is a Task Group, the IEEE 802.11s, developing a mesh networking standard. A mesh Wireless Metropolitan Area Network (WMAN) can be based in IEEE 802.16 WiMAX, which has defined basic support of mesh functionalities. One vision in LTE is that a mesh topology support the wireless interconnection of base stations. This flexible architecture provides the freedom to place base stations/access points at arbitrary locations, recurring to only few gateways to the fixed Internet, enabling gains in coverage, throughput and cost.

4.6. General comparison among different systems

In this section, a general comparison among different wireless systems is made. This comparison is based on main systems characteristics, Table 6.

Table 6 – Comparison among different groups of wireless systems.

Main Characteristic	WLAN	Cellular	FWA
System Architecture	Simple	Complex	Simple
Services Characteristics	Data	Circuit-Data	Data
QoS	Low	Medium	High
Mobility	Low	High	Medium
Throughput	High	Low-Medium	Medium/High
Working Environments	Outdoor/Indoor		
Spectrum Licence	Free	Regulated	
Capacity	High	High	Medium
Coverage	Low	High	Medium/Low
Power Levels	Low	Medium	Medium/High
Deployment Cost	Low	High	Medium
Operational Cost	Low	High	Low
Billing Policies	Free/Volume	Time and Volume	Contract
Frequency bands	2.4, 5.2 and 5.8 GHz	400…2000 MHz	10…66 GHz

5. Wireless channel

In this section, possible impairments that should be taken into account when considering wireless channels, and their influence on network performance, are discussed.

5.1. Channel impairments

There are fundamental differences between wireline and wireless networks resulting from the inherent characteristics of the propagation channel [CaKC06]. One of the most important issues in wireless networks is that a radio link from the MT to a wired network infrastructure is inherently less reliable than a fixed wired connection. This characteristic is familiar to users of cellular phones and wireless networks who have experienced signal degradation and dropped connections. This inherent low reliability of wireless links leads to a need for considerably more complexity in the physical-layer design than the one for wired networks.

Another important characteristic of wireless networks is the fundamental limitation on the spectrum availability. For systems that operate in licensed frequency bands, e.g., cellular systems, each service provider operates its network within a fixed band, thus, resources must be provided to manage the sharing of allocated bandwidth among a large number of users. This bandwidth limitation problem also gives rise to the need for additional complexity in the design of source coding, compression and modulation techniques, so as to reduce the amount of bandwidth needed for each user, while maintaining the required QoS.

Another practical issue for users of mobile wireless devices is the necessary reliance on batteries, with the need for periodic recharging, thus, leading to the application of elaborated power management techniques in the design of mobile devices, as well as on the communication protocols being used. The limited amount of power available at the device compromises battery life and processing power needed to carry out intensive processing.

Concerning security, from the point of view of fraudulent intrusion, the use of wireless transmission creates a vulnerability problem resulting from sharing the physical medium, since there is no physical barrier that can separate an intruder from the network.

The inherent advantage of wireless networks, user mobility, adds complexity to the network due to handover. This calls for greater complexity in registration and call routing techniques than are needed in wired networks, and a need for an addressing scheme to support mobility. Moreover, this increase in complexity can introduce additional security vulnerabilities.

Some of the recent research tendencies tend to incorporate QoS and mobility towards the concept of always best connected, which means that the terminal will always select the best possible available connection.

Concerning the wireless propagation channel itself, observed unreliability is usually caused by Radio Frequency (RF) propagation itself. It is well known that, in wireless mobile and cellular environments, the signal experiences different kinds of attenuation and losses due to several phenomena involved in the physical mechanism of wave propagation in multipath environments, e.g., signal loss and fading [CaCo03], [CaCo05], together with the influence of atmospheric elements that that cause additional link degradation at given frequencies.

Moreover, since one is talking of a shared medium, interference is an additional issue. One must remember that, in cellular environments, link availability is usually dependent on interference rather than on coverage (power).

In order to provide an insight on which channel impairments can influence the overall network behaviour, several channel impairments should be considered. These can be classified as being Radio Channel, User Behaviour or System specific, Table 7. This is not an extensive list, but rather an initial set of channel impairments that should be taken into account when dealing with wireless channels.

Table 7 – List of channel impairments.

User	Radio	System
• Operating environment • Speed	• Tx power • Time variability • Signal loss and fading • Interference	• Channel bandwidth • Spectrum availability • Access technique • Handover • UL/DL asymmetry

Physical channel impairments impose restrictions to the overall network behaviour, since it can affect throughput, maximum delay, packet loss, and packet error, thus imposing additional restrictions that are not usually found in wired systems. Moreover, due to the inherent characteristics of the wireless propagation channel, issues such as mobility, QoS, security, and privacy, should be accounted for in the whole physical layer virtualisation process.

The mobility issue, together with the needs for efficient handovers, imposes additional complexity in terms of network signalling.

Since a user moves in a complex environment, link reliability is not assured, thus, increasing the complexity of traffic control and packet scheduling algorithms.

As far as network resilience is concerned, wireless channel impairments impose extra difficulties, due to link availability and reliability. Hence, as a first approach several network parameters/characteristics should be taken into account in order to access how they are affected by different wireless impairments. Examples of possible parameters to be considered are presented in Table 8 (again, this is not an extensive list).

Table 8 – Network parameters/characteristics.

• Throughput • Blocking • Delay • Jitter • Packet loss	• Packet error • Packet scheduling • Traffic control • Signalling • Network resilience	• Link reliability • Interoperability • Mobility • Energy awareness • Scalability

By assessing the influence of different wireless channel impairments on these parameters, as presented in Table 9, it will be possible to access the main issues that should be taken into account in the whole physical layer virtualisation process, this being one of the main motivations for future developments concerning the theme of Physical Layer Awareness, in particular in what concerns wireless channels. Table 9 aims at providing an easy approach to evaluate how different network parameters/characteristics are affected by different channel impairments (or inversely). This influence is characterised as being High (H) or Medium (M), depending on the higher or lower dependence/influence between a given channel impairment and a network parameter/characteristic. A blank cell means that there is no relevant relation among the items being considered.

Table 9 – Wireless channel impairments.

			Network parameters/characteristics														
			QoS														
			Throughput	Blocking	Delay	Jitter	Packet loss	Packet error	Packet scheduling	Traffic control	Signalling	Network resilience	Link reliability	Interoperability	Mobility	Energy awareness	Scalability
Wireless channel impairments	System	Channel bandwidth	H				M	M					M	M	M	M	
		Spectrum availability	H	H	H	H			M	M	M	H	H		M	H	H
		Access Technique	M	H	H	H			M	M	H	H	H	H	M	M	H
		Handover		M	H	H	M	M	M	H	H	H	H	H	H	M	M
		UL/DL asymmetry	H		H	H			M	M			M	H		M	M
	Radio	Tx power	M				H	H			M	M	H		M	H	M
		Time variability	H		M	H	M	H	M	M	M	M	H		M	H	
		Signal loss and fading	H		M	H	H	H	H	M	M	H	H		M	M	
		Interference	H		M	M	H	H	H	M	M	M	H		H	H	M
	User	Operating environment	M				M	M	M				M		H		
		Speed	H		M	M	H	H		M	M	H	H	H	H		

5.2. Channel impairments explained

This section is intended to provide general considerations, aiming at justifying how different relations between wireless channels requirements and system/network parameters were classified. Two different groups were created, one for High dependency, the ones classified as **H** in Table 9, and the other for Medium (**M**) ones. Within each group the analysis is performed at System, Radio and User levels. In order to keep it simple, no detailed explanation for each relation is given, instead one provides a simple bulleted text structure where for each Channel impairment a rationale is provided for each network parameter/characteristic classification. This simple rationale aims at characterising the main issue(s) that is(are) the basis for the given classification.

5.2.1. System level

High dependency

Channel Bandwidth

- **Throughput**: There is a direct dependence between the throughput of a channel and its bandwidth (Shannon's Formula).

Spectrum Availability (here considered as N times the available channel bandwidth)

- **Throughput**: See Channel bandwidth.
- **Blocking**: When considering Circuit Switched (CS) data, more channels are associated to less blocking for the same traffic conditions.
- **Delay**: The same reason as pointed out for blocking but for Packed Switched (PS) data services.
- **Jitter**: The same reason as pointed out for delay.
- **Network resilience**: More available channels, allows improved network recovering capabilities.
- **Link availability:** For the same channel bandwidth, the larger the spectrum, the larger the number of available links.
- **Energy awareness**: For the same channel power the radiated power increases as a function of the number of available channels.
- **Scalability**: The number of available channels puts restrictions to scalability.

Access technique

- **Blocking**: The ability of the access technique to manage the available bandwidth is directly related to the blocking probability.

- **Delay**: The same reason as pointed out for blocking but for Packed Switched (PS) data services.
- **Jitter**: The same reason as pointed out for delay.
- **Signalling**: It is directly related to the access technique being used.
- **Network resilience**: With respect to interference from other systems.
- **Link reliability**: For example, hidden terminal problem, deaf nodes, etc.
- **Interoperability**: Interoperability is about connecting different systems that can be based on different access techniques.
- **Scalability**: Number of timeslots, codes, frequencies, reuse capacity, etc.

Handover

- **Delay**: The network has to re-arrange the traffic depending on the handover profile.
- **Jitter**: See delay.
- **Traffic control**: Traffic control can generate handovers.
- **Signalling**: You need to control/signal the handover.
- **Network resilience**: Always Best Connected (ABC) concept [SeCo06].
- **Link reliability**: Handover allow recovering from link drops.
- **Interoperability**: In the case of vertical handovers.
- **Mobility**: The Handover profile is closely connected with the mobility one.

UL/DL asymmetry

- **Throughput**: TDD techniques.
- **Delay**: Depending on the UL/DL asymmetry it can be High for bi-directional traffic.
- **Jitter**: Same reasons as pointed out for delay.
- **Interoperability**: Both systems need to have equal UL/DL symmetry.

Medium dependencies

Channel Bandwidth

- **Packet loss**: Packet loss depends on fading, which is related with the available bandwidth.
- **Packet error**: See packet-loss.
- **Link reliability**: See packet-loss.
- **Interoperability**: different systems need to have sufficient bandwidth to become interoperable.
- **Mobility**: In OFDM systems, e.g., WiMAX, the data rate depends on the distance between the BS (or AP) and the MT.

- **Energy awareness**: Usually, for the same channel power, you need more power for larger bandwidths.

