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Frequency Allocation and Management for Optical Wireless Communication

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Supervisor:

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Institute of Microwave and Photonic Engineering,

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Abstract

Spectrum management was established around 100 years ago. The spectrum of interests has been shifted with every decade to higher frequencies. The present frequency allocation tables cover a frequency range from around 10 kHz to 3 THz. This includes radio-, microwave- and terahertz radiation but excludes the optical radiation.

Nowadays consumer electronics and the whole wireless communication market depend on high data rates. The high demand on wireless broadband communications can hardly satisfied by radio frequency based applications only. The used UHF and VHF bands cannot provide the amount of bandwidth which would be necessary. This leads to an increasing interest on optical radiation and optical wireless communication systems.

The aim of this thesis is to propose possibilities of spectrum management for optical radiation. The advantages and disadvantages of a change from a not regulated spectrum to a regulation and allocation of certain spectrum bands are pointed out. Therefore, the spectrum management used for radio and microwave radiation was under investigation. This includes the regulation bodies on national, regional and international level, how these organizations work, what objectives they follow and what strategies they use. Some success stories and also failures in spectrum management of the last decades are used as examples.

This thesis is divided in four parts. The first part should give a short overview of the used resource electromagnetic spectrum and the history of wireless communication in particular the optical communication. The second part provides an introduction of the regulation bodies and the theory of spectrum management. In the third part, the UHF band is analyzed as example for spectrum management in the last decades. The evolution of the mobile telecommunication and the TV broadcast is pointed out. The last part gives a proposal for a regulation of the optical radiation and show how the common approaches could be transferred from radio and microwave to optical radiation.

Kurzfassung

Spektrum Management wurde vor rund 100 Jahren erstmals betrieben. Der Teil des Spektrums, welches für kabellose Kommunikation von Interesse ist, hat sich mit jedem Jahrzehnt zu höheren Frequenzen verschoben. Die heutzutage genutzten Frequenzzuteilungstabellen decken einen Frequenzbereich von etwa 10 kHz bis 3 THz ab. Dies impliziert Funk-, Mikrowellen- und Terahertz-Strahlung, schließt aber die optische Strahlung aus.

Heutige Unterhaltungs- und Haushaltselektronik und der gesamte Telekommunikationsmarkt sind abhängig von hohen Datenraten. Die hohe Nachfrage an drahtloser Breitbandkommunikation kann nur schwer durch radiofrequenzbasierte Systeme erfüllt werden. Die verwendeten UHF und VHF Bänder können nicht die Menge an Bandbreite zur Verfügung stellen, die erforderlich wären. Dies führt zu einem steigenden Interesse an optischen drahtlosen Kommunikationssystemen und optischer Strahlung.

Das Ziel dieser Diplomarbeit ist es, Möglichkeiten der Frequenzverwaltung für optische Strahlung vorzustellen. Die Vor- und Nachteile einer Änderung von einem nicht geregelten Spektrum zu einer Regulierung und einer Zuweisung bestimmter Frequenzbänder werden untersucht. Die Frequenzverwaltung für Funk- und Mikrowellenstrahlung wird analysiert und die dafür zuständigen Regulierungsstellen auf nationaler, regionaler und internationaler Ebene vorgestellt, sowie dessen Organisationsstrukturen, Ziele und Strategien beleuchtet. Einige Erfolgsgeschichten und auch Misserfolge der letzten Jahrzehnte werden als Beispiele der Frequenzverwaltung angeführt.

Diese Arbeit ist in vier Teile gegliedert. Der erste Teil soll einen kurzen Überblick über das elektromagnetische Spektrum bieten und die Geschichte der drahtlosen Kommunikation, insbesondere die optische Kommunikation darstellen. Der zweite Teil enthält eine Einführung in die Regulierungsorganisationen und die Theorie der Frequenzverwaltung. Im dritten Teil wird das UHF-Band als Beispiel für die Frequenzverwaltung in den letzten Jahrzehnten analysiert. Im Speziellen wird auf die Entwicklung des Mobilfunks und des Fernsehrundfunks eingegangen. Im letzten Teil wird ein Vorschlag für eine Regulierung der optischen Strahlung präsentiert. Dabei wird gezeigt, welche Ansätze von Funk- und Mikrowellenstrahlung auf die optische Strahlung übertragen werden können.

Acknowledgments

I would like to thank Prof. Dr. Erich Leitgeb, who have been supporting me since 2008. He guided me through the challenges of the last years including this and a former thesis, helped in countless situations with word and deed and have been opening a lot of doors for me.

Ein ganz besonderes Dankeschön gilt meinen Eltern, die mir das Studium ermöglichten und mich immer unterstützt haben. Für die Unterstützung in jeglicher Lebenslage, für Rat und Tat möchte ich mich bei meinem Bruder und meinen besten Freunden bedanken.

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List of Abbreviations and Symbols

1G	First generation
2G	Second generation
3G	Third generation
3GPP	Third Generation Partnership Project
4G	Fourth generation
ANSI	American National Standards Institute
APD	Avalanche photo diode
APT	Asia Pacific Telecommunity
ATSC	Advanced Television Systems Committee standards
ATU	African Telecommunications Union
BW	bandwidth
CDMA	Code Division Multiple Access
CEPT	European Conference of Postal and Telecommunication Administrations
CERP	European Committee for Postal Regulation
CIE	International Commission on Illumination
CITEL	Inter-American Telecommunication Commission
Com-ITU	Committee for ITU Policy
CT	Cordless telephone
CTU	Caribbean Telecommunications Union
D-AMPS	Digital Advanced Mobile Phone System
DECT	Digital Enhanced Cordless Telecommunication
DTMB	Digital Terrestrial Multimedia Broadcast
DVB	Digital Video Broadcasting
EC	European Commission
ECA	European Common Allocation
ECC	Electronic Communications Committee

ECM	Electronic Countermeasures
ECO	European Communications Office
EEA	European Economic Area
EFIS	ECO Frequency Information System
EHF	Extremely high frequency
EICTA	European Information and Communication Technology Industry Association
ERC	European Research Council
ERO	European Radiocommunications Office
EMC	Electromagnetic Compatibility
ENTO	European Telecommunications Network Operators
ETSI	European Telecommunications Standards Institute
EU	European Union
FCC	Federal Communications Commission
FIR	Far infrared
FLO	Forward Link Only
FSO	Free Space Optics
GPRS	General Packet Radio Service
GSM	Group Special Mobile
	Global Systems for Mobile Communication
HF	High frequency
HSPA	High Speed Packet Access
IARU	International Amateur Radio Union
ICT	Information and communication technology
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronic Engineering
IMT	International Mobile Telecommunications
infoDEV	Information for Development Program (World Bank)
InGaAsP	Indium Gallium Arsenide Phosphide

IR	Infrared
ISDB	Integrated Services Digital Broadcasting
ISM	Industrial, scientific and medical
ISO	International Organization for Standardization
ITU	International Telecommunication Union
LAS	League of Arab States
LASER	Light Amplification by Stimulated Emission of Radiation
LD	Laser diode
LED	Light emitting diode
LF	Low frequency
LoU	Letter of Understanding
LTE	Long Term Evolution
MIR	Mid infrared
MoU	Memorandum of Understanding
NIR	Near infrared
NRA	National Regulatory Authority
NTSC	National Television System Committee
NTIA	National Telecommunications and Information Administration
OAS	Organization of American States
PAL	Phase Alternating Line
PCC	Permanent Consultative Committee
PCS	Personal Communications Systems
PD	Photo diode
PT	Project team
R&TTE	Radio and Telecommunications Terminal Equipment Compliance Association
RCC	Regional Commonwealth in the field of Communications
RR	Radio Regulation
RTR	Rundfunk und Telekom Regulierungs-GmbH

SEAMCAT	Spectrum Engineering Advanced Monte Carlo Analysis Tool
SECAM	Séquentiel couleur à mémoire
Si	Silicon
SHF	Super high frequency
TACS	Total Access Communication System
TDMA	Time Division Multiple Access
THF	Tremendously high frequency
UHF	Ultra high frequency
UMTS	Universal Mobile Telecommunications System
UN	United Nations
USA	United States of America
USSR	Union of Soviet Socialist Republics
UV	Ultraviolet
VHF	Very high frequency
VL	Visible light
VLC	Visible light communication
VLF	Very low frequency
WAN	Wide area network
WARC	World Administrative Radio Conference
WG	Work group
WLAN	Wireless local area network
WiFi	Synonym for WLAN
WRC	World Radiocommunication Conference

c	speed of light = 299,792,458 m/s $\approx 3*10^8$ m/s
f	frequency
λ	wavelength

1 Introduction

This master thesis presents an investigation of the technical and economical use of a frequency allocation and regulation above 3 THz considering the common approaches in spectrum engineering and management.

1.1 Motivation

In its Information and Communication Technology (ICT) Regulation Toolkit – Radio Spectrum Management – the International Telecommunication Union (ITU) write in the Chapter Spectrum as a Resource following statement [1]:

"The demand for spectrum is increasing and many frequency bands are becoming more congested especially in densely populated urban centers. Spectrum managers are taking various approaches to improve efficiency; using administrative methods including inband sharing, changes to licensing such as spectrum leasing and spectrum trading, and use of unlicensed spectrum (the spectrum commons) combined with the use of low power radios or advanced radio technologies including ultra-wideband and multi-modal radios".

This citation should illustrate the situation in radio spectrum engineering and management nowadays. The demand on fast wireless data connections for a huge variation of applications causes problems in technical and also economic manner.

Different approaches, as mentioned before in the citation, lead to a more efficient use of the radio spectrum. Another approach is the use of a completely different range of the electromagnetic spectrum for wireless communication. In the last two decades plenty of investigations have been done on optical wireless communication. Corresponding communication systems, so called Free Space Optical (FSO) communication systems have been developed and are available on market.

Due to this increasing interest on optical wireless communication and with it the cumulative use of this part of the electromagnetic spectrum, this thesis investigate the possibilities, advantages and disadvantages of a regulation of this frequency spectrum range.

1.2 Structure of the thesis

After a short introduction and the motivation in Chapter 1, Chapter 2 covers the basics for this thesis. The electromagnetic spectrum with its different bands is described and a background of optical communication is given.

In Chapter 3 the regulation bodies national, regional and international are mentioned. The mechanisms and the links between these national authorities and international institutions are illustrated.

The spectrum management and its core functions including spectrum planning, engineering, authorization and monitoring are described in Chapter 4.

In Chapter 5 the frequency allocation done in the last decades for a frequency range up to 3 THz is under investigation. The conclusions of this investigation should provide a basis for a potential regulation of the electromagnetic spectrum above 3 THz.

Chapter 6 points out the possible mechanism and the technical and economic advantages or disadvantages of a regulation of the optical radiation.