Spectrum availability

- **Packet scheduling**: You have more channels to transmit to.
- **Traffic control**: See Packet Scheduling.
- **Signalling**: You need to signal/control the channels.
- **Mobility**: Reuse distances in cellular networks can be related with the number of available channels.

Access technique

- **Throughput**: Because of guard bands, time windows, number of timeslots, etc.
- **Packet scheduling**: The access technique is associated to scheduling when each packet is transmitted, but does not influence the scheduling algorithm of a number of packets.
- **Traffic**: Traffic on each channel depends on the packet scheduling scheme.
- Mobility: Time-synchronisation is dependant on mobility, e.g., TDMA systems such as GSM.
- **Energy awareness**: Can be an issue in beacon signalling based systems as one can found in WSNs.

Handover

- **Blocking**: You could be blocked during the handover.
- **Packet loss**: Depends whether the terminal transmits packets during the handover or not.
- **Packet error**: For similar reasons as pointed out for packet loss.
- **Packet scheduling**: Depending on soft-handovers.
- **Energy awareness**: You can do a handover to transmit to a “closer” base station.
- **Scalability**: Handover can increase the flexibility of the network, e.g., performing vertical handovers.

UL/DL asymmetry

- **Packet scheduling**: It depends on how the channels are managed (with respect to symmetry).
- **Traffic control**: Traffic control can change the asymmetry ratio.
- **Link reliability**: The same reasons as pointed out for channel bandwidth.
- **Energy awareness**: Depends on the Tx/Rx time window.
- **Scalability**: You can change the symmetry ratio to improve scalability.

5.2.2. Radio level

High dependency

Tx power

- **Packet loss**: Fading of the channel, hence, fading margins and Tx power are related, thus, having influence on packet loss.
- **Packet error**: See packet loss.
- **Link reliability**: Sufficient Tx power "almost" guarantees a link.
- **Energy Awareness**: Tx power.

Time variability

- **Throughput**: High time variability causes low throughput.
- **Jitter**: Due to the time variability of the channel.
- **Packet error**: Due to time synchronisation problems, timeouts, etc.
- **Link reliability**: Time variability can lead to link failure.
- **Energy Awareness**: Due to power control.

Signal loss and fading

- **Throughput**: Signal loss drops a link.
- **Jitter**: Fading can cause jitter between packets.
- **Packet loss**: Due to signal loss.
- **Packet error**: Due to fading.
- **Packet scheduling**: Signal loss drops a link.
- **Network Resilience**: Signal loss impacts resilience.
- **Link reliability**: Fading and loss gives unreliable channels.

Interference

- **Throughput**: Interference decreases throughput.
- **Packet loss**: Interference can cause packet loss.
- **Packet error**: For similar reasons as pointed out for packet loss.
- **Packet scheduling**: If a link drops due to interference packets need to be rescheduled.
- **Link reliability**: Interference can cause link drops.
- **Mobility**: Mobility changes interference patterns.
- **Energy Awareness**: Depending in the way channels are managed to avoid interference.

Medium dependencies

Tx/Rx power

- **Throughput**: Tx power limits SNR, which has an impact on the modulation/coding scheme, hence, on throughput.
- **Signalling**: In the case of power control.
- **Network resilience**: Power control.
- **Mobility**: Tx power limits cell range.
- **Scalability**: Breathing cells, cell-splitting.

Time variability

- **Delay**: Time variability can cause jitter, thus, having impact on delay.
- **Packet loss**: Due to time-varying fading.
- **Packet scheduling**: Different packet scheduling schemes should be used to overcome the time variability of the channel.
- **Traffic control**: Same reason as pointed out for Packet scheduling.
- **Signalling**: Power control.
- **Network resilience**: Because of link reliability.
- **Mobility**: Allowed mobility within a given cell is influenced by the time varying properties of the channel.

Signal loss and fading

- **Delay**: In the case of loss there is an infinite delay.
- **Traffic control**: You could change to a less fading channel.
- **Signalling**: Traffic control involves signalling.
- **Mobility**: Due to mobility you can move into a shadowed area or worse channel conditions.
- **Energy Awareness**: If there is a link drop or bad channel conditions it can happen that there is a need for retransmission.

Interference

- **Delay**: Because of packet losses.
- **Jitter**: Because of packet losses.
- **Traffic control**: Due to packet scheduling issues.
- **Signalling**: Due to packet scheduling issues.
- **Network resilience**: Because of link reliability.
- **Scalability**: Interference limits the number of users, e.g., in CDMA networks.

5.2.3. User level

High dependency

Operating environment (indoors/outdoors/etc.)

- **Mobility**: Whether you can be mobile depends on the environment.

Speed

- **Throughput:** High speed usually implies low throughput.
- **Packet loss:** Because of loss due to fading variable conditions.
- **Packet error**: Same as pointed out for Packet loss.
- **Network resilience**: At high speeds it can be difficult for the network to recover.
- **Link reliability**: Due to fading variability.
- **Interoperability**: Both systems need to support the similar maximum speed.
- **Mobility**: Speed is directly related to mobility.

Medium dependencies

Operating environment (indoors/outdoors/etc)

- **Throughput**: In mobile environments throughput is usually dependent on the operating environment.
- **Packet loss**: Depends on the fading/mobility in a given environment.
- **Packet error**: Same as pointed out for Packet loss.
- **Packet scheduling**: Depends on the different types of users/services.
- **Link reliability**: Depends on the fading properties of each environment.

Speed

- **Delay**: Because of throughput.
- **Jitter**: Influences throughput.
- **Traffic control**: Can cause more handovers.
- **Signalling**: Same as pointed out for Traffic control.

5.3. Wireless Channel Requirements

By assessing the influence of different wireless channel impairments on the whole network behaviour, it will be possible to access the main issues that should be taken into account while deriving requirements at different levels. A list of main wireless Physical Layer Requirements is presented in Table 10.

Table 10 – Wireless Physical Layer Requirements.

Identifier	Name	Short Description
14.00.01	Environment (PHY)	Capable to operate in different physical environments
14.00.02	Mobility (PHY)	Capable to operate in different mobility environments
14.00.03	Power (PHY)	Capable to operate with different power level requirements
14.00.04	Fading (PHY)	Capable to operate in time-dependent fading environment
14.00.05	Interference (PHY)	Capable to operate in multi-system/technology interfering environments
14.00.06	Bandwidth (PHY)	Capable to operate with different bandwidth requirements
14.00.07	Access Technique (PHY)	System performance should be independent of the access technique being used.
14.00.08	Handover (PHY)	Capable of performing horizontal and vertical handover.
14.00.09	Performance (PHY)	Capable to provide the required performance independently of the required Service Settings

Different environments, ranging from pico-cellular indoors to macro-cellular outdoors as well as different mobility schemes, ranging from pedestrian to vehicular impose different restrictions to the whole network/system performance/parameters. Additionally, radiated power levels depend on the required coverage area. Globally, any system should be capable to operate in different physical environments with different power level requirements and mobility profiles (Reqs. 14.00.01, 14.00.02 and 14.00.03, according to D2.1 numbering scheme) [4WAR08]. The term “operate” stands for all users having access to the network with given quality conditions.

The time-varying nature of the wireless fading channels is one of the main issues that should be taken into account forcing different strategies to be used in order to allow wireless systems to be capable to properly operate in this type of environments (Req. 14.00.04).

Concerning interference, any system should be able to operate simultaneously with other systems working in the same, or adjacent, frequency bands (Req. 14.00.05).

Since spectrum scarcity is actually one of the main problems (this being critical when high data rates are required), any system should be able to provide the required QoS as a function of the allocated bandwidth (Req. 14.00.06).

Different systems, being based on different technologies, use different channel access techniques, having impact on systems performance. Moreover, these systems should be able to interoperate irrespective to the technologies being used, and as transparent to the user as possible (Reqs 14.00.07 and 14.00.08).

When referring to the type of Service being delivered, different services have different characteristics and parameters affecting the whole system performance, therefore, any system should be capable to provide the required performance independently of the required service settings (Req. 14.00.09).

In order to fulfil the requirements in Table 10, taking into account that a wireless link is subject to time and location varying fading, signal attenuation, interference and noise, therefore, resulting in bursty errors and varying channel capacities, it is desirable that higher layers (RRM, scheduling, etc.) have the following features [FaLe02]:

- **Efficient link usage:** The system must use channels efficiently. Transmission slots should not be assigned to currently bad links since the transmission will simply be wasted;
- **Delay bound:** Delay bound guarantees for individual sessions should be provided in order to support delay-sensitive applications;
- **Fairness:** Available resources should be redistributed fairly across sessions according to different QoS requirements;
- **Throughput level:** Different Throughput levels should be allowed according to different service requirements;
- **Low complexity algorithms**: Low-complexity algorithms are needed in order to allow real-time control of all wireless link parameters;
- **Service adaptation to link quality:** Data rates and QoS requirements should be adapted dynamically according to the link quality;
- **Isolation:** QoS requirements for a session should be maintained even in the presence of sessions whose demands are in excess of their reserved values;
- **Energy consumption:** The algorithm should take into account the need to prolong the MT battery life;
- **Delay/bandwidth decoupling:** Since, the delay is usually tightly coupled with the available bandwidth. This being closely connected to the type of scheduling algorithms being used. An efficient decoupling between these two parameters should be provided;
- **Scalability:** The system should operate efficiently as the number of sessions sharing the channel increases, by fairly sharing the resources among different sessions.

6. Different Perspectives of Physical Layer Awareness

In this section different perspectives of Physical Layer Awareness are presented according to different views of the impact of physical channel impairments in the overall network performance.

6.1. Business Innovation

Different things can be observed from the current user behaviour and service demand. First of all, the number of users [WoSt08a], [ITU08] and devices [RIPE07], [Hobb08] are basically increasing, which is true also for an increased usage of bandwidth [Cisc08] and the duration. From the current viewpoint, it is not clear at which point of time this growth will decline or saturate; different statistics speak from doubling every 18 months according to Moore's Law for integrated circuits [CoOd02], [PhEl08], [Cher08], or observed over the last decades a 50% increase in their connection bandwidth [Niel08]. From this it can be concluded that the Internet will grow in terms of bandwidth; on the other hand, the number of connected devices and hosts is very difficult to predict. Combined statistics have outlined that the current Internet penetration in the population is round about 20% [WoSt08b]. Assuming that these numbers will growth over the next decades and Internet will become an essential part of everyday's life, 6 to 7 billion users can be assumed. The type of access will shift to mobile with strong backhaul needs for the fixed network. In addition, different forecasts are available, e.g., Forrester is predicting 125 million Mobile Internet users in Western Europe only in 2013 already [Forr08], [Nuth08].

Another potential issue from service perspective is the knowledge of the availability, access bandwidth and statistics about key parameters. This may also include functions in order to fulfil the "always best connected" requirement, e.g., [Nuth08], where the starting point for the optimisation is the knowledge about available physical networks, which is strongly correlated with the mobility theme. The access bandwidth is required to use services properly, e.g., to let the services know which bandwidth can be consumed or to which bandwidth the service must be adapted. In today's xDSL access networks functions (ANCP/L2CP) are used to determine the available bandwidth; in wireless networks, these functions are implemented as well. In general, this is strongly correlated with the QoS topic, also for the optimisation of connection services in the "always best connected" environment with the mobility theme. The statistics about key parameters are important for the business environment as well; contracts are typically coupled to Service Level Agreements (SLA) including e.g. availability and throughput.

6.2. New Architecture Principles and Concepts

An Architecture Framework was developed to represent and design future networks architectures. This set of concepts and procedures can be used to model existing networks as well as future solutions, applying a Design Process that provides a systematic approach to guide the network architect.

The Architecture Framework provides two views on network architectures: the macroscopic view focuses mainly on structuring the network at a higher level of abstraction, and introduces the concept of stratum as a flexible way to layer the services of the network; the microscopic view concentrates more on the functions needed in the network, their selection, and composition to Netlets (containers that provide a certain networking atomic service) that are instantiated in the physical nodes of the network, Figure 6.

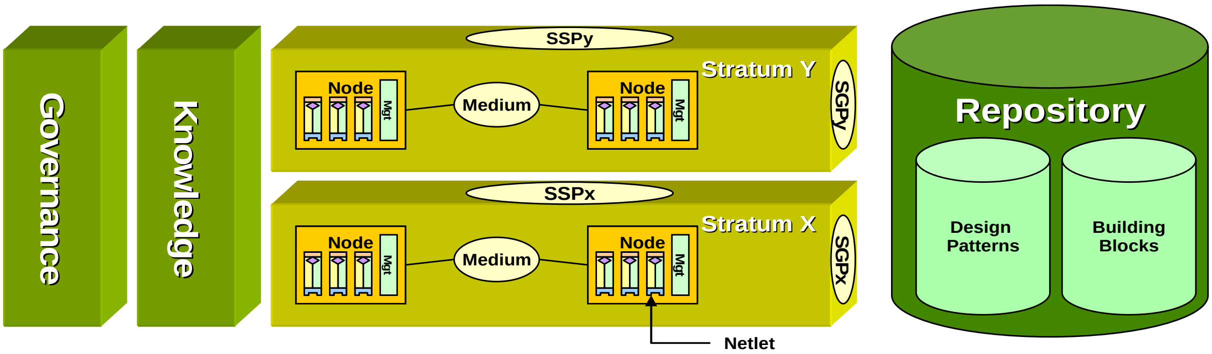

Figure 6 – Architectural Framework.

The stratum is a structural element of the network architecture, being used for designing, realising and deploying distributed functions in a communication system. The functionality of a stratum is encapsulated by and offered as a service to other strata via a Stratum Service Point (SSP). A stratum implementing the same or a similar distributed function, but in a different domain (thus, assuming independent implementations), can interoperate via a Stratum Gatewaying Point (SGP). Horizontal Strata provide the resources and capabilities for communication and information management across networks; Vertical Strata are those responsible for listening and ordering other strata.

Netlets consist of functionalities required to provide the end-to-end services, containing protocols and, therefore, provide the medium for the strata they belong to. Inside the same Netlet there could be functionalities that are related to different strata. With the principle of hiding protocol details, but yet providing a number of properties via its interfaces, Netlets can be easily exchanged without the need to change application or network interfaces.

Signalling capabilities must be present in any stratum in order to coordinate their own internal operations, and to interoperate with other strata as well. In addition to mobility, the accumulation of control information in different system elements needs to be considered. Both are related to dynamicity, because the state of the network might have changed during the transmission of control information. Thus, signalling is needed to find out the current level of dynamicity and react in real-time to minimise overhead.

In the two phased signalling principle, observation capabilities are used to track the current situation in the network. Observation capabilities should have minimum functionalities embedded into it, and new observation capabilities could be created for different situations adaptively. The actual implementation could be different depending on the stratum. The control and signalling functionalities are adapted to signalling requirements according to the observation information. The required functionalities are derived from the repository and the needed instances are created for the signalling and control actions. These functionalities take care of actual signalling for different types of communication, like signalling for real-time (delay sensitive traffic, delay variance sensitive traffic) and non-real-time traffic. A signalling example for a wireless network is presented in Figure 7.

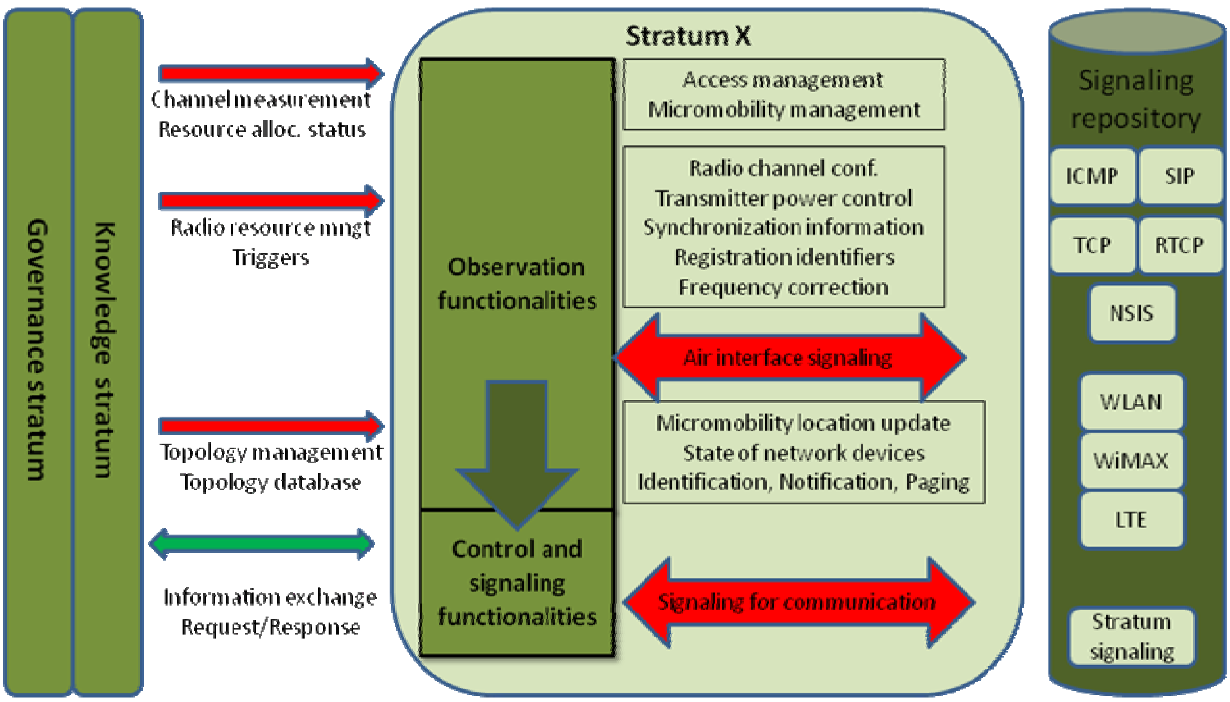

Figure 7 – Signalling for wireless networks.

Observation capabilities collect Radio Resource Management related data over the air interface, and exchange information with the other strata with the minimal amount of signalling in shared service and control channels. The observation information, at the minimum, includes the topology information needed to route the packet through the network and deliver it to the intended destination for connection establishment. In addition, observation capabilities should, e.g., get the state of network devices, perform channel measurements, and take care of handover control for micro-mobility. This information is then used to adapt control and signalling functionalities to meet, e.g., application requirements.

6.3. Network Virtualisation

6.3.1. General considerations

At the highest level, the use of network virtualisation enables the coexistence of multiple network architectures on a shared infrastructure, in order to meet the diverse requirements of the Future Internet. In a Virtual Network (VNet) approach, a three roles model was chosen for splitting up provider roles into infrastructure and service providers, Figure 8.

The Infrastructure Provider (InP) is responsible for maintaining physical networking resources, such as routers, links, wireless infrastructure, etc., and enabling the virtualisation of these resources. The InP also offers a resource control interface for the virtualised resources, through which InPs can make virtual resources and partial virtual topologies available to virtual network providers, which are the customers of the InP.

The VNet Provider (VNP) constructs virtual networks using virtual resources and partial topologies provided by one or more InPs or other VNPs. This role in essence adds the layer of indirection, which virtualisation provides. The resource control interface is used, which is offered by the InP who owns the resource, to request and configure these virtual resources; a newly constructed VNet can be made available to a virtual network operator or to another VNP, who can recursively use it to construct an even larger VNet.

The VNet Operator (VNO) operates, controls, and manages the VNet in order to offer services. Once the VNet has been constructed by a VNP, the VNO is given console access to the virtual resources (i.e., its “slices” of the physical resources) setting up the VNet, allowing it to configure and manage them just like a traditional network operator manages physical network resources.