A final conclusion of this investigation of frequency engineering and management for optical radiation is given in Chapter 7.

2 Fundamentals of optical communications

The following chapter should give a short overview of the electromagnetic spectrum, interesting investigations and the most important developments in case of optical communication since the beginning of the 20th century.

2.1 The electromagnetic spectrum

The electromagnetic spectrum is a valuable and natural, but limited resource. Like for any other natural resource, every country is responsible by itself for its use. Worldwide national, regional and international organizations try to harmonize the efficient use of the spectrum. For a more in-depth discussion of regulation bodies see Chapter 3.

The electromagnetic spectrum is split up in three major parts:

- Radio and microwave radiation
- Optical radiation
- Ionizing radiation

Figure 1 shows the spectrum with the frequencies and related wavelength. The most common used frequency bands are mentioned.

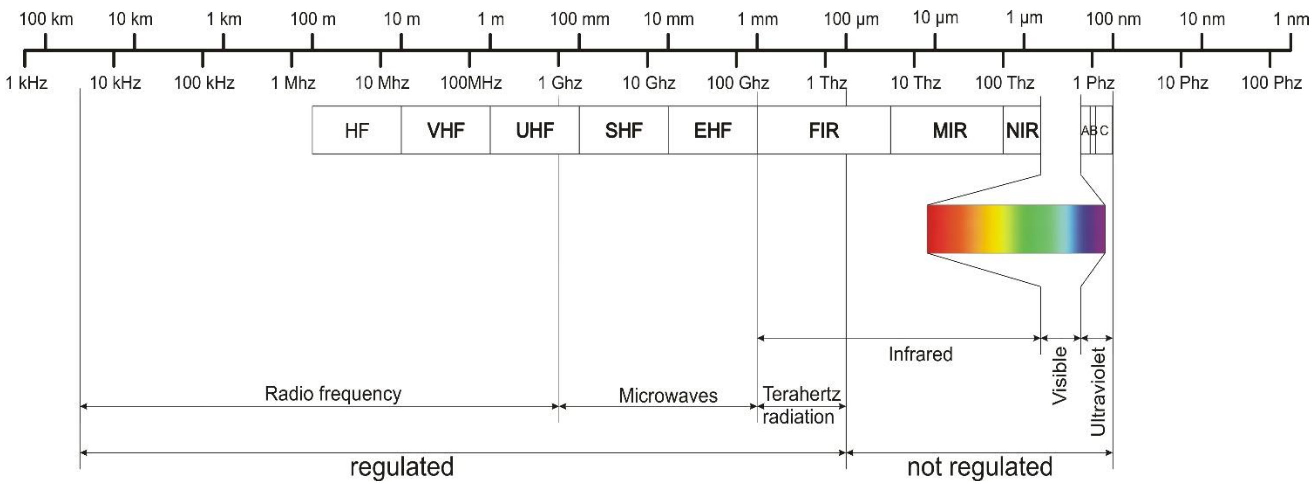

Figure 1: Electromagnetic spectrum

The frequency range of 8.3 kHz to 3000 GHz is regulated by the European Table of Frequency Allocations and Applications (ECC Report 25) [2]. This range with the corresponding wavelength of 36 km to 100 µm and the optical radiation are used spectrum ranges for wireless communication and explicate in the following subchapters.

Frequency	**IEEE**	**EU, NATO, US ECM**	**ITU No.**	**ITU Abbr.**
		A		TLF
3 Hz			1	ELF
30 Hz			2	SLF
300 Hz			3	ULF
3 kHz			4	VLF
30 kHz			5	LF
300 kHz			6	MF
3 MHz	HF		7	HF
30 MHz	VHF		8	VHF
250 MHz		B		
300 MHz	UHF		9	UHF
500 MHz		C		
1 GHz	L	D		
2 GHz	S	E		
3 GHz		F	10	SHF

Frequency	**IEEE**	**EU, NATO, US ECM**	**ITU No.**	**ITU Abbr.**
4 GHz	C	G	10	SHF
6 GHz		H		
8 GHz	X	I		
10 GHz		J		
12 GHz	Ku			
18 GHz	K			
20 GHz		K		
27 GHz	Ka			
30 GHz			11	EHF
40 GHz	V	L		
60 GHz		M		
75 GHz	W			
100 GHz				
110 GHz	mm			
300 GHz			12	THF
3 THz				

Table 1: Comparison of radio band designation standards [3]

Table 1 shows the designation standards from different organizations. For several labels with the same name the frequency range differ from one organization to the other.

In the following chapters the ITU abbreviations are used.

2.1.1 Radio frequency and microwaves

The radio frequency spectrum is the portion of electromagnetic spectrum that carries radio and microwaves. The boundaries of radio spectrum are usually considered to range from 9 kHz up to 300 GHz. Roughly the upper three decades with a wavelength between 1 m and 1 mm are called microwaves. The lower limit varies in literature, but is mostly set to 1 GHz or 3 GHz. In this case the upper parts of the UHF band and the SHF and EHF bands (Table 2) can be summarized as microwaves.

Table 2 depicts some of the many uses of radio spectrum associated with various bands derived from their inherent propagation characteristics [1].

Band	Frequency	Use	Bandwidth
VLF	3-30 kHz	Long range radio-navigation	Very narrow
LF	30-300 kHz	Same as VLF, Strategic Communications	Very narrow
MF	0.3-3 MHz	Same as VLF, Strategic Communications	Moderate
HF	3-30 MHz	Global broadcast, Point to Point	Wide
VHF	30-300 MHz	Broadcast, PCS, Mobile, WAN	Very wide
UHF	0.3-3 GHz	Broadcast, PCS, Mobile, WAN	Very wide
SHF	3-30 GHz	Broadcast, PCS, Mobile, WAN, Satellite Communication	Up to 1 GHz
EHF	30-300 GHz	Microcell, Point to Point, PCS, Satellite Communication	Up to 10 GHz

Table 2: Radio frequency propagation [1]

2.1.2 Terahertz radiation

The frequency band from 300 GHz to 3 THz is the overlapping part of the radio frequencies and the optical radiation and has to be seen from two perspectives. In the view of radio waves this radiation is called terahertz radiation and the band THF. For this case this band is mentioned in [2] but not allocated to any services or applications. In case of IR this part of the spectrum with a wavelength of 0.1 mm to 1 mm is defined as far infrared (FIR).

2.1.3 Infrared radiation

The second major part of the electromagnetic spectrum is the optical radiation. The included bands are characterized by the wavelength and not with the corresponding frequency as for RF.

The part of the spectrum from 1 mm to 780 nm is called infrared radiation. This spectrum is split up in three sub bands. The boundaries of these bands can vary depending on the standardization organization. Depending on the application the divisions are chosen by these committees. Table 3 shows two possible sub divisions for IR from ISO [4] and CIE [5]. In the following chapters the ISO scheme is used.

ISO [4]	**Near IR**		**Mid IR**	**Far IR**
	780 nm – 3 µm		3 µm – 50 µm	50 µm – 1 mm
CIE [5]	**IR-A**	**IR-B**	**IR-C**	
	700 nm – 1.4 µm	1.4 µm – 3 µm	3 µm – 1 mm	

Table 3: Commonly used sub-division of IR

Near IR and mid IR up to a wavelength λ = 10 µm are used for wired and also wireless communication systems. Because of a low losses for special wavelength depending on the fiber material or the atmospheric gases, optical windows are defined (Figure 2).

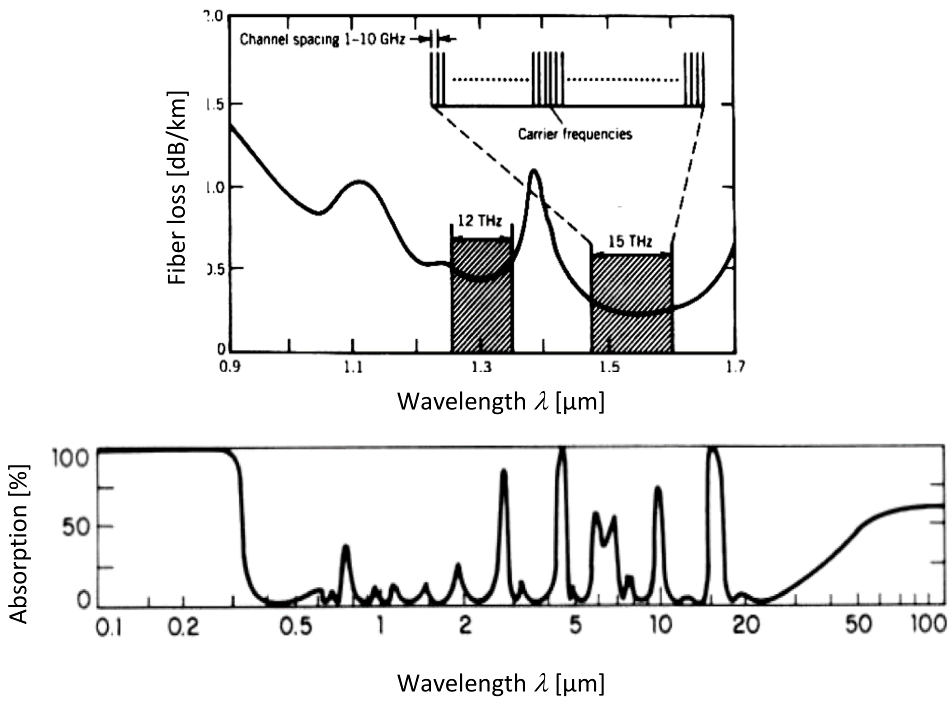

Figure 2: Optical windows; Top: fiber loss of IR; Bottom: atmospheric absorption of IR [6]

2.1.4 Visible radiation

Special for humans the part of the spectrum from 380 nm till 780 nm is very important. It is the visible light (VL). The spectral colors include all colors which can be produced by the visible light and are shown in Table 4.

Wavelength	Color
780 – 635 nm	Red
635 – 590 nm	Orange
590 – 560 nm	Yellow
560 – 490 nm	Green
490 – 450 nm	Blue
450 – 380 nm	Violet

Table 4: Wavelength and color of VL [6]

Since the development of LEDs and the use for room illumination, the visible light gets also interesting for FSO data communication. This technology is called visible light communication (VLC).

2.1.5 Ultraviolet radiation

In optical radiation, the band with the highest frequencies is the ultraviolet light (UV). The UV spectrum (100 nm till 380 nm) is split in 3 sub bands as seen in Table 5.

	Wavelength
UV-A	315 – 380 nm
UV-B	280 – 315 nm
UV-C	100 – 280 nm

Table 5: Ultraviolet sub bands [6]

2.2 Historical background

The very first optical communications were realized with flags, smoke or fires from one hill or mountain to the next [6]. With the development of the telegraphy and the telephone in the 19th century, big steps were done to connect people with each other and to transmit information in a not know speed for this time.