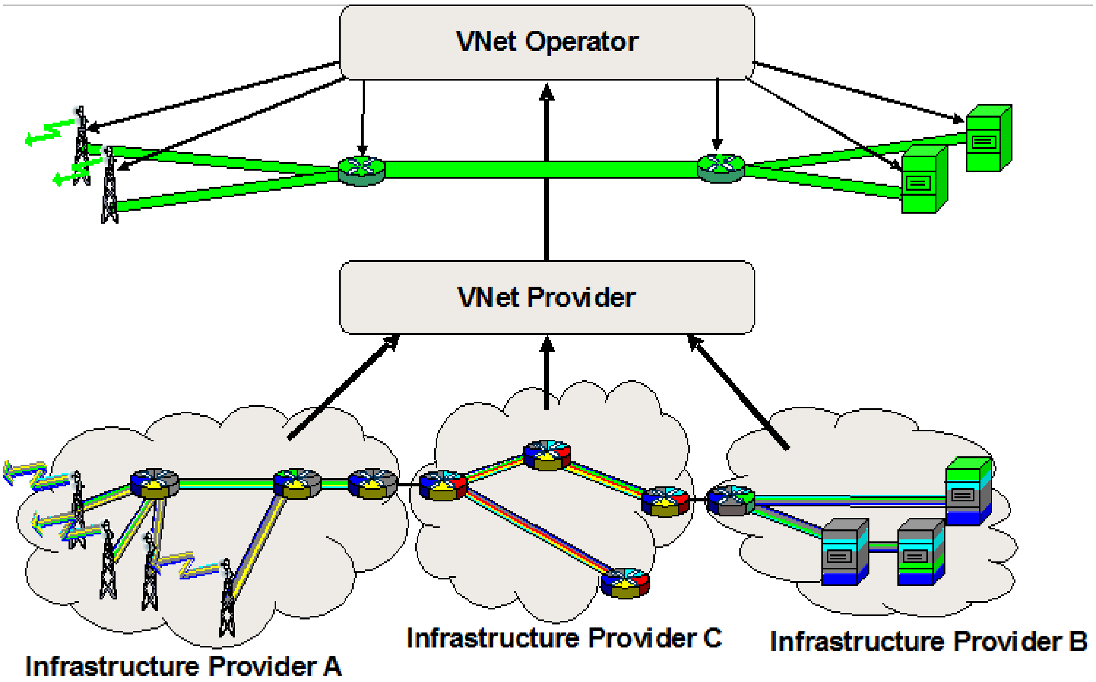

Figure 8 − VNet Provider roles as proposed in 4WARD.

In the virtualisation process, a relevant issue that should be considered is the occupancy and management of resources in the VNet s/VNodes and their possible (re)utilisation by another service/flow, that belongs to another VNet, which can be used to optimise their efficiency. After the creation of the VNet, physical resources that have been allocated for it may not be in use, which can lead to an inefficient use of the physical resources. In order to accomplish this, an entity, in the VNet architecture, must manage the VNet s/VNodes resources occupancy. To manage VNets, some entities are required, which, based on Virtualisation Framework proposed in [LoZH08], have their location and interactions depicted in Figure 9:

- An entity that must take into consideration the overall resources, and select dynamically the best one to establish or maintain the user connectivity. This entity besides an initial selection of the best resource, should consider Vertical Handover (VHO) procedures in order to, e.g., avoid disconnections due to lack of coverage, avoiding overload, a opportunistic QoS improvement, support users' and operators' preferences or load balance among resources. It is designated by Cooperative Virtual Radio Resource Management (CVRRM);
- An entity responsible for having the established relations with and among VNet operators, preferences, etc., i.e., a Policy Management entity;

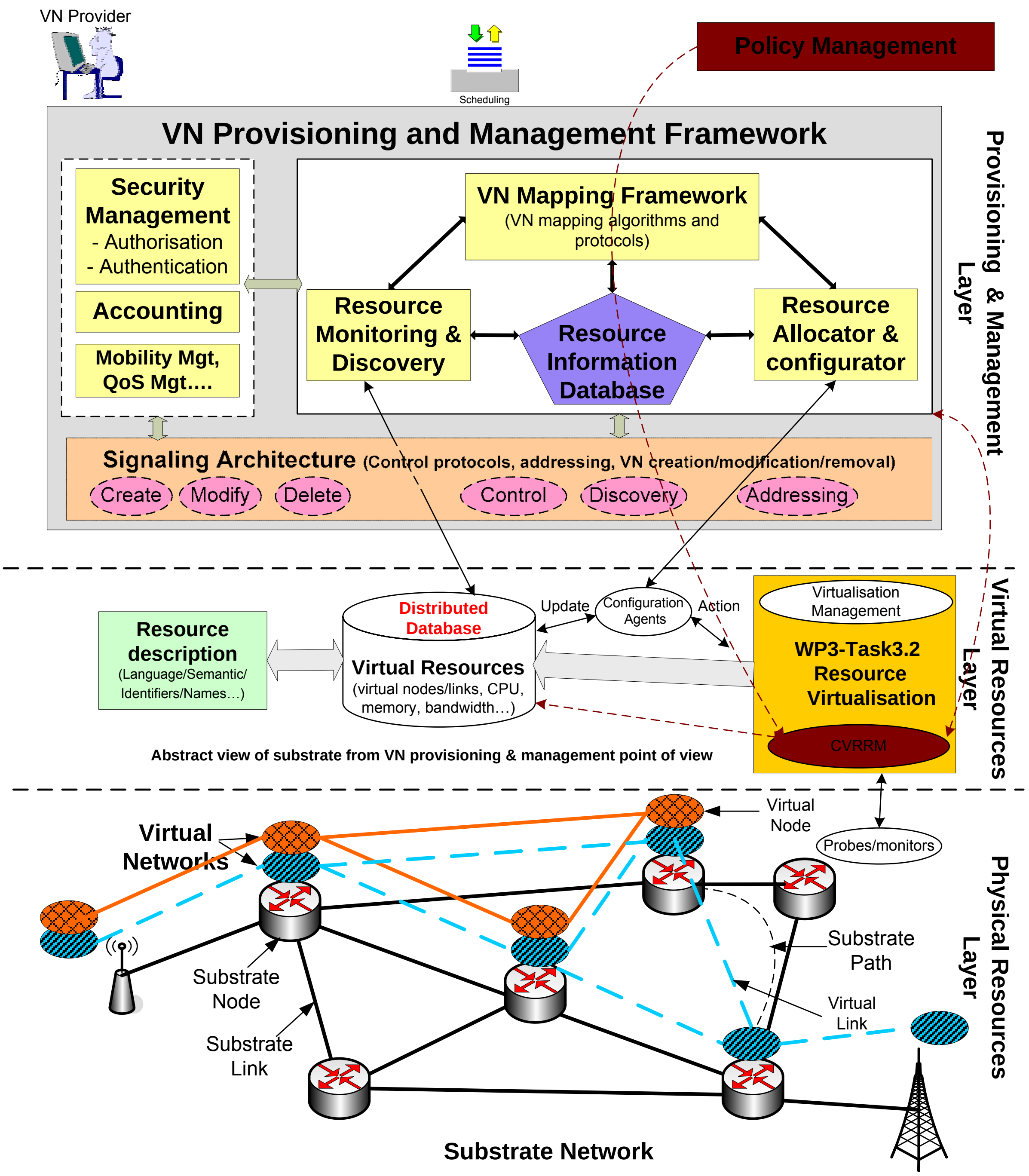

Figure 9 − Virtualisation Framework with entities and interactions identified (extracted from LoZH08]).

- An entity that is responsible for allocating physical nodes to a VNet, as a consequence of a VNet request. On the one hand, this entity must know the occupancy/availability of the physical resources (including the characteristics of the VNodes already created), and on the other, receive the requirements for the VNet namely the QoS requirements. Additionally, this entity must know the information about the radio resources availability of the nodes, according to the wireless medium changes (distinguished by the ones allocated to VNet s and the ones available to allocate);

- An entity that must be aware of the available resources, and the resources occupied by VNodes instantiated within the physical resources in the (substrate node/substrate link) in terms of bandwidth, processor capacity, percentage of loss, etc. These functions have been identified as belonging to Virtualisation Management entity;
- A database that reflects the overall resources in the Virtualisation Framework, with their allocation, availability, capabilities and capacity;
- An entity that monitors the wireless medium changes, namely, reduction of bandwidth, error bursts, etc., and updates the database with the changes in resources status;
- An entity that must manage the VNet s/VNodes resources occupancy.

6.3.2. Mobility of physical resources

The mobility comprises any physical entity that can affect virtual network performance due to its mobility. On a first analysis, and without particularising depending on the entity of the network in motion, these are the main topics discovered so far.

Physical resources comprise any physical entity of the network with the ability to be in motion (from the network resources to the end-users' devices). Further analysis will go deeper into the specific matters depending on the role of every type of entity in the network (mainly differences between network resources and end users).

VNets are directly related to physical resources underneath, and any change in the availability of resources (mobility generates a lot of them) affects the performance of the virtual networks that use them. Detection and reaction to any physical changes in the topology of the network are key issues in the management of the network. Detection is an aspect that should probably be covered by In Network Management work package (called management layer from now on). The physical reaction to these changes (if necessary) is also part of the In Network Management, and VNet (called virtualisation layer from now on), with the information regarding the changes provided by the management layer, will react to these physical changes rearranging the corresponding virtual networks to the new physical topology.

The technical challenges include:

- **Dynamics of the network and the reaction time:** no matter the rate of changes of the physical network, it should have enough time to be aware of the changes and take the corresponding counter-measures. The time that a network has at its disposal to detect the changes due to mobility and take the corresponding actions is the "Reaction Time Window (RTW)" (this time goes from the detection of the physical topology changes to the moment the network is stable and ready to offer the services for which is used). When the network is able to detect changes and react in the RWT, the network is considered to work online. Depending on the mobility of the network, sometimes the network even being aware of the changes, it is not capable of reacting to those changes (especially in high mobility networks) or even it is not interested in doing it at that time. Nevertheless, recording those changes and analyse them offline to help decide in future similar situations can be an interesting issue. RTW depends on the type of network and technology involved, being classified as:
  - High mobility network. The RTW is not long enough for the network in order to detect the changes and take actions online. The only possible way to work with these networks is offline;
  - Low mobility network. The RTW is long enough for the network in order to detect the changes and take actions online. Static networks would be inside this group. These networks let work online, but working offline can be also very interesting.

  Once the physical changes have been detected and the virtualisation layer has been informed accordingly, it has to evaluate the impact of these changes in the virtual networks and counteract them quicker than the remaining RTW if working online.
- **Overhead that mobility implies to react to the changes happened in the network:** mobility is not only a matter of how quick the network can react to changes. How this reaction affects the network performance in terms of overhead is crucial too. Aspects such as requirements of bandwidth, memory, CPU and battery can discard a solution to the mobility problem, even if the network is capable of fitting the RTW. A tradeoff solution will be probably the better approach.

An important question to be answered is if it is VNet's responsibility to take care of this type of mobility or it only affects VNet's performance but it is clearly someone else's responsibility. The Virtualisation layer should be able to react to any change in the physical resources underneath that directly affects virtual networks' performances. Mobility of physical resources, as the basis of virtual entities, clearly affects virtual networks performance.

On a first analysis, the whole process from the detection of the changes due to mobility in network resources, to the countermeasures taken, the responsibilities seem to be:

- Detection of the mobility: management layer;
- Reaction to the mobility: management and virtualisation layer.

The virtualisation layer receives the information regarding the mobility implications in the physical topology.

6.4. In Network Management

When dealing with network management processes, which are normally performed by a network operator, as parameters are affected by channel impairments, we might want to consider also the performances of those management processes: examples are temporary fault reports ("event storming" is a pathological case) or even the need for a re-planning of the network

In a wireless access network, channel impairments can cause temporally or permanent error conditions in management processes. Temporary error conditions (e.g., those caused by bad weather) require advanced correlation and anomaly detection tools to identify, suppress; eventually some optimisation processes must take place to counteract the channel impairments. Permanent error conditions require a re-planning of the network, like frequency or coverage re-allocation due to interferences unforeseen in the first planning phase or even deployment of new base stations.

6.5. Forwarding and Multiplexing for Generic Paths

The notion of a channel and also of physical layer properties could be considered in a more general fashion. For example, a path through a backbone network is also a communication channel, with certain characteristics about errors, delays, autocorrelation of these parameters, etc. There could also be diversity inside a backbone network along different paths, but for that, an understanding/description of the network/channel needs to be available. One should keep in mind that we might have to deal with vastly different physical networks, optical to poor wireless. Networks no longer only transmit, they also store data (both in link and, possibly substantially, in buffers). And they might be able to explicitly store/cache data and process data. In this sense, an information transmission channel turns into an information processing channel (which might even happen on the air), and this is also a more general notion of "physical layer" awareness (in a generic sense of what a "lower" layer might be), in the sense that information processing could be regarded as a function of the physical layer.

To add to the above: one can consider an entire network as a "channel" - and in this sense as something that can be described just like a physical layer. A very nice example is done in the context of "coding for networks" (generalising network coding, in a sense) [RAKo08]. In [RAKo08] a "channel-like" description for networks is made, such that it becomes possible to do channel coding for an entire network. It would be brilliant to turn this into a non-memoryless channel, representing caches, buffers, etc., inside the network. Then, such a description of a "general Network Channel" can possibly be realised by a generic path.

7. Physical Layer Aspects in 4WARD

7.1. Introduction

During the 4WARD timeframe, several deliverables have been issued by the different Work Packages (some deliverables due in M30 are not considered here, as well as the ones that do not present significant relevance from a Physical Layer perspective):

- D2.1 Technical Requirements [4WAR08c]
- D2.2 Draft Architectural Framework [4WAR09f]
- D2.3 Architectural Framework: new release and first evaluation results [4WAR10a]
- D3.1.0 Virtualisation Approach: Concept (Draft) [4WAR09b]
- D3.2.1 Virtualisation Approach: Evaluation and Integration [4WAR10b]
- D4.1 Definition of Scenarios and Use Cases [4WAR08b]
- D4.2 In-network Management Concept [4WAR09d]
- D4.3 In-network Management Design [4WAR10c]
- D5.1 Architecture of a Generic Path [4WAR09c]
- D5.2.0 Description of Generic Path Mechanism [4WAR09e]
- D5.2 Mechanisms for Generic Paths [4WAR09g]

In this Section, the most relevant deliverables are addressed from a Physical Layer Awareness perspective, aiming at identifying if where and how physical layer issues are treated and general considerations are made. These general considerations aim at focusing on different aspects that should be considered in the whole network design, at different levels.

7.2. Architecture Principles and Concepts Related Deliverables

Deliverable D2.1 describes the technical requirements for a future global communication network, the 4WARD Framework, as identified in the first phase of the FP7 project “4WARD”. In this deliverable, the overall technical requirements are derived and related to the views of the different technology areas as well as of the vertical technical themes. Detailed requirements are listed, serving as a mandatory benchmark for the research directions and results expected by 4WARD.

Deliverable D2.2 describes, at a first stage, the 4WARD Architecture Framework to support the Network Architect in the design of new network architectures. Among other architecture aspects, the document presents some best practices to be followed by the network architect. In this context, the composition of functionalities is studied as a way to meet multiple requirements, and some interoperability scenarios have been studied to infer best practices to assure the interoperability between different network domains. Finally, a set of use cases are defined to support and validate the Architecture Framework.

Deliverable D2.3 describes the evolved 4WARD Architecture Framework and related validation studies. First, it provides an overview of the main concepts related to the basic constructs of the Architecture Framework, the proposed Design Process and guidelines for interoperability and composition of functionalities. Then, evaluation activities validating the aforementioned concepts are presented; which include use cases, prototypes and simulation studies.

Among all these deliverables D2.1 describes the technical requirements of 4WARD framework and is strongly linked with physical layer awareness. Most of the high level technical requirements listed in the deliverable (specific examples include, e.g., mobility, wireless awareness and monitoring) contain detailed requirements that map directly to physical layer awareness issues. Although such list can never be complete, D2.1 serves a good benchmark for research directions without forgetting topics related to physical layer. It is clearly stated that the Generic Path (GP) concept should be able to encapsulate and hide the specifics of the physical communication technologies from the using entities, i.e., be “technology independent”. However, for the sake of efficiency, it might be preferable for the GP internal features to be “Physical Layer Aware”, i.e., to adapt to lean sensor networks, ad-hoc networks or advanced optics or wireless techniques (such as network coding and other upcoming cross layer techniques).

In D2.1, mobility requirements are also presented, some of which being closely related to Physical Layer awareness. Among them, one emphasises:

- **Mob.010 – Service provisioning for mobile entities:** The 4WARD Framework shall support mobile access of its user entities to available 4WARD Networks and their information objects as an integral built-in functionality that preserves reachability, connectivity, quality of service, and security relations as far as possible without (functional) deduction compared to fixed entities’ access.
- **Mob.020 – Connectivity for mobile entities:** The 4WARD Framework shall provide means for basic connectivity of mobile entities to communicate with the 4WARD networks and information objects in order to set up and maintain the full mobile service.
- **Mob.060 – Service continuity:** The 4WARD Framework shall provide means to maintain the (possibly virtual) communication relation of a user entity to a 4WARD network during relocation over space and time, within a scope that is (pre-)defined

between the mobile entity and the network. This may result in different levels of quality of (service) experience that could range from "seamless" (handover without noticeable interruption), "loss-less" (without data or information loss) to "nomadic" (delay or disruption tolerant) experience.

- **Mob.090 – Generic heterogeneous access and physical layer awareness:** Mobility within the 4WARD Framework shall be provided in a generic way across heterogeneous access technologies, easily extensible even to future technologies and 4WARD architectures; however being aware that wireless access in particular may pose specific restrictions based on different physical environments, power level requirements, time dependent fading environments, multi-system/technology interfering environments and bandwidth requirements. Special considerations shall be given to cooperative techniques for improving dynamic transmission conditions to mobile entities via multiple transmission paths.
- **Mob.100 – Virtual network support:** Mobility within the 4WARD Framework may be realised based on physical or virtualised networks.

Deliverables D2.2 and D2.3 develop a generic Architectural Framework, which does not directly refer to specific issues of physical layer awareness. However, the concepts and principles are supposed to be applicable at all level of networks. When the Architectural Framework is applied to specific use cases and validation studies, then the physical layer awareness is at least implicitly present. Although often these aspects are hidden into a virtual machine stratum, with the exception of the signalling related studies.

7.3. Network Virtualisation Related Deliverables

Deliverable D3.1.0 provides a comprehensive internal draft description of the work at the Network Virtualisation level. It describes the scenarios and business perspectives developed to realise the benefits of the approach. The overall architecture and virtualisation framework together with the new actors involved and their interfaces are described. The chosen approaches for the virtualisation of physical resources, the scalable and dynamic provisioning and management of virtual networks, and the new concepts for the interoperability of the different coexisting networks are presented and described.

In D3.1.0, it is referred that as today's Internet Service Providers, Infrastructure Providers operate their own networks and enable end users to attach to their networks. Infrastructure Providers in the VNet Architecture need to fulfil additional requirements:

- Virtualise their physical resources and provide deterministic degrees of isolation among them in order to equip virtual networks with corresponding guarantees;
- Provide an interface that allows third parties to negotiate and lease virtual resources;
- Monitoring and management of their physical resources and on-demand creation of virtualised resources on top of them.

This is accounted by the VNet provider and by their provisioning and management framework, where the VNet embedding process is handled and other issues, such mobility, resources provisioning, links setup and general VNet management.

It is also referred that link virtualisation may have different implications for different types of physical links. In particular, virtualisation of wireless channels involves non-trivial challenges due to the specific characteristics of the channel such as fading, interference, etc. On the other hand, the open nature of wireless channels introduces new opportunities for advanced spatial diversity techniques.

The wireless impairments are evaluated in the Wireless Link Virtualisation section in D3.2.1, where different base stations virtualisations techniques are presented, showing the impact of wireless channels impairments.

7.4. Network Management Related Deliverables

In D4.1, scenarios and use cases have been selected and described. The four selected scenarios comprise self-management in wireless multi-hop networks, network management in large operator networks, home networks and large-scale adaptation in response to dramatic events.

D4.2 reports on the 4WARD progress towards developing the paradigm of In-Network Management (INM), a clean-slate approach to network management, aimed specifically at the effective management of large, dynamic networks, where a low rate of interaction between an outside management entity and the network will be required. D4.2 complements D4.1; it contains a first version of the INM framework design, which defines the structure of the management plane inside the network, supports the embedding of management functions and provides reusable components to compose collaborating self-managed entities. Second, it presents a set of algorithms and concepts developed for real time management, with emphasis on distributed monitoring in large-scale dynamic environments. Third, it reports on work that demonstrates the feasibility of rapid reconfigurability for selected management algorithms and functions under the INM paradigm.

Starting from D4.1, it is referred that a device is aware of the current network conditions, like delay times or reliability of the link between the other components. This would allow choosing the best mechanism to disseminate the configuration change. In general, the new capabilities are expected to work on links of different reliability, but the device should be aware of the probability of error related to the link. On the other hand, it is clear that the limitations of the physical link will have an impact on the overall performances of the fast switching mechanism, e.g., a considerable transmission time over a noisy wireless channel will inevitably impact on the time to complete a re-configuration process.