2.2.1 Laser, LED

Between 1957 and 1960 researchers started to develop independently infrared radiation in the USA and the USSR. 1959 the appellation LASER (Light Amplification by Stimulated Emission of Radiation) was defined by Gordon Gould and in 1960, Theodore H. Maiman operated the first functioning laser [7].

1962 Nick Holonyak, Jr. invented the first visible light LED [8]. Since this time, LEDs have been developed in each color of the visible light spectrum as well as for UV- and IR-spectrum.

2.2.2 Optical fiber

After using fibers for light and image transmission in the 1920s, 1966 the first optical fiber patent application for data communication was hand in [9]. The attenuation of this time fibers was around 1000 dB/km. In the following years the high attenuation could be cut down with new materials, cleaner glass and doping the glass [6].

1970, the attenuation reached the magic level of 20 dB/km [6].

1978 first fibers were designed for a wavelength of 0.8 µm. A data rate of 50 Mbit/sec up to 100 Mbit/sec over a length of 10 km could be achieved. The first generation of optical fibers for infrared light was born [6].

With the discovery of the InGaAsP-LASER, 1980 optical fibers for a wavelength of 1.3 µm were designed. With this new fiber the attenuation could be could down again to 1 dB/km and the data transmission rate could be increased to 2 Gbit/sec. This fiber is also known as the second generation of optical fiber communication [6].

With the end of the 1970s and the beginning of the 1980s the third generation was developed. By using Si-cables and a wavelength of 1.55 µm the attenuation decreased again to 0.2 dB/km. Problems with dispersion could be eliminated with a new fiber design, so called dispersion shifted fibers. Due to this improvements the data rate could be increase to 4 Gbit/sec [6].

The fourth generation is using coherent systems and frequency multiplex architecture. In this way extremely high data rates can be achieved by using slim impulses [6].

In the fifth generation optical fiber communication systems using amplifiers to keep the attenuation low and to run a long distance [6].

2.2.3 Free space optical communication

Free space optical communication (FSO) is a wireless optical communication technology. The information carrier is visible or infrared light and the transmission media is air, outer space or vacuum, so called free space as in comparison to optical fiber cables [10]. LEDs or LASERs are used as transmitter and photo diodes as receiver. FSO is based on optical fiber communication and therefore most of the components and equipment are similar or based on the wired technology.

The advantages of FSO are high security against espionage like tap-proof or man in the middle attacks. Because of the focused beam crosstalk and interferences to other systems are very low. In comparison to optical fiber systems, no hauling for the cables need to be done. Comparing RF radio links with FSO, the transmitter and receiver parts are smaller because large antennas are not necessary and the transmission rate is higher because of the available large bandwidth in the optical spectrum [6].

The biggest disadvantages of FSO communication are the need of line of sight, the attenuation of the atmosphere (fog, rain, snow, etc.) depending on the wavelength and the issue of eye safety. The power of the transmitter must be limited to an eye safety level. Another disadvantages is the beam dispersion. If the beam is very narrow, it is hard to set up the connection. If the beam angle is wider, a lot of transmission energy get lost [6].

Nowadays free space optical communication is used in several commercial applications. One of these commercial used applications is the communication between satellites. Neither eye safety nor atmospheric attenuation have to be considered and so high data rate links can be realized with FSO for satellite to satellite communication. The use of optical uplinks for satellites is under investigation and will be realized in the next years. FSO communication is also used for data links between the earth and orbiters like the Messenger spacecraft [10].

Terrestrial optical wireless communication systems are realized with infrared (IR) or visible light sources. Point to point connections are using most of the time IR from in a range of 800 nm to 1550 nm. The commercial products can be designed for indoor or outdoor applications. These data links are used for so called last mile connections or as flexible and temporary extender for fixed installed optical fiber networks. For short distances (several 100 m) a FSO link can be easily and fast set up and removed again.

Figure 3: FSO module

In the last view years a lot of investigations were done in the field of visible light communication (VLC). Since LEDs are used instead of light bulbs it is possible to use this light source not only for room lighting, but also for transmitting data at the same time. The modulation frequency is so high, that the human eye cannot recognize it. With an optical device the data can be received and used.

3 Regulation bodies

In this chapter the regulation bodies national, regional and international are mentioned. The different tasks, the mechanisms and the links between these national authorities and international institutions are illustrated.

3.1 National

The electromagnetic spectrum is a natural resource and therefore each nation claim the exploitation right within its territory. The competence is located in ministries or in special formed administration offices. The tasks of national regulation offices are to set up frequency allocation tables, frequency trading and allocation of exploitation right in certain bands. Furthermore licensing radio stations and applications and the control of the use of the spectrum is done by those offices. The legal basis for the regulation of the spectrum must be set out in legislation and detailed in regulations made pursuant to the legislation [1].

In 193 countries all over the world telecommunication regulatory bodies are installed [11]. Two countries are cite as examples for national regulation bodies.

3.1.1 Austria

On the basis of my origin the Austrian spectrum regulation authorities are mentioned here.

The Federal Minister of Transport, Innovation and Technology is the highest telecommunications authority, the business is handled by Division III. Members of Division III also represent Austria in international regulation bodies (CEPT, ITU, etc.). The frequency utilization plan for Austria is published in Federal Law Gazette BGBI.II Nr.307/2005 and in additional amendment BGBI.II Nr.068/2011 [12].

Special parts of the spectrum are handed over to the Austrian Regulatory Authority for Broadcasting and Telecommunications (RTR) for allocation. The RTR was established under Austrian law in 2001. As shown in Figure 4 RTR is split up into the Media division and in the Telecommunications and Postal Service division. This subdivisions provides operational support for all three boards [13].

- The Austrian Communications Authority (KommAustria) is the regulatory authority for electronic audio media and electronic audiovisual media. KommAustria is responsible for issuing licenses to private television and radio stations, managing broadcasting frequencies, handling the legal supervision of private broadcasters, as well as preparing and launching digital broadcasting and is also in charge of administering the Austrian federal government's press and journalism subsidies [13].

- The Telekom-Control-Commission is responsible for regulating the telecommunications market. The tasks and responsibilities are specified in the Austrian Telecommunications Act of 2003 like frequency assignment procedures, the approval of general terms and conditions of business and also monitoring the fees charged by telecommunications companies [13].

- The Post-Control-Commission is the third board and was set up 2008 and is responsible for postal service regulations [13].

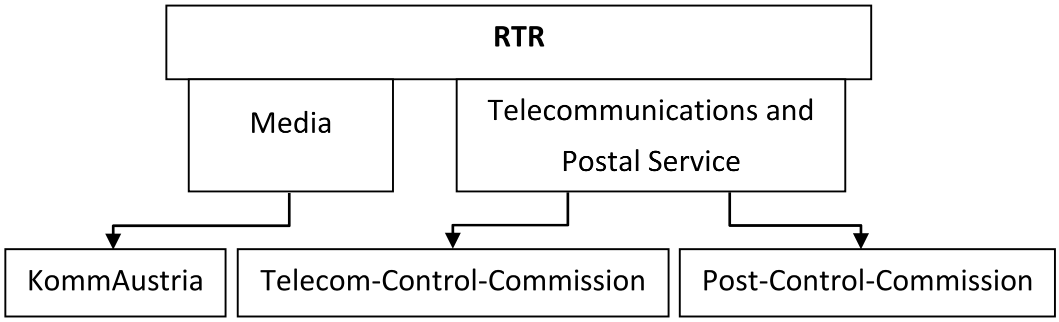

Figure 4: Structure of RTR

3.1.2 United States of America

One of the most important national regulation bodies with a deep influence on international spectrum management decisions is the U.S. Federal Communications Commission (FCC). Established by the Communications Act of 1934, it is charged with regulating interstate and international communications by radio, television, wire, satellite, and cable. FCC is responsible for the non-federal use and frequency allocation in the USA [14].

The counterpart for federal users is the National Telecommunications and Information Administration (NTIA) established by the U.S. Department of Commerce in 1978 [15].

The organization structure of spectrum management in the United States of America is illustrated in Figure 5.

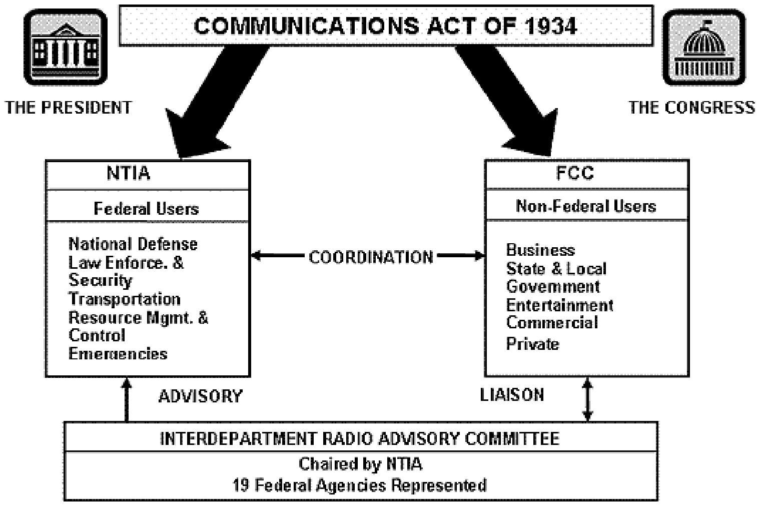

Figure 5: US spectrum regulation bodies [15]

3.2 Regional

The propagation of electromagnetic waves do not mind boundaries and country's territories. Without special agreements between countries, interference cannot be avoid along the border line. For this reason not only the International Telecommunication Union (ITU) was found, also several regional cooperative bodies were established to harmonize the spectrum use in this particular area. Figure 6 shows seven organization spread over the whole globe.