Design elements being discussed in D4.2 build a highly distributed architecture, where Management Capabilities can be discovered and executed on a peer to peer basis. Network Management exercises control over a network and has tight relationships with the structure(s) of the network. The classical structure is to manage groups of devices using an element manager, while several of these are controlled by a domain manager, and on top of everything, the actual network management. The state of the art is represented by larger, umbrella-like Network Management (NM) systems that cover several smaller Network Management systems. NM is used to create or modify network structures, and mostly this involves human operators to perform the separation of node sets.

When looking at management operations at high level (e.g., key performance indicators), the characteristics of the physical layer are in most of the cases not included. The reason is that these characteristics introduce additional complexity in managing the network, and in traditional network architecture it is preferred to back trace the source of problem (e.g., channel impairment) instead of including more detailed information in the real-time management of the network.

The use of aggregation and domains in INM has the benefit of simplifying management information at different levels of the network. One useful application is then the aggregation of nodes that have similar characteristics in the physical layer. Taking a deployment of wireless networks as example, base stations with similar channel characteristics are aggregated and then handled through the same interface for management. This approach has the advantage of introducing control of characteristics of the physical channels, but also to avoid additional complexity in the high level interfaces for network management. Figure 10 shows an example, where the aggregation of metrics through INM is used in different domains of an infrastructure provider’s network. The use of aggregated metric based on characteristics of the physical layer allows real-time correlation of management information, like faults related to bad channel quality, poor QoS, etc.

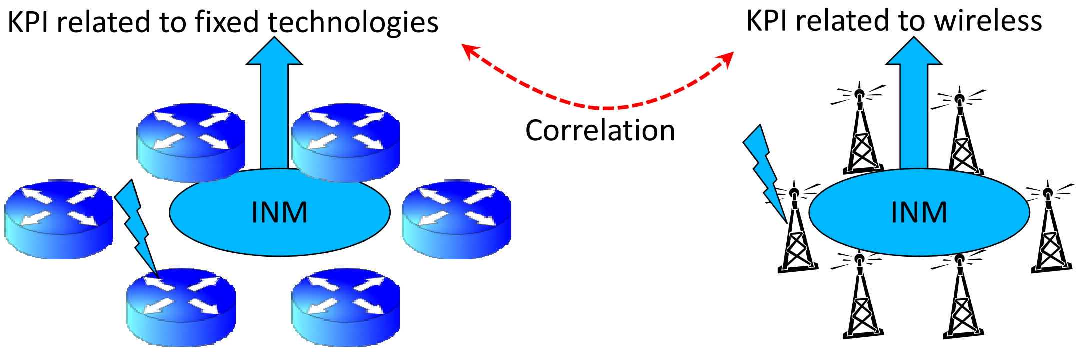

Figure 10 – Creation of aggregate metrics according to PLA.

It is referred that one capability in the QoS module is *composite metric calculation*. The metric will be calculated using the traffic parameters, received from hardware or measured using dedicated sub-modules and provided as a service to the routing module or other service functional components like NetInf, Vnet or ForMux if requested. As a final step, the global information obtained for management purposes (not for operational tasks) will be published into NetInf through the service interface, so that every network entity to be able to acquire the metric that characterises a certain physical link. Because the performance of a communication channel varies in time, QoS will constantly perform measurements and recalculate the composite metric, updating its value. Pre-defined metrics for the links/network are referred:

- links/paths delay;
- links/paths delay jitter;
- links/paths offered capacity;
- links/paths usage level;
- links/path reliability/ reputation;
- links/paths BER/PER;
- nodes power reserve (important in case of battery powered nodes).

The formula used in the testbed for an overall perspective of the links with neighbours (for hop-by-hop data transport) was:

$$CM = \frac{k_0}{ATR[bps]} + \frac{OWD[s]}{k_1} + k_2 \times BER \qquad (1)$$

where $k_0 = 10^9$ b/s, $k_1 = 10^{-5}$ s, and $k_2 = 0$. The formula should be interpreted in a similar way Cisco's EIGRP composite metric is used in Network Layer. This means that the maximum ATR (Available Transfer Rate) envisaged was 1 Gbps, the minimum OWD (One-Way Delay) was 10 μs, and the BER was not involved in fixed networks-based testbed. Obviously, additional work is needed to demonstrate that this formula seizes the dynamicity of the physical links. However, as a first step we may consider the composite metric provided as criteria for triggering events handling, QoS-aware routing, etc. [RuBa10].

Concerning Distributed Cooperative Anomaly Detection, it is stated that within 4WARD methods for anomaly detection and fault localisation that can be used to both detect abnormal behaviour, and localise the source of the anomaly in the network are being developed. In future networks, distributed methods for autonomously detecting anomalies and network faults are essential to maintain critical functionality within the network.

The distributed algorithm for anomaly detection does not define the specific test function to be used. A test function must be provided based on the type of anomaly to be detected, or in other words, the anomaly detection must be co-design with the particular network function to be monitored. This approach allows for a powerful probing mechanism at different levels and can be applied to testing a physical level as well. For example, the anomaly detection can rely on 802.1 frames for tests in wireless links: in this case an accurate estimate of link delay deviation could be estimated independently of the behaviour of the routing stack. In optical networks, GMPLS ping packets can be coupled with the anomaly detection algorithm.

Clearly, in wireless networks the anomaly detection can be used to identify alteration of the channel quality (like link delay, throughput dynamically changing over time, while in optical networks the detection would behave more like a green/red alarm notification. Figure 11 shows the dynamic testing of the anomaly detection.

Figure 11 – Real-time detection of PLA anomalies.

The probing interval is adapted dynamically according to the channel condition (appropriate for wireless channels), while an alarm status reports the actual estimation of the channel (a latency deviation is more likely in a wireless channel, while a complete node failure more likely on a fixed link).

7.5. Generic Path Related Deliverables

The goals of D5.1 are to define the generic path abstraction and to elaborate a functional architecture based on generic paths. The architecture is intended to be sufficiently flexible to allow a broad range of communication paradigms to coexist. Different types of generic path are structured in a class hierarchy where the functionality of a given type is derived by adding specific features to a common basis inherited from its parent. The architecture is constructed using two other structures, the Mediation Point and the Compartment that are also defined in multiple types within a class hierarchy. The base classes define the functions and interfaces that are common to all members of the respective hierarchies. These base classes will be more fully defined in a future version of the architecture specification. The document explains how specific generic paths will be instantiated, identifying the essential operations and functions that are required to establish the paths, manage their topology and actually realise data transport. Specific mechanisms that realise the identified functions for various path types will be further described in future deliverables. To illustrate the flexibility of the elaborated concepts, D5.1 shows how they are applied in a number of use cases representing typical communication scenarios.

D-5.2.0 contains preliminary results of the development and evaluation network coding and routing mechanisms to enable cooperation of nodes along a path to improve the stability and performance of data transport. An update on the Generic Path functional architecture is presented recalling the essential elements that are to be exploited to realise the envisaged cooperation. A framework is proposed that simplifies the introduction of cooperation techniques like network coding in the protocol stack and detects situations when applying such techniques is beneficial. Routing mechanisms in real networks increasingly depend on the nature of the physical layer, leading to specialised algorithms for wireless and optical media or delay-tolerant networks. Multi-path routing is identified as an important feature of the future Internet leading to more efficient traffic engineering and enhancing resilience to failures. Several routing algorithms are analysed, demonstrating the advantage of a path-oriented cooperation. Considered algorithms all have their own routing metrics and path selection algorithms.

In D5.1, it is referred that the basic functions which seem to be essential in order to manipulate Generic Paths (resource management, routing, etc.) as it has been identified. Nevertheless, all these functions appear as empty boxes. Specific mechanisms realising any particular function will be investigated and specified in forthcoming deliverables.

In D5.2.0, inter-domain routing metrics are presented:

- Transfer availability;
- Total traffic between providers (ISPs);
- Amount of traffic transferred between providers;
- Duration of sustained peak traffic load;
- Size of the routing table;
- Connectivity;
- Packet reordering;
- Packet transfer delay;
- Delay variation (jitter);
- Latency;
- Throughput;
- Packet error ratio;
- Packet loss ratio;
- AS path length (number of crossed providers);
- Failure notification propagation;
- Specific routing protocol;
- Autonomous System Compartment length;
- Transit cost;
- Peering factor;
- Stability factor;

In particular when referring to the Stability factor, it is referred that this metric illustrates how stable a path is based on the related detailed metrics like path length, packet error/drop rate, failure detection time, etc.

D5.2 presents mechanisms for the Generic Path in its evolved architecture since project start. Based on the current definition of the GP architecture, the document focuses on the final achievements for the GP support to cooperation and coding and to multi-path, inter-layer and inter-domain routing. Physical layer awareness is introduced in this routing context through energy consumption awareness, thanks to the use of dynamic ILR (Inter Layer Routing) in IP over WDM networks. Proposed solutions aim to reduce the number of active lightpaths and line cards in order to save energy. The chapter dedicated to management and sharing of GP Resources also introduces physical layer awareness considerations thanks to several proposals based on resources ontology and resource management database.

8. Conclusions

In this deliverable Physical Layer Awareness in future Internet 4WARD networks was addressed.

In optical core and access networks there are two main situations where physical impairments should be taken into account: planning and network operation. As opaque networks are especially designed to guarantee the quality of transmission link by link, physical layer awareness is usually dependent of a single parameter, loss of light. The knowledge of physical impairments is not required at higher levels to operate such networks. Focus should be given to transparent and translucent networks for which physical layer awareness is seen as a major requirement particularly for control plane functions.

An important conclusion on the description of the different effects affecting optical transmission is that they are very dependent on system parameters, such as bit rate and modulation format. The way impairments are compensated is very dependent on system vendors' technological choices, being closely related to the prohibitive cost for deploying new cable structures that drive operators to exploit their installed infrastructure.

From the wireless access perspective, physical channel impairments impose restrictions to the overall network behaviour, since it can affect throughput, maximum delay, packet loss, and packet error, among other parameters, thus, imposing additional restrictions that are not usually found in wired systems. The mobility issue, together with the needs for efficient handovers, imposes additional complexity in terms of network signalling, moreover, link reliability is not assured, thus, increasing the complexity of traffic control and packet scheduling algorithms. As far as network resilience is concerned, wireless channel impairments impose extra difficulties, due to link availability and reliability.

4WARD has developed a generic Architectural Framework containing both the microscopic and macroscopic views for current and future networks. The concepts and principles are applicable at all level of different networks. When the Architectural Framework is applied to specific use cases then the physical layer awareness is at least implicitly present, although these aspects are often assumed to be hidden into a virtual machine stratum containing the actual physical networks.