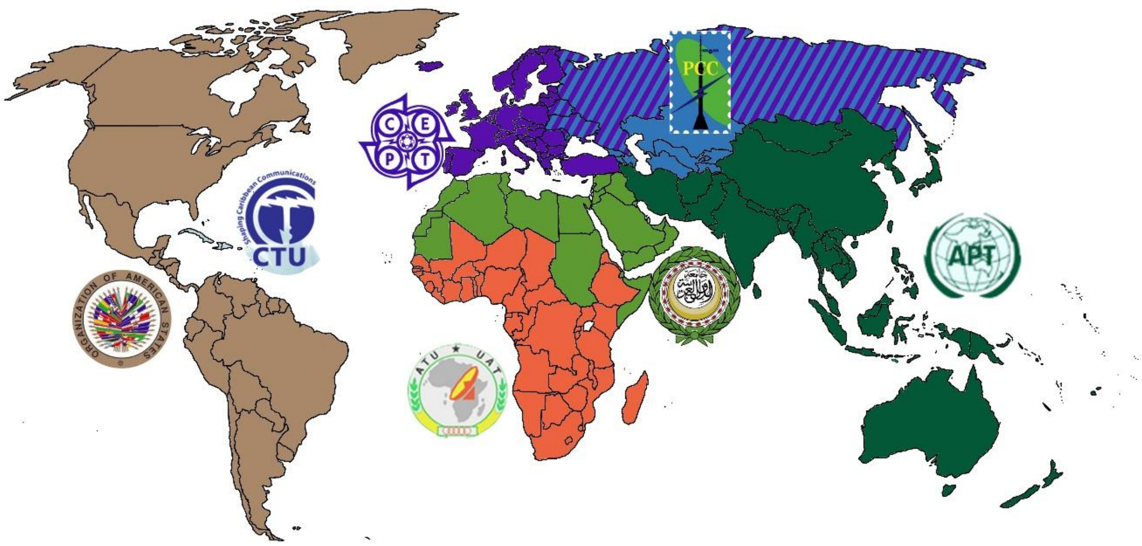

Figure 6: Regional spectrum regulation bodies

3.2.1 Europe

In Europe the cooperative body is the European Conference of Postal and Telecommunications Administration (CEPT). In difference to the European Union (EU), CEPT represents the international cooperation process between European countries on a single policy for postal and electronic communications. Figure 7 shows the relationships between CEPT (blue marked), EU, National Regulation Authorities (NRAs) and other international organizations.

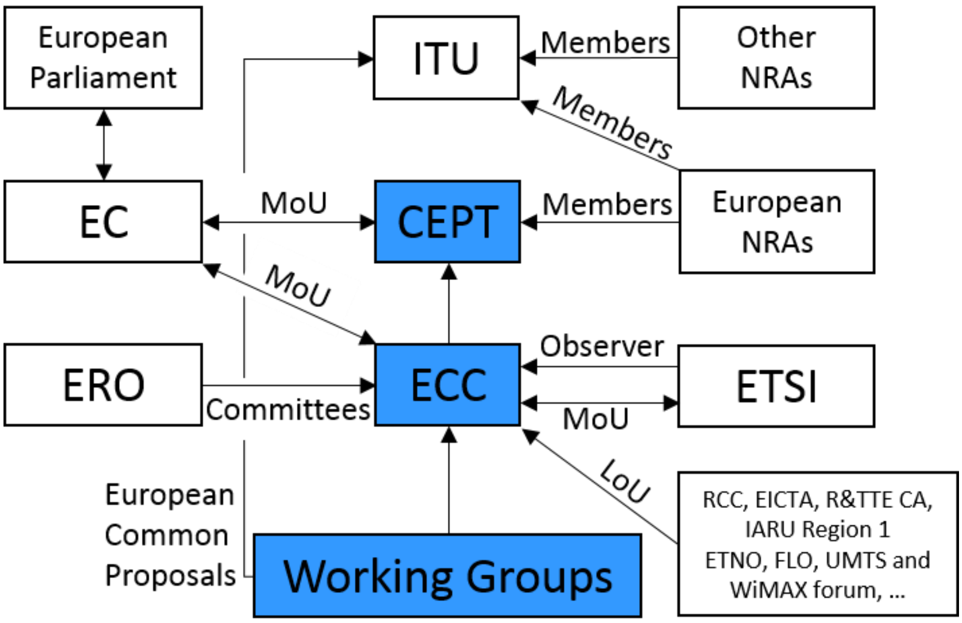

Figure 7: The main players in European spectrum regulation [16]

The CEPT was established in 1959 by 19 countries. Nowadays CEPT unify 48 national regulatory administrations in the field of posts and telecommunication and conducts its work through three autonomous business committees (Figure 8) [17]:

- Electronic Communications Committee (ECC)
- European Committee for Postal Regulation (CERP)
- Committee for ITU Policy (Com-ITU)

The chairs of these committees form the organization's Presidency, supported by the European Communications Office (ECO). In relation to the topic of this thesis only ECC and Com-ITU are mentioned in detail.

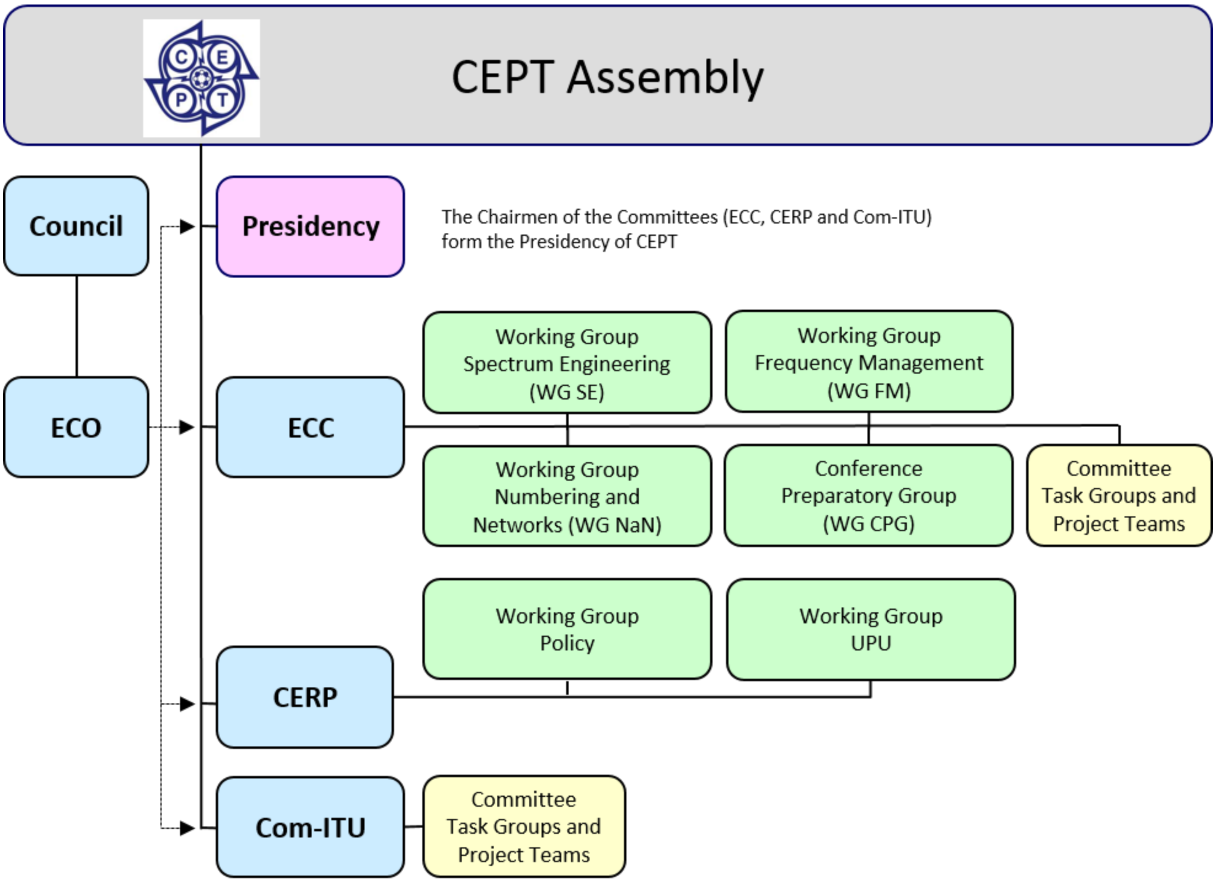

Figure 8: Structure of CEPT [17]

ECC

ECC develops common policies and regulations in electronic communications for Europe, and is a focal point for information on spectrum use. Its primary objective is to harmonize the efficient use of the radio spectrum, satellite orbits and numbering resources across Europe. It also prepares common proposals to represent European interests in the ITU and other international organizations [17].

As seen in Figure 8, ECC itself is supported by working groups (WG) and project teams (PT) which carry out expert regulatory, technical studies and consultations. The two main outputs of ECC are Decisions and Recommendations on major harmonization issues. ECC Reports and CEPT Reports are studies which respectively inform ECC decisions and decisions of the European Commission (EC) [17].

Com-ITU

Com-ITU is responsible for organizing the CEPT's engagement with the ITU. The committee coordinates its members' positions for the Plenipotentiary Conferences, World Telecommunication Development Conferences, World Telecommunication Standardization Assemblies, and various other meetings. Furthermore the committee also plays an important role in communicating the CEPT's views directly to the ITU Council [17].

Members of CEPT can be divided in members and observers to the committees or assembly.

- **CEPT member**: In accordance with the CEPT arrangement, Postal and Telecommunications Administrations of the European countries which are members of the Universal Postal Union or member states of ITU may be members of CEPT [17].

- **Observer to the committees**: Representatives of organizations having agreed on a Memorandum of Understanding (MoU) or a Letter of Understanding (LoU) with either CEPT or the relevant committee are invited to participate to the meetings of committees and their WG according to the terms of MoUs and LoUs. Members of these organizations can also participate to PT unless it is decided differently in the terms of reference of the PT [17].

- **Observer at the assembly**: In accordance with the CEPT Rules of Procedure, representatives of the permanent organs of ITU and the Universal Postal Union shall normally be invited to participate at the meetings of the assembly as observers. Observers may participate in the discussions but have no right to vote. Moreover, the European Commission (EC) and the Secretariat of the European Free Trade Association (EFTA) are invited to participate in the activities of the assembly in an advisory capacity, with the right to speak but not to vote [17].

3.2.2 America

The main regional organization in North and South America is the Organization of American States (OAS). OAS is the oldest regional organization in the world and its roots go back to 1826 [18].

The Inter-American Telecommunication Commission (CITEL) is an entity of OAS. All members States (35 independent states) of the OAS are members of CITEL. In addition CITEL works together with more than 110 regional and international organizations as Associate members. CITEL is structured in 6 branches [19]:

- Assembly of CITEL
- Permanent Executive Committee (COM/CITEL)
- Steering Committee
- Permanent Consultative Committee I (PCC.I): Telecommunications/ICT
- Permanent Consultative Committee II (PCC.II): Radiocommunications
- Secretariat of CITEL

PCC.I and PCC.II are advisory committees to CITEL. PCC.I concentrates on the area of telecommunications/ICTs. PCC.II objectives are promoting the planning, coordination, harmonization, and efficient use of the radio spectrum. Further tasks includes geostationary and non-geostationary satellite orbits for radio communication services and broadcasting. PCC.II is split up in different groups and offices as pictured in Figure 9 [19].

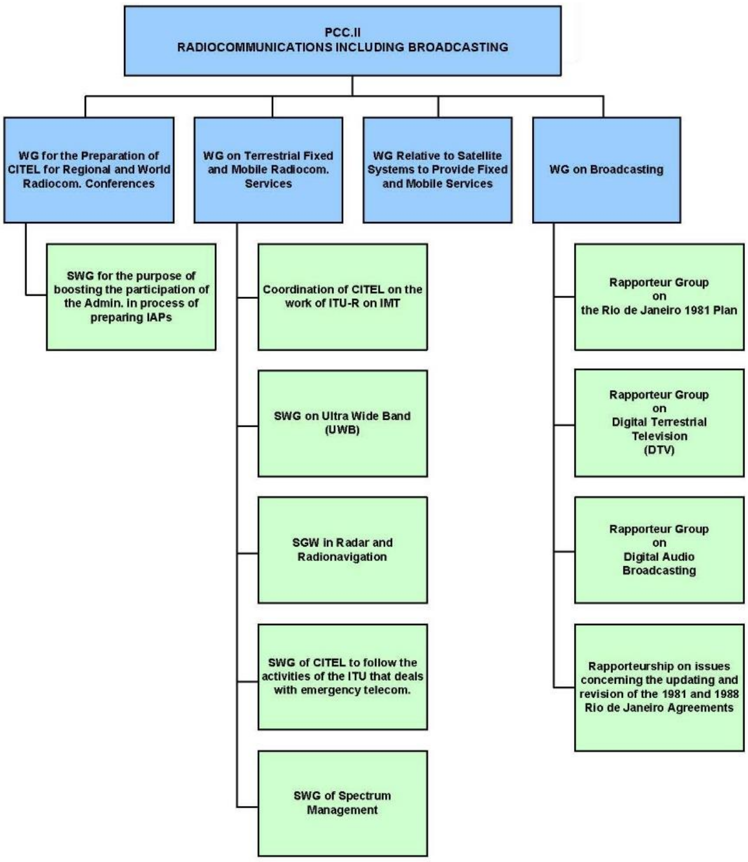

Figure 9: Structure of CITEL PCC.II [19]

Another player in this region is the Caribbean Telecommunications Union (CTU). CTU was established by the Heads of Caribbean Governments in 1989. This organization connect 20 Caribbean countries to create an environment in partnership to optimize returns from ICT resources [20].

3.2.3 Asia

The Regional Commonwealth in the field of Communications (RCC) was established in 1991 out of 12 former USSR countries. Till now RCC has 12 member states and 6 observers [21].

The Asia Pacific Telecommunity (APT) was founded in 1979 on the joint initiatives of the United Nations Economic and Social Commission for Asia and the Pacific and the International Telecommunication Union. The APT covers 38 member countries, with 4 associate members (Figure 10) and 130 affiliate members [22].

Figure 10: Members of APT [22]

Objectives of APT are [22]:

- Providing a platform to the telecommunications and ICT policy makers and regulators
- Providing an opportunity to the top policy makers and regulators to share information, best practices and experiences
- Providing consultative support to members
- Promote sharing of expertise for addressing key issues of concern
- Facilitating intra-regional collaboration on policy and regulatory issues

3.2.4 Africa

The African Telecommunications Union (ATU) was established in 1977 as specialized agency of the Organization of African Union. ATU counts 44 member states and 24 associate members from private sector [23].

The core programs of ATU are [23]:

- Human & Institutional Capacity
- ICT Infrastructure
- Integrating Regional Markets
- Global Decision Making

The League of Arab States (LAS) was founded in 1945. Nowadays LAS has 22 members (Figure 11) and 4 observers [24].

Figure 11: Members of LAS [24]

3.3 World wide

In 1865 the International Telegraph Union was established in Paris. The goal of the antecessor of today's ITU was to simplify the cross border telegraph communication. In the early 20th century first maritime radio communication applications were used. In the year 1930 already five different international organization were working on radio communication regulations. With the fusion of these organizations in 1934 the International Telecommunication Union (ITU) was born. Big structural changes of the ITU were done in 1947; ITU was integrated into the United Nations (UN) and a permanent bureau was built up in Geneva, Switzerland [11].

ITU currently has a membership of 193 countries and over 700 private-sector entities and academic institutions. The headquarters is still located in Geneva and there are twelve regional and area offices around the world [11].

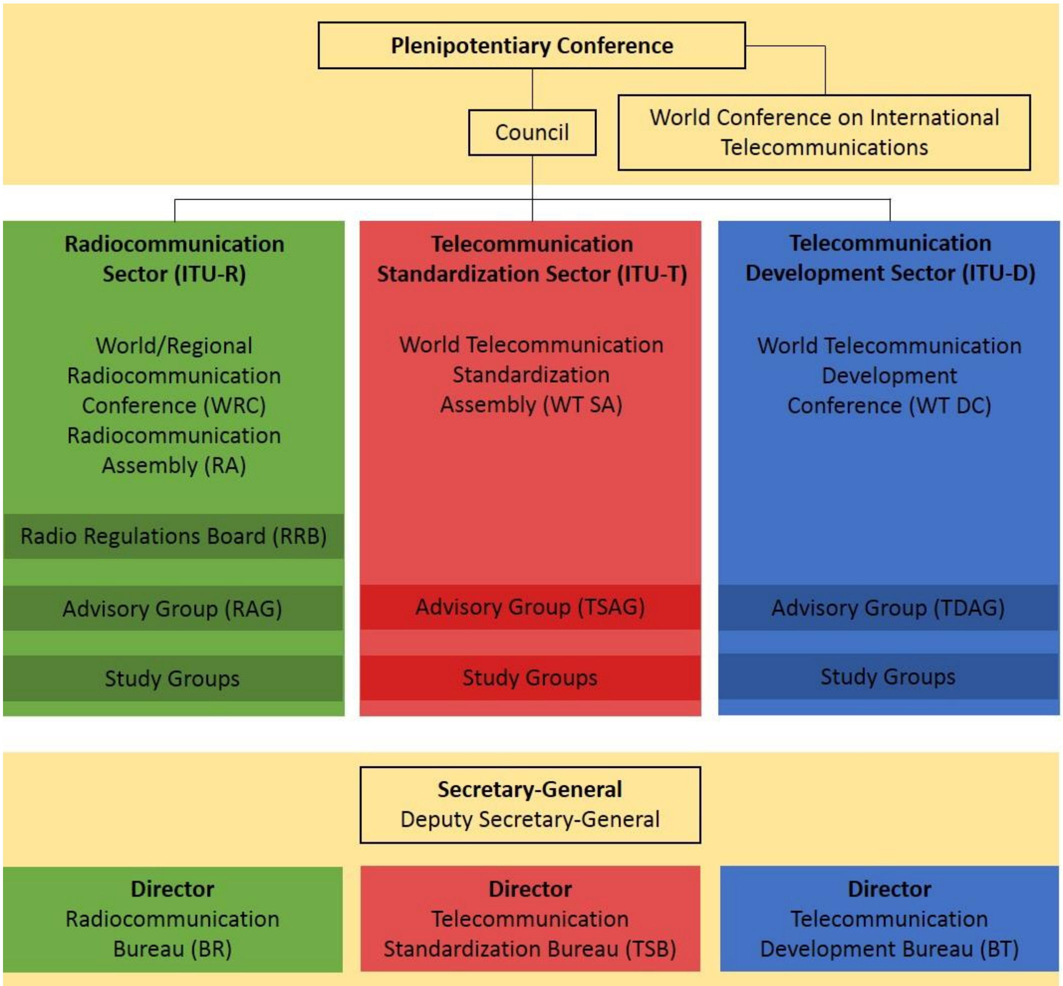

Figure 12: Structure of ITU [11]

As pictured in Figure 12, ITU is built up in three levels. First level is the Plenipotentiary Conference, the World Conference on International Telecommunications (WCIT) and the Council. The Plenipotentiary Conference is the key event at which ITU Member States decide on the future role of the organization. The ITU Council determines revisions to agendas for the different conferences by taking recommendations of previous conferences into account. The World Conference on International Telecommunications is a superordinate conference for all sectors and main topics of ITU. The last WCITs were held in 1988 and 2012. The second level and the main part of ITU is based on three sectors. In the following subchapters those sectors are explained in detail. The third level is the Secretary-General and the directors of the three ITU bureaus.

3.3.1 Radiocommunication Sector (ITU-R)

ITU’s Radiocommunication Sector coordinates this vast and growing range of radiocommunication services, as well as the international management of the radio frequency spectrum and satellite orbits.

Since the global use and management of frequencies requires a high level of international cooperation, one of the principal tasks of ITU-R is to facilitate the complex intergovernmental negotiations needed to develop legally binding agreements between sovereign states. These agreements for an efficient and economical use and global frequency harmonization, are embodied in the Radio Regulations (RR). This tables are the basis for world and regional frequency allocations plans for different space and terrestrial services and should eliminate harmful interference between radio stations of different countries [11].

Another task is the development and strengthening of national, regional and international broadband network infrastructure [11].

The third main subject of ITU-R is the coordination of satellite orbits. Within this task ITU-R’s role is to effect the allotment and the registration of orbital positions in the geostationary satellite orbit in order to avoid interference between radio stations. Furthermore it encourages public and private partnerships to promote the provision of high speed satellite services for underserved areas [11].

All these activities are done within different elements of ITU-R. The structure of ITU-R and the distribution between ITU members and the radiocommunication bureau is shown in Figure 13.

World and Regional Radiocommunication Conference (WRC) are held every two or three years. The WRC's agenda is set four to six years in advance at the second last conference. The output of the WRC is published as new RR. The main WRC tasks are [11]:

- Review and revise the Radio Regulations
- Discuss worldwide radiocommunication matters
- Instruct and review the Radio Regulations Board and Radiocommunication Bureau

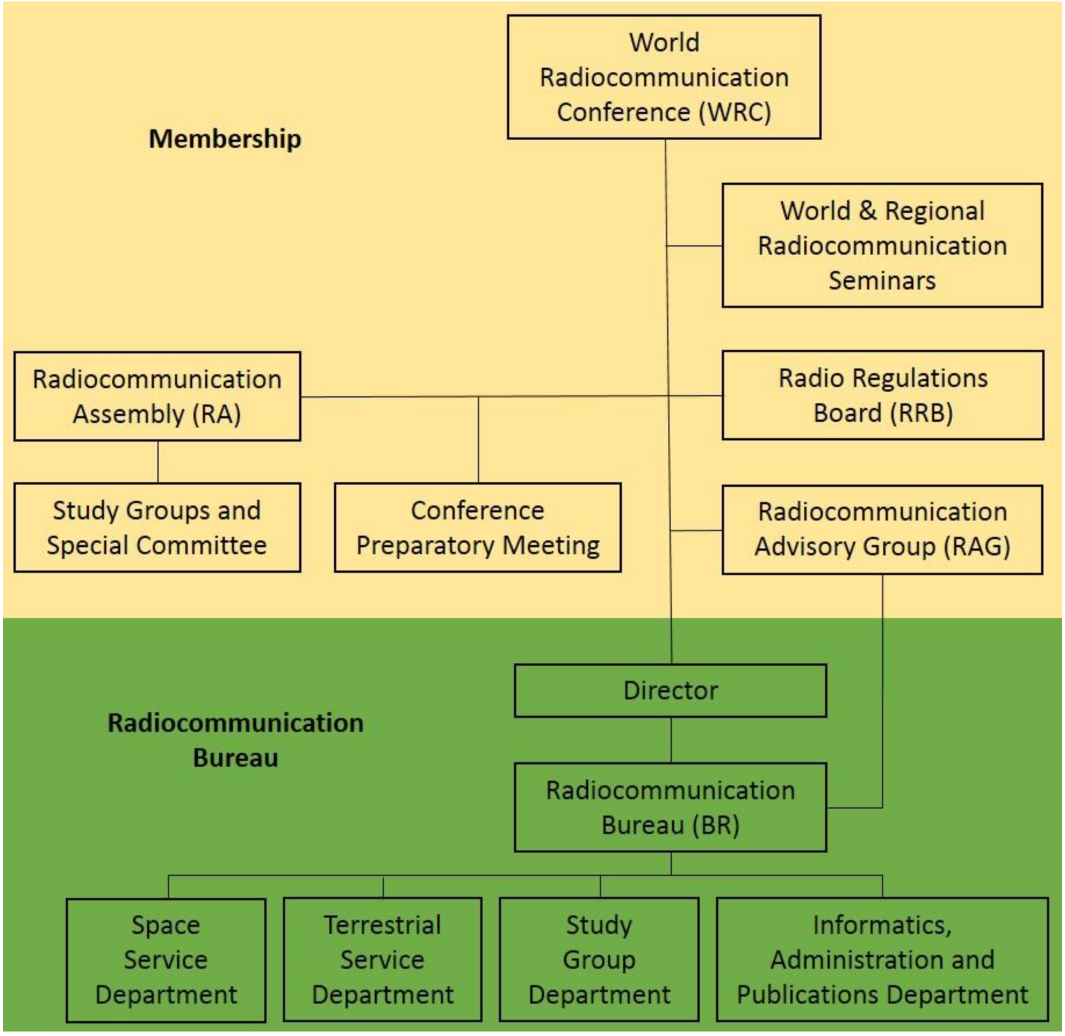

Figure 13: Structure of ITU-R [11]

Radiocommunication Assemblies (RA) are held every four years, normally within the WRCs. RAs are responsible for radiocommunication studies in case of structure, program and approval [11].

The Radio Regulations Board (RRB) counts twelve members and meets up to four times a year. RRB approves Rules of Procedure, used by the Radiocommunication Bureau (BR) and addresses matters referred by the BR that cannot be solved by the Radio Regulations and the Rules of Procedure. It is also an advisory board for the WRC and the RA [11].

The Radiocommunication Bureau is the executive arm of the ITU-R. The BR has different tasks. One is to provide administrative and technical support to all ITU-R units. Another is to record and register frequency assignments and orbital characteristics of space services and to maintain the Master International Frequency Register. Also the assistance of member states in case of equitable, effective and economical use of the radio spectrum and satellite orbits is one task. This advices and assists are used to resolve cases of harmful interferences between states. All ITU-R publications are published by the BR as the Radio Regulations, the Final Acts of World and Regional Radiocommunication Conference, the Rules of Procedure, ITU-R Recommendations, reports and handbooks [11].

Arose from a dispute of frequency allocation from 30 MHz to 300 MHz between Europe and America in the late nineteen-twenties and early thirties, 1928 and 1932 the ITU conferences divided the RF allocation into two parts, a European region and other regions. 1947 at the ITU conference the world has been split up in case of frequency allocation into three regions as shown on the map (Figure 14) and described as follows [11] [16]:

- **Region 1** includes the area limited on the east by line A and on the west by line B: Europe, Middle East, Africa, former USSR Countries
- **Region 2** includes the area limited on the east by line B and on the west by line C: North and South America
- **Region 3** includes the area limited on the east by line C and on the west by line A: Asia, Australia and the Pacific Rim

The lines A, B and C are defined as follows [11]:

- **Line A** extends from the North Pole along meridian 40° East of Greenwich to parallel 40° North, thence by great circle arc to the intersection of meridian 60° East and the Tropic of Cancer, thence along the meridian 60° East to the South Pole.
- **Line B** extends from the North Pole along meridian 10° West of Greenwich to its intersection with parallel 72° North, thence by great circle arc to the intersection of meridian 50° West and parallel 40° North, thence by great circle arc to the intersection of meridian 20° West and parallel 10° South, thence along meridian 20° West to the South Pole.

- **Line C** extends from the North Pole by great circle arc to the intersection of parallel 65° 30` North with the international boundary in Bering Strait; thence by great circle arc to the intersection of meridian 165° East of Greenwich and parallel 50° North, thence by great circle arc to the intersection of meridian 170° West and parallel 10° North, thence along parallel 10° North to its intersection with meridian 120° West, thence along meridian 120° West to the South Pole.

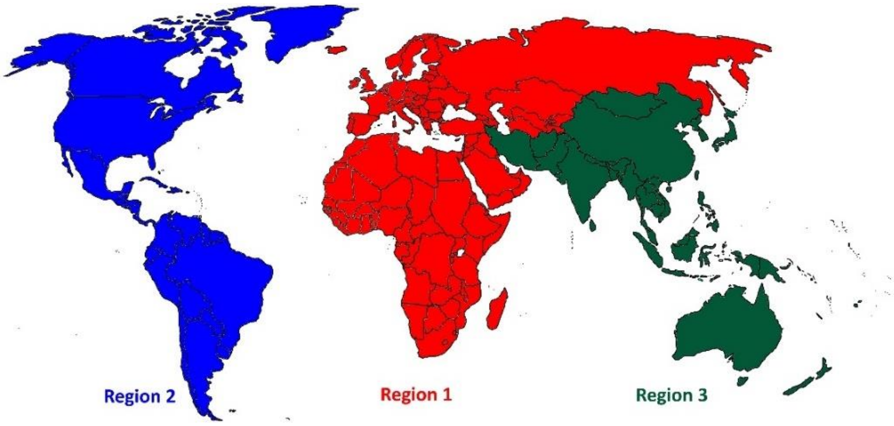

Figure 14: ITU Regions

3.3.2 Telecommunication Standardization Sector (ITU-T)

The Telecommunication Standardization Sector (ITU-T) is responsible for ITU standards, also called Recommendations. These Recommendations are fundamental to the operation of today's ICT network and allow systems to work locally and globally. As shown in Figure 12 the ITU-T structure is similar to ITU-R or ITU-D. The World Telecommunication Standardization Assembly (WT SA) sets the overall direction and structure for ITU-T. This meeting is held every four years. In addition the Telecommunication Standardization Advisory Group, Study Groups (SG), Focus Groups (FG) and Joint Coordination Activities (JCA) are completing the structure of ITU-T [11].

3.3.3 Telecommunication Development Sector (ITU-D)

The ITU Telecommunication Development Sector (ITU-D) is addressing the many aspects of expanding ICT access. Especially in developing countries, ITU-D foster international cooperation and solidarity in the delivery of technical assistance, development and improvement of ICT equipment and networks. ITU-D offers a broad spectrum of services for developing ICT business [11].

4 Spectrum management

This chapter should give an introduction to spectrum management. Spectrum management reflects four key functions [1]:

- Planning
- Engineering
- Authorization
- Monitoring

In addition to these key activities the spectrum licensing and pricing are two more tasks of spectrum management. These functions are discussed in detail in the following section.

In the last twenty years the business of spectrum management has changed with the enormous growth of the ICT market. Was the technique itself the limiting factor in the 1990s, now the electromagnetic spectrum, especially the bands between 30 MHz and 30 GHz are the limitation. From 14 national regulators worldwide in 1990 nearly every country all over the world has established his own national regulation authority as seen in Figure 15.

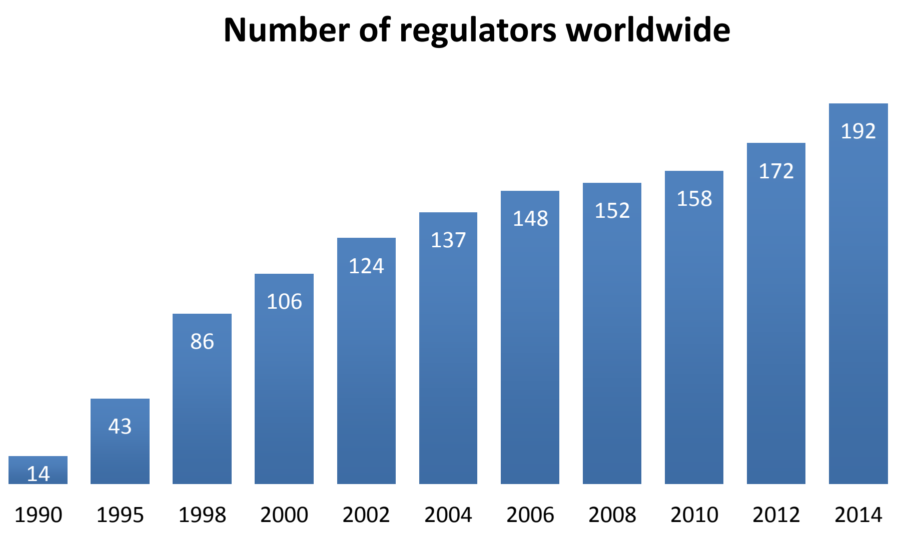

Figure 15: Number of regulators worldwide [1] [11]

How the regulation body is organized, varies from country to country. Some countries split the regulation authorities in sector specific regulators, to be able to follow the fast changing ICT environment. Other nations have moved towards merging existing separate regulatory authorities into one national regulator. But not only has the organization changed in the last decade, also the spectrum management itself. Next to the increasing number of users of the spectrum and with it the growth of administrative and management issues for spectrum purposes, the spectrum management approaches had to be adapted for these new challenges. Significant developments have moved the administrative regulatory approaches to more flexibility of marked based regulation [1].

4.1 Objectives of spectrum management

The key functions of spectrum management bases on three objectives.

4.1.1 Economic efficiency objectives

The economic efficiency objectives ensures that spectrum is used in ways which meet the country's goals. The main economic objective of a country should be to provide goods and services to end users. That can be on free market or provided to citizens by government. This lead to several questions, which have to be considered for a most economic and efficient way of spectrum allocation and use [1]:

- Which communication sector should get which frequency band?
- How many MHz bandwidth are necessary for an efficient use?
- Should one band be used by more than one sector?
- Should the allocation be uniform worldwide?
- Can services be replaced to other bands?

ITU's recommendation to spectrum managers regarding those questions is like follows [1]:

- In practice, many frequencies can be used for more than one specific use; hence, using traditional approaches the spectrum manager can split up one band for three or four uses.
- A uniform allocation of spectrum on a global basis yields to big advantages for manufacturers of radio communications equipment.
- A lot of services can handle different frequencies for their purposes. As a result more flexibility in spectrum management is given.
- It is often possible to replace spectrum in the provision of another service (e.g. replacing spectrum in a mobile telephone network).

4.1.2 Technical efficiency objectives

In the same way as for economic objectives, the technical efficiency objectives are aimed to an efficient and fullest possible use of spectrum. How efficient a spectrum band is used can be measured by time, in the sense of how constant or heavy usage is over a given period of time. In case of ICT applications another reference parameter is the data rate in terms of bits per second. In many cases these measurement methods have minor significance. If a system sends meaningless data (e.g. synchronization frames) in a very short period of time, the spectrum is used efficient, but the use is still meaningless [1].

One example for a change to a technical efficient use of spectrum is the changeover from analog to digital TV broadcast. With modern digital transmission methods, the technical efficiency can be increased, more TV channels can be transmitted within the same spectrum band. This digital dividend can be applied also to other ICT applications. Even though the digital efficiency has great benefits for bands where spectrum is scarce, it is not the sole goal in itself. For future use of spectrum, every technical possibility should be under consideration to achieve the goal of maximizing economic effects and welfare [1].

4.1.3 Policy objectives

Every government's policy objective should be to foster economic, technical, and social development. This includes initiatives to promote competition and create preferences to rebalance opportunities for certain disadvantaged groups in society. In the case of radio spectrum, the policy objective ensures that sufficient spectrum is available and accessible for current and future needs. In particular this bands are used for public safety and security requirements. This objective should be maintainable with other government goals and objectives and after all based on realistic assessments of actual circumstances. To reach this objective priorities have to be set and strategies need to be established; the full range of stakeholders need to be involved in the development of policy objectives [1].

4.2 Management approaches

The fundamental management approaches for spectrum allocation describe three different methods. The regulators duty is to keep the right balance among administrative assignment, use of markets and unlicensed spectrum [1].

4.2.1 Administrative method

With the aim of minimizing harmful interference the administrative method is used by all spectrum management authorities all over the globe. Since the first steps of spectrum management till now, this method has been based on detailed rules and constraints affecting how, where and when spectrum can be used and who has access to spectrum. In case of administrative method we have to differ between two stages [1]:

- **Allocation stage**: This stages includes the broad decisions on spectrum use at WRCs. This decisions are published in the RRs and are implemented in national frequency allocation tables.
- **Assignment stage**: Licenses are assigned to particular users for certain spectrum use. This will be explained in detail in 4.5 Spectrum authorization.

4.2.2 Market methods

With the intention to increase the efficient use of spectrum, market based methods took over the last years. It is still in the national regulators hand to decide what method is used for what band, but a liberalization in spectrum management implicate a greater flexibility in how spectrum is used.

If an owner of a license see no use in the band anymore, the rights and any associated obligations to use this band can be sold to a new user. Therefore spectrum trading results in more efficiency, because a trade will not take place if the spectrum is more worth to the old than to the new user. In case of administrative method this efficiency gains could not be realized. The EC identifies different forms of spectrum trading methods like sale, buy back, leasing and mortgage [1].

The benefits of spectrum trading are

- an increase of spectrum use efficiency,
- an easy access to spectrum for new market participants,
- a boost in market competition, and
- an easy way to expand licensees more quickly.

4.2.3 Unlicensed spectrum

In comparison to the allocated spectrum by administrative and market methods, some bands in the electromagnetic spectrum are unlicensed. These bands are free from centralized control and anyone can transmit without a license. Most of these bands are so called Industrial, Scientific and Medical (ISM) bands. The ISM bands are listed in Table 6.

Frequency range		**Bandwidth**	**Availability**
6.765 MHz	6.795 MHz	30 kHz	Subject to local acceptance
13.553 MHz	13.567 MHz	14 kHz	Worldwide
26.957 MHz	27.283 MHz	326 kHz	Worldwide
40.66 MHz	40.7 MHz	40 kHz	Worldwide
433.05 MHz	434.79 MHz	1.74 MHz	Region 1 only
902 MHz	928 MHz	26 MHz	Region 2 only
2.4 GHz	2.5 GHz	100 MHz	Worldwide
5.725 GHz	5.875 GHz	150 MHz	Worldwide
24 GHz	24.25 GHz	250 MHz	Worldwide
61 GHz	61.5 GHz	500 MHz	Subject to local acceptance
122 GHz	123 GHz	1 GHz	Subject to local acceptance
244 GHz	246 GHz	2 GHz	Subject to local acceptance

Table 6: ISM bands [2], [11]

The availability and use of ISM bands differ from ITU region to region or are subject to local acceptance of national regulation authorities. A lot of communication systems of everyone's daily life are located in one of those bands, e.g. WiFi, Bluetooth, NFC and many more. The most common band for consumer radio communications and therefore very dense of applications is the 2.4 GHZ to 2.5 GHz band.

4.3 Spectrum planning

Spectrum planning is one of the key functions of spectrum management and includes the whole process of frequency allocation. All focus lies on an efficient use of the electromagnetic spectrum.

4.3.1 International spectrum planning

In respect to the importance of the electromagnetic spectrum worldwide, only a top down spectrum planning is meaningful. To cope with this challenge ITU-R is responsible for spectrum planning worldwide. As mentioned in Subchapter 3.3.1 spectrum related issues are processed by the ITU members and the radiocommuniation bureau in different activities. The World Radiocommunication Conference discuss the results of these activities, revise and pass decisions. These decisions are published as radio regulations and are binding for ITU-member states. The big players in ITU are the US, CEPT with its leading countries Germany, France and Great Brittan, Russia, Japan, and China.

4.3.2 Regional spectrum planning

From the beginning of the worldwide spectrum allocation Europe have been competing against the USA. Some examples are shown in Table 7.

	Europe	**USA**
Electrical power supply	50 Hz	60 Hz
TV	PAL	NTSC
Digital TV	DVB-T	ATSC
2G mobile phone service	GSM	CDMA
3G mobile phone service	UMTS	CDMA 2000

Table 7: Technical standards Europe vs. USA

Caused by this rivalry, ITU-R divided the world in 3 regions for spectrum allocation as mentioned in 3.3.1 and shown in Figure 14. Region 1 combine different sovereign markets; Region 2 is dominated by the US. Region 3 has no unified approach and is influenced by Region 1 and Region 2.

Europe, Africa and the Middle East form Region 1. In Region 1 CEPT takes a special position, but has no legislative basis. CEPT is responsible for spectrum planning in three different ways. First, CEPT coordinates spectrum planning in Europe by connecting the national spectrum authorities with each other. The members develop common but not binding recommendations and decisions; national regulatory authorities are encouraged to implement the CEPT/ECC recommendations. Second, Com-ITU elaborate proposals for the WRC to represent the CEPT member states with one consent at ITU. Third, CEPT cooperates with the European Union (see Figure 7) and provides input for the EC. The EU institutions adopt five different types of legal actions [16]:

- Regulations have binding legal force throughout every member state, on a par with national laws.
- Directives are used to bring different national laws into line with each other. They are binding to all member states and addressed to national authorities.
- Decisions are legally binding and resolve particular cases.
- Recommendations are no legal obligations to member states by the Council or the EC.
- Other non-binding measures like Council or Parliament resolutions, Council conclusions or EC papers.

The decisions in case of spectrum allocation are mandatory harmonization measures within the EU. The implementation is mandatory for EU member states, European Economic Area (EEA) countries, bilaterally “associated” countries and any accession country before joining EU. In Europe and also in the rest of the Region 1 the hegemony of the EU in spectrum management leads to an adoption of EC decisions even in non EU-countries. The top down regulation structure forced by EU, CEPT and ITU overcomes national power. Region 1 and especially Europe is a good example for unifying the spectrum engineering and management. This harmonize the spectrum and raise efficiency. Examples for this successful approach is GSM and DVB-T [16], [25].

Region 2 connects North and South American countries. CITEL influences Region 2 far from how CEPT influences Region 1; the main player in Regions 2 and also the dominating country in CITEL is the USA. In South America the US, Europe and even Japan have more influence than CITEL [16].

4.3.3 National spectrum planning

National frequency allocation tables are developed within the framework of the regional RR. In addition regional cooperative bodies, as mentioned in Chapter 3.2, influence the national tables. A national frequency allocation table includes a number of columns, which can be specified as follows [1], [2]:

- **Column 1**: ITU, RR Region (1, 2, 3) Article 5, frequency bands.
- **Column 2**: Regional or national allocation of major use, RR Article 5 footnotes, Regional footnotes.
- **Column 3**: Relevant information and recommendations to particular radio applications (e.g. center frequency, sub bands, etc.).
- **Column 4**: Application.
- **Column 5**: Additional cross references.
- **Column 6**: Information to application standards.
- **Column 7**: Notes (does not consist in every national table).

A national frequency allocation table is set up in several steps. First, the national authorities specify the spectrum bands for general use or cancel different aspects of the RR, if they are not required or used in the given country. These frequency bands can have territorial, time or objective predefinitions. Second, sub-allocations are done and the sub-bands are detailed allocated for certain uses. Applications with similar technical parameters are put together in the same bands. In the third step, the allocations are rated on primary or on secondary basis. Stations on second level are not allowed to influence first ranked stations in case of harmful interferences. Furthermore stations of a secondary service have no right to object to harmful interferences caused by first ranked services [1].

The national allocation tables need to be regularly updated. The whole spectrum planning process is subject to different time frames [1]:

- Long range planning (>10 years) is a strategic forecast of spectrum use.
- Medium-term planning (5-10 years): Regional or national spectrum policies can be adapt for identified changing spectrum needs.
- Short-term planning (<5 years) is necessary to rapidly adjust spectrum policy.

4.4 Spectrum engineering

Spectrum engineering involves the development of electromagnetic compatibility standards for equipment that emits or is susceptible to radio frequencies. The goals of those standards are the minimization of harmful interference and operational restrictions. Existing radio stations benefit from spectrum engineering as well as new radio applications with entering the spectrum.

On all levels of spectrum management spectrum engineering is necessary. Different working groups are focusing on this topic. At ITU-R the Working Party 1A – Spectrum Engineering Techniques and on European level at CEPT/ECC the Working Group Spectrum Engineering (WG SE) follow similar main tasks as seen in Table 8.

ITU-R Working Party 1A	**CEPT/ECC – WG SE**
Technical definitions	Technical guidelines
Technical aspects of sharing	Sharing criteria
Frequency tolerance	Compatibility criteria
Unwanted emissions	
Computer programs	Software tools

Table 8: Tasks of spectrum engineering [11], [17]

4.4.1 Technical Standards

Technical standards (synonym for definitions or guidelines) help to achieve electromagnetic compatibility between radio equipment and services. The abidance by these standards reduce interference between different services like broadcasting, radiocommunication or navigation and increase the quality of service for end users.

The most important institutions for technical standards are:

- International Telecommunication Union (ITU)
- International Organization for Standardization (ISO)
- International Electrotechnical Commission (IEC)
- Institute of Electrical and Electronic Engineering (IEEE)
- European Telecommunications Standards Institute (ETSI)
- American National Standards Institute (ANSI)

4.4.2 Equipment parameters

Technical standards characterize radiocommunication equipment parameters and limit threshold values for these parameters. Without control of this limits, harmful interference would occur and influence other systems. The focus is on following parameters [26]:

- **Carrier frequencies**: The used carrier has to correspond to the application's assigned frequency band.
- **Transmitter power**: Some standards define limits for peak and average power; they should be limited to a minimum suitable operation level.
- **Frequency tolerance**: It is the maximum tolerable carrier frequency shift outside of the allocated frequency band.
- **Bandwidth**: The occupied bandwidth shall be as efficient and as low as possible in the nature of the application.
- **Unwanted emissions**: Emission outside of the necessary bandwidth is declared as unwanted emission.
- **Intermodulation products**: The products are generated by non-linear elements. Out of two or more signals unwanted harmonics appear.
- **Sensitivity of radio receivers**: The sensitivity is defined by the signal to noise ratio criteria.

The parameters differ between licensed and non-licensed equipment. Radiocommunication equipment only get licensed if the equipment fulfills the dictates for the correspondent spectrum band. This guaranty best performance between radio stations of the same system and also good coexistence with other applications within one band and the neighbor bands. Unlicensed radio equipment is only commit to work within the unlicensed bands (e.g. ISM bands) and reduce unwanted emissions to a minimum. Within the band only the maximum radiation power is limited. In case of interference, each system need to be aware of the possibility to be interfered by others or be the source of interference itself.

4.4.3 Interference analysis

The interference analysis deal with the statistical analysis of environmental and system related parameters. A receiver input signal is mainly degraded by co-channel, adjacent channel, desensitization and intermodulation interferences [26].

Different software tools and computer simulations have been developed to estimate interferences. These programs calculate the interference power, carrier-to-noise and wanted-to-interfering signal ratios. The most common simulation methodology and used by ITU-R bases on the “Monte Carlo” technique; it can address virtually all radio interference scenarios. The European Radiocommunications Office (ERO) implemented this methodology in the Spectrum Engineering Advanced Monte Carlo Analysis Tool (SEAMCAT). This European tool is the most common used interference analysis program worldwide and offers independent compatibility studies to their users. The program is free available at the ERO website [26].

4.5 Spectrum authorization

ITU-R defines spectrum authorization as follows [1]:

“*With spectrum authorization, the spectrum manager approves the use of radiocommunication equipment and permits the use of radio frequencies to specific users or classes of users, in accordance with the national and international table of frequency allocations*”.

This means potential spectrum users need to be authorized and radiocommunication equipment has to be licensed. For the purpose of user authorization several administrative and economic methods are at spectrum manager’s disposal: first come first served, beauty contest, lottery and/or auctions. Those methods can be used independent or together in several steps. Further details are explained in 4.7 Spectrum pricing. The radio equipment need to be licensed; this represents the technical part of spectrum authorization. If the application uses one of the unlicensed bands, the equipment have to be authorized, even when no license is required for using the band itself. The license and the authorization guaranty a minimum of control of radio stations and the use of assigned frequencies.

Trends to more liberalization, like deregulation and privatization in spectrum management and technical innovations to the fullest possible use of spectrum impact the spectrum authorization. This leads to a greater use of market-based mechanism and more flexibility in licensing; a more efficient use of spectrum is possible [1].

4.6 Spectrum monitoring

Inappropriate and incompatible usage of radios causes unwanted emissions, interfere other applications and reduce the efficient use of the electromagnetic spectrum. Therefore the spectrum authorization need to be controlled. Spectrum monitoring provides support to spectrum planning, engineering and authorization. It gives spectrum managers the opportunity to offer interference free assignments bases on measurement data from electromagnetic compatibility (EMC) verifications. With a growing competition on the ICT market, operators ask for such assignments to offer competitive wireless services.

The technical execution of spectrum monitoring is done with fixed, remote, unmanned or mobile monitoring stations. In urban areas rotatable antennas are well positioned for remote measurements. Mobile monitoring equipment can be installed in a van for road measurement campaigns. The equipment for fixed or mobile use includes basically a radio receiver, spectrum analyzer, direction finding equipment and antennas. For different frequency ranges, different measurement equipment is necessary. The price of measurement equipment rises proportional with increasing the frequency and the complexity of the technology [1].

4.7 Spectrum pricing

Natural resources are used to create value for the society. The size of the group of profiteer can vary from a single person (e.g. dictator) to a small group (families, business group) or to a whole nation. The distribution of the generated benefit is highly influenced by political decisions. Electromagnetic spectrum is also a natural resource and is trade in the same way as other resources. ITU gives several recommendations for spectrum trading and pricing to maximize the benefit to the society.

Every administrative effort and management processes demands human and technical power and those resources cost money. With the increase of wireless communication applications the amount of spectrum management is rising up too and with it the administrative costs.

Hence, the aim of spectrum economics is to set prices for the spectrum to, first, cover the costs of spectrum management, second, to ensure an efficient use of the resource, third, to ensure the end users benefit of used spectrum by different applications, and fourth, to maximize the economic benefits to the country and the revenue to the government [1].

4.7.1 Spectrum pricing methods

The spectrum price depends on the requirements of individual administrations based on national law. The height of the spectrum price consists of fees, the cost recovery for spectrum management and other charges.

Simple Fee

Simple fees are single payments for spectrum licenses. These fees can be based on a national flat rate for all licenses and varying with specific criteria like frequency band, occupied bandwidth or the geographic area. The simple fees are not necessarily covering the administrative costs. In this case national budget is used to fund the spectrum regulator authority.

Cost recovery

In case of cost recovery the fee's height is set to cover all administrative costs. In this way overcharging and also national financing are avoid. The administrative costs are paid once with "buying" the license for a certain frequency band. Additional, annual fees are charged for covering daily business costs of the administration, e.g. to keep the bands free of interference.

Other charges

As explained in the subchapters before a lot of different activities are done by spectrum regulators. The spectrum planning, authorization and licensing can be funded by selling licenses. The daily business for spectrum engineering and spectrum monitoring accumulate also costs. These costs can be paid by different other charges [26]:

- **Equipment approval**: Fees are charged to approve and test radio equipment to be allowed to set this equipment on the market. The test laboratories can be owned by the administration itself or external independent test laboratories are in charge of the accreditation. Depending on the region or country the certificate valid for one country or for a whole region. For worldwide use often many different specifications have to be fulfilled to get the certificates.
- **Inspection fees**: It is a fee for inspections of already installed equipment. The fee can be included in the cost recovery fees.
- **Interference management**: A fee can be charged in case of handing in an interference complaints to the regulator.

- **Operator certificate fees**: Fees are charged for radio amateurs or maritime examinations and certificates.
- **Annual fee**

4.7.2 Spectrum trading approach

In the past, different approaches for spectrum trading and spectrum assignments have been used. The most successful and most often used are mentioned bellow.

First come-first served

First come-first served is an administrative approach and is frequently used. The applicant needs to meet the application criteria to be allowed to participate the spectrum assignment. This mechanism is fitting best for large spectrum bands where a high number of applicants can be satisfied. The costs of this approach are covered by spectrum fees as mentioned before and often by national funding. First come-first served is highly effective and easy to forecast the revenue out of the spectrum allocation [26].

Beauty contests

A beauty contest is often used for broadcasting and public mobile systems. Applicants compete with each other; proposals for operating services are compared by regulation authorities and their specialists. A proposal should include an estimation of the population coverage, an explanation of the quality of service, the speed of implementation and furthermore a business plan of the company. In case of broadcasting information about the program (average time of children, educational, news or other content) should be mentioned too [26].

The analysis of the proposals is time consuming and resource intensive. The decision and the review can be subjective and less transparent then in other spectrum trading approaches. The losing party has the possibility of judicial review and this would cost again a lot of time. Hence, this way of spectrum trading is applicable for a small number of participants for special applications. Otherwise the licensing process takes too long and would causes high costs.

Comparative bidding – Auctions

In the same way as for other spectrum trading approaches some entrance criteria for applicants are defined. Auctions are very simply, quick and transparent. The highest bidder, which bids the most, gets the license. Most important is a fair competition between participants to achieve an effective auction and to generate the highest possible social benefit out of the spectrum allocation. In the last years, high attraction and attention was on spectrum auctions for mobile phone licenses like 3G or LTE. These licenses were sold for billions of euros or dollars. But not all auctions are that spectacular and generate a revenue of billions for the state. Most of the auctions are quite small and the biddings are low.

The advantage of auctions is that the one who sees the highest value in the spectrum band, pays the most, and gets the assignment. One disadvantages is that the price might not scope the real market value of the spectrum. Auctions suites not for all cases of spectrum assignments, especially when the volume is high and the value of the frequency band low [26].

Lotteries

A lottery is a gamble. As for any other lottery also for spectrum trading the participant have to pay entrance fees to participate at the lottery. The advantage of a lottery is the easy way to handle a big amount of applicants in case of the spectrum assignment itself. The procedure is quick and transparent. The drawbacks are on the one hand a time and resource consuming review process of the participating applicants if they suite the allocation. With a high number of applicants also high administrative costs accrue. It has to be ensured, that the lucky winner is qualified for the use of the offered spectrum band. On the other hand the lucky winner gets it all, for free. The spectrum can be used exclusively for his own purpose within the allocation characteristics [26].

4.7.3 Secondary market

For whatever reason assigned spectrum can become not usable anymore for one party. If no open marketplace is available for trading these goods, only a restoration to the national spectrum authority is possible. A secondary market offers a platform for transferring spectrum rights and licenses from one user to another without national regulator.

If spectrum licenses are changing the owner, the national spectrum regulation authority needs to be informed about the transaction and the transfer need to be registered. In order to prevent hoarding of spectrum or price fixing by a small group of big players on the market, the national administration is encouraged