A key element in the Virtualisation process is the provisioning process, virtual networks being embedding into physical substrate, the main challenge in the 4WARD context is scalability. Distributed embedding algorithms for virtual networks were implemented and tested at scale using the GRID5000 experimental platform. The algorithms were found to perform favourably in comparison to known centralised approaches; in particular, they are able to map a VNet with shorter delays than a centralised approach. The tests were performed both for initial embedding of new VNets, and adaptive embedding of existing VNets, e.g., in response to failing network resources. In the latter case, it was found that the distributed algorithm can improve the delay by up to a factor of ten when the number of substrate nodes is large.

Promising results were also achieved in the area of mobility-aware embedding, i.e., the mapping of virtual networks in the presence of mobile resources in the physical substrate. The main challenge here is to maintain suitable mappings and thus a coherent virtual network when mobile resources are moving. Simulations of the algorithms demonstrated the benefits of path splitting and migration techniques for mobile substrates, and showed that high ratios of repairing and remapping can be achieved without suffering unacceptable delays.

Maximisation of the usage of resources in the future Internet requires enhanced control functions that support granular access to the physical layer and real-timeliness in the optimisation process. The complexity of the sources for channel impairments can be analysed through management functions that derive root cause analysis from the network configuration and drive the adequate optimisation functions. 4WARD has proposed the In-Network Management (INM) design to build a distributed architecture for network management. Monitoring and adaptation are co-designed with the transport function of the physical devices and distributed algorithms are executed to build aggregated objectives. The approach allows for two major features. The first one is the establishment of an effective monitoring function that gather common characteristics of the physical layer (e.g., wireless area vs. wired area); the second one is the availability of real-time information on network performances that can be mapped to operator’s objectives.

The tools introduced by INM are expected to be beneficial to support real deployments of advanced services in the future Internet. The ubiquity of services and their richness in content requires an adequate level of reliability that makes channel impairments invisible to end-users and this can be achieved through the distributed architecture of the INM functions.

Overall, the achieved results are of key relevance for a Physical Layer Aware Network Architecture for the Future Internet.

References

[3GPP00a] 3GPP, *UE Radio Transmission and Reception (TDD)*, Technical Specification Group Radio Access Network, Report No. 25.102 v3.2.0, France, Mar. 2000 (http://www.3gpp.org).

[3GPP00b] 3GPP, *UE Radio Transmission and Reception (FDD)*, Technical Specification Group Radio Access Network, Report No. 25.101 v3.2.0, France, Mar. 2000 (http://www.3gpp.org).

[4WAR08] 4WARD, Deliverable D-2.1 *Technical Requirements*, European Commission, Brussels, Belgium, Aug. 2008.

[4WAR08a] 4WARD Deliverable, *D-6.1 First NetInf architecture description*, European Commission, Brussels, Belgium, Jan. 2008.

[4WAR08b] 4WARD Deliverable, *D-4.1 Definition of scenarios and use cases*, European Commission, Brussels, Belgium, June 2008.

[4WAR08c] 4WARD Deliverable, *D-2.1 Technical Requirements*, European Commission, Brussels, Belgium, Aug. 2008.

[4WAR09a] 4WARD Internal Technical Report, 4WARD-WP5-IST-007-3.0-EXT-Theme_Physical_Layer_Awareness.doc, *Physical Layer Awareness*, IST-TUL, Lisbon, Portugal, Jan. 2009.

[4WAR09b] 4WARD Deliverable, *D-3.1.0 Virtualisation Approach: Concept (Draft)*, European Commission, Brussels, Belgium, Jan. 2009.

[4WAR09c] 4WARD Deliverable, *D-5.1 Architecture of a generic path*, European, Commission, Brussels, Belgium, Feb. 2009.

[4WAR09d] 4WARD Deliverable, *D-4.2 In-network management concept*, European Commission, Brussels, Belgium, Feb. 2009.

[4WAR09e] 4WARD Deliverable, *D-5.2.0 Description of generic path mechanism*, European Commission, Brussels, Belgium, Feb. 2009.

[4WAR09f] 4WARD Deliverable, *D-2.2 Draft Architectural Framewor*k, European Commission, Brussels, Belgium, Feb. 2009.

[4WAR09g] 4WARD Deliverable, *D5.2 Mechanisms for Generic Paths*, European Commission, Brussels, Belgium, Dec. 2009.

[4WAR10a] 4WARD Deliverable, *D-2.3.0 Architectural Framework: new release and first evaluation results*, European Commission, Brussels, Belgium, Jan. 2010.

[4WAR10b] 4WARD Deliverable, *D3.2.1 Virtualisation Approach: Evaluation and Integration*, European Commission, Brussels, Belgium, Jan. 2010.

[4WAR10c] 4WARD Deliverable, D-4.3 *In-network Management Design*, European Commission, Brussels, Belgium, Jan. 2010.

[Agra89] G.P. Agrawal, *Nonlinear Fibre Optics*, Vol. 1, 2nd ed., Academic Press, London, UK, 1989.

[Agra97] G.P. Agrawal, *Fibre-Optic Communication Systems*, Vol. 1, 2nd. ed., Academic Press, London, UK, 1997.

[AGRS04] S. Acharya, B. Gupta, P. Risbood and A. Srivastava, "PESO: Low Overhead Protection for Ethernet over SONET Transport", *Proc. of INFOCOM 2004 – 23rd Annual Joint Conference of the IEEE Computer and Communication Societies*, Hong-Kong, China, Mar. 2004.

[APMS07] V. Agnastopoulos, C. Politi, C. Matrakidis and A. Stavdas, "Physical layer impairment aware wavelength routing algorithms based on analytically calculated constraints", Optics Communications, Vol. 270, Nº 2, Feb. 2007, pp. 247-254.

[Bern08a] G. Bernstein, A Framework for the Control and Measurement of Wavelength Switched Optical Networks (WSON) with Impairments, draft-bernstein-ccamp-wson-impairments-00.txt, IETF, 2008.

[Bern08b] G. Bernstein, Signaling Extensions for Wavelength Switched Optical Networks, , IETF, 2008.

[BeRS04] G. Bernstein, B. Rajagopalan, S. Saha, Optical network control: Architecture, Protocols & Standards, Reading, Addison-Wesley, MA, 2004.

[Boua07] N. Bouabdallag, "Sub-Wavelength Solutions for Next-Generation Optical Networks", *IEEE Communications Magazine*, Vol. 45, No. 8, Aug. 2007, pp. 36-43.

[BTGF03] D. Breuer, H.J. Tessmann, A. Gladisch, H.M. Foisel, G. Neumann, H. Reiner and H. Cremer, "Measurements of PMD of the installed plant of Deutsche Telekom", Digest of the LEOS summer topical meetings, MB2.1, 2003.

[CaCM05] R. Cardillo, V. Curri and M. Mellia, "Considering Transmission Impairments in Wavelength Routed Networks", IEEE Proceedings of the ONDM, Milano, Italy, 2005.

[CaCo03] F.D. Cardoso and L.M. Correia, "Fading Depth Dependence on System Bandwidth in Mobile Communications – An Analytical Approximation", *IEEE Transactions on Vehicular Technology*, Vol. 52, No. 3, May 2003, pp. 587 594.

[CaCo05] F.D. Cardoso and L.M. Correia, "A Time-domain Based Approach for Short-Term Fading Depth Evaluation in Wideband Mobile Communication Systems", *Wireless Personal Communications*, Vol. 35, No. 4, Dec. 2005, pp. 365-381.

[CaKC06] F.D. Cardoso, W. Kotterman and L.M. Correia, “Channel Characterisation (Sec. 4.5)”, in L.M. Correia (ed.), *Mobile Broadband Multimedia Networks – Techniques, Models and Tools for 4G*, Academic Press, London, UK, 2006.

[CAVC04] F. Cugini, N. Andriolli, L. Valcarenghi and P. Castoldi, "A novel signalling approach to encompass physical impairments in GMPLS networks", IEEE Globecom 2004, Dallas, Texas, USA, Nov./Dec. 2004.

[Cher08] S. Cherry, Edholms Law of bandwidth, IEEE Spectrum, July 2004.

[Cisc08] Cisco, http://www.cisco.com/en/US/solutions/collateral/ns341/ns525/ns537/net_implementation_white_paper0900aecd806a81aa.pdf, 2008.

[CoOd02] K. Coffman and A. Odlyzko, Internet growth: is there a "Moore's law" for data traffic?, http://portal.acm.org/citation.cfm?id=779232.779236&coll=portal&dl=ACM, 2002.

[Dijk59] E.W. Dijkstra, "A note on two problems in connexion with graphs", Numerische Mathematik, Vol. 1, 1959, pp. 269–271.

[EsRM02] R. Essiambre, G. Raybon and B. Mikkelsen, "Optical Fibre Telecommunications", volume IVB, chapter 15, pages 725-861, Elsevier Science Imprint, 2002.

[FaLe02] H. Fattah and C. Leung, “An Overview of Scheduling Algorithms in Wireless Multimedia Networks”, IEEE Wireless Communications, Vol. 9, Nº 5, Oct. 2002.

[FeSC06] L. Ferreira, A.S. Serrador, L. Correia, “Concepts of Simultaneous Use in Mobile and Wireless Communications”, in *Wireless Personal Communications*, Springer Vol. 37, No. 3-4, May, 2006, pp. 317-328.

[Forr08] http://www.forrester.com/ER/Press/Release/0,1769,1203,00.html, May 2008.

[Hobb08] Hobbes Internet timeline, http://www.zakon.org/robert/internet/timeline/, May 2008.

[HoTo00] H. Holma and A. Toskala, *WCDMA for UMTS*, John Wiley, Chichester, UK, 2000.

[IEEE03a] IEEE, *Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications Amendment 4: Further Higher Data Rate Extension in the 2.4 GHz Band, 802.11g*, USA, Jun. 2003 (http://standards.ieee.org).

[IEEE03b] IEEE, *IEEE Trial-Use Recommended Practice for Multi-Vendor Access Point Interoperability via an Inter-Access Point Protocol Across Distribution Systems Supporting IEEE 802.11 Operation, 802.11f*, USA, Jun. 2001 (http://standards.ieee.org).

[IEEE03c] IEEE, *Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications Amendment 5: Spectrum and Transmit Power Management*

Extensions in the 5 GHz band in Europe, 802.11h, USA, Oct. 2003 (http://standards.ieee.org).

[IEEE04a] IEEE, *Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications Amendment 6: Medium Access Control (MAC) Security Enhancements, 802.11i*, USA, Jul. 2004 (http://standards.ieee.org).

[IEEE04b] IEEE, *P802.3ah Ethernet in the First Mile Task Force*, http://www.ieee802.org/3/efm, 2004

[IEEE07a] IEEE, http://www.ieee802.org/3/av, Feb. 2007.

[IEEE07b] IEEE, *Local and metropolitan area networks-Specific requirements, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*, USA, June 2007 (http://standards.ieee.org).

[IEEE09] IEEE, http://www.ieee802.org/16/relay, Dec. 2009

[IEEE10] IEEE, http://www.ieee802.org/21, May 2010.

[IEEE99a] IEEE, *Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications High-speed Physical Layer in the 5 GHz Band, 802.11a*, USA, 1999 (http://standards.ieee.org).

[IEEE99b] IEEE, *Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: Higher-Speed Physical Layer Extension in the 2.4 GHz Band, 802.11b*, USA, Sep. 1999 (http://standards.ieee.org).

[ITUD08] ITU, http://www.itu.int/ITU-D/ict/statistics/ict/, May 2008.

[ITUT00] ITU-T Recommendation G.828, "Error performance parameters and objectives for international, constant bit rate synchronous digital paths", 2000.

[ITUT03] ITU-T G.709, “Interfaces for the Optical Transport Network”, Mar. 2003 (http://www.itu.int/rec/T-REC-G.709/e).

[ITUT04] ITU-T Recommendation G.697, "Optical Monitoring for DWDM systems", 2004.

[ITUT06a] ITU-T Recommendation G.7042, "Link capacity adjustment scheme (LCAS) for virtual concatenated signals", 2006.

[ITUT06b] ITU-T Recommendation G.691, "Optical Interfaces for single channel STM-64 and other SDH systems with optical amplifiers", 2006.

[ITUT06c] ITU-T Recommendation G.6653, "Characteristics of a dispersion-shifted single-mode optical fibre and cable", 2006.

[ITUT07] ITU-Y Recommendation G.707, "Network node interface for the synchronous digital hierarchy (SDH)", 2007

[ITUT08a] ITU-T Recommendation G.7041, "Generic framing procedure (GFP)", 2008.

[ITUT08b] ITU-T Recommendation G.680, "Physical Transfer functions of Optical Network Elements"; Correspondence work for the revision, 2008.

[ITUT08c] ITU-T Recommendation G.984.1, “Gigabit-capable passive optical networks (GPON)”, 2008

[ITUT09a] ITU-T Recommendation G.709, "Interfaces for the Optical Transport Network (OTN)", 2009

[ITUT09b] ITU-T Recommendation G.652, "Characteristics of a single-mode optical fibre and cable", 2009

[ITUT09c] ITU-T Recommendation G.655, "Characteristics of a non-zero dispersion-shifted single-mode optical fibre and cable", 2009

[ITUT88] ITU-T Recommendation G.602, "Reliability and availability of analogue cable transmission systems and associated equipments", 1988.

[JoJo96] M. Joindot and I. Joindot, *Telecommunications by Optical Fibres* (in French), 1st. ed., Dunod, 1996.

[Kart04] S.V. Kartalopoulos, *Next Generation SONET/SDH, Voice and Data*, IEEE Press/Wiley Interscience, NY, USA, 2004.

[KiKr00] J. Kim and M. Krunz, “Bandwidth Allocation in Wireless Networks with Guaranteed Packet-Loss Performance”, IEEE/ACM Transactions on Networking, Vol. 8, No. 3, June 2000.

[KoJo02] H. Kogelnik and R.M. Jopson, "Optical Fibre Telecommunications", volume IVB, chap. 15, Elsevier Science Imprint, 2002, pp. 725-861.

[LiES00] M. Listanti, V. Eramo and R. Sabella, “Architectural and technological issues for future optical internet networks”, IEEE Communications Magazine, Vol. 38, No. 9, Sep. 2000, pp. 82-92.

[LLLB07] B. Lavige, F. Leplingard, L. Lorcy, E. Balmefrezol, J.C. Antona, T. Zami and D: Bayart, "Method for the determination of a quality of transmission estimator along the lightpathhs of partially transparent networks", ECOC, Dresden, Germany, Sep. 2007.

[LoZH08] W. Louati, D. Zeghlache, and I. Houidi, *Provisioning of Virtual Networks and Virtualisation Management*, 4WARD Project, Draft document, Mar. 2008.

[Mart08] G. Martinelli, A Framework for defining Optical Parameters to be used in WSON networks through GMPLS, draft-martinelli-ccamp-opt-imp-fwk-00.txt, IETF, 2008.

[MPCW06] R. Martinez, C. Pinart, F. Cugini, L. Wosinska, J. Comellas and G. Junyent, "Challenges and requirements for introducing impairment-awareness into the management and control planes of ASO/GMPLS WDM networks", IEEE Comm. Mag., 2006.

[Niel08] J. Nielsen, Nielsen's Law of Internet Bandwidth, http://www.useit.com/alertbox/980405.html, May 2008.

[Nuth08] P. Nuthal, European Mobile Forecast: 2008 To 2013: http://www.forrester.com/Research/Document/0,7211,42199,00.html, Mar. 2008

[PeMP] J. Pedro, P. Monteiro and J. Pires, "Wavelength Contention Minimisation Strategies for Optical Burst-Switched Networks", *Proc. of GLOBECOM'2006 - IEEE Global Communications Conference*, Washington, DC, USA, Nov. 2006

[PGWV06] S. Pachnicke, T. Gravemann, M. Windmann and E. Voges, "Physically constrained routing in 10Gbit/s DWDM networks including fibre non-linearities and polarisation effects", J. Lightwave Technology, Vol. 24, No. 9, 2006.

[PhEl08] Nortel blog from Phil Elmond, http://blogs.nortel.com/enterpriseblog/2007/11/14/bandwidth-growth/, May 2008.

[PiLMo7] C. Pinart, E. Le Rouzic and I. Martinez, "Physical-layer considerations for the realistic deployment of impairment-aware connection provisioning", ICTON 2007, Rome, Italy, July 2007.

[RAKo08] R. Koetter, "Codes for Networks", (keynote talk) WiOpt'08 - 6th Intl. Symposium on Modeling and Optimisation in Mobile, Ad Hoc, and Wireless Networks, Berlin, Germany , Mar./Apr. 2008 (http://www.wiopt.org/pdf/talk_Koetter_WiOpt08.pdf).

[RaSi02] R. Ramaswami and K. N. Sivarajan, *Optical Networks- A Practical Perspective*, Morgan Kaufmann Publishers, San Francisco, CA, USA, 2002.

[RaSi95] R. Ramaswami and K.N. Sivaraja, "Routing and wavelength assignment In all-optical networks", IEEE/ACM Trans. On networking, Vol. 3, No. 5, 1995, pp. 489-500.

[RDFH99] B. Ramamurthy, D. Datta, H. Feng, J.P. Heritage and B. Mukherjee, "Impact of transmission impairments on the teletraffic performance of wavelength-routed optical networks", IEEE J. Lightwave Technology, Vol. 17, No. 10, 1999, pp. 1713-1723.

[RhMK03] J.K. Rhee, R. Madara and J. Kondis, "Group Delay Dispersion Performance Requirement for Optical Cross Connects and Add-Drop Multiplexers in Ultralong-Haul DWDM Transport Systems", IEEE Photonics Technology Letters, Vol. 15, No. 6, 2003, pp. 876-878.

[RIPE07] RIPE Annual Report 2007, Slide 16, http://www.ripe.net/ripe/draft-documents/gm-may2008/annualreport2007.pdf, Dec. 2007.

[RuBa10] A.B. Rus, M. Barabas, G. Boanea, Z. Kiss, Z. Polgar and V. Dobrota, “Cross-Layer QoS and Its Application in Congestion Control”, 17th IEEE Workshop on Local and Metropolitan Area Networks LANMAN 2010, Long Branch, NJ, USA, May 5-7, 2010.

[SGCC07] N. Sambo, A. Giorgetti, I. Cerutti and P. Castoldi, "A contention detection scheme for lightpah restoration in GMPLS networks", IEEE Comm. Lett., Vol. 11, No. 10, 2007, pp. 820-822.

[ShGu99] Y. Shen, K. Lu K. and W. Gu, "Coherent and Incoherent Crosstalk in WDM Optical Networks", IEEE Journal of Lightwave Technology, Vol. 17, No. 5, 1999 pp. 759-764.

[SLSD05] M. Scuster, G. Lehmann, D.A. Schupke, S.S. Duhovnikov, G. Göger, " Wavelength dependent reach in transparent optical networks", Broadband Europe, 2005.

[VCPP07] B. Vieira, D. Conceição, J. Pedro and J. Pires, “Evaluating the Impact of Physical Impairments of an All-optical WDM Ring under Dynamic Traffic”, *Journal of Optical Communications*, Vol. 28, No. 1, Jan. 2007, pp. 66-72.

[Wein01] S. Weinstein, “Realizing the Optical Ethernet”, *IEEE Communications Magazine*, Vol. 39, No. 7, Jul. 2001, pp. 10.

[WiMa05] WiMax Forum, *WiMax Technology-Technical Information Overview*, April, 2005, (http://www.wimaxforum.org/technology).

[WoSt08a] Internet World Stats, http://www.internetworldstats.com/stats.htm, May 2008.

[WoSt08b] http://www.internetworldstats.com/stats.htm, May 2008

[YaRa05] X. Yang and B. Ramamurthy, "Dynamic Routing in Translucent WDM Optical Networks: the Intradomain Case", IEEE Journal of Lightwave Technology, Vol. 23, No. 3, 2005, pp. 955-971.

[ZAPR04] T. Zami, J.C. Antona, P. Peloso, E.L. Rouzic, A. Morea, M. Joindot, B. Fracasso, P. Gravey and M. Gagnaire, "Dimensioning of WDM transparent networks based on the Quality of Transmission", Proceedings of BroadBand Europe, Brugge, 2004.

[ZBPC02] J. Zyskind, R. Barry, G. Pendock, M. Cahill and J. Ranka, "Optical Fibre Telecommunications", Vol. IV B, Chap. 5, Elsevier Science Imprint, 2002, pp. 198-231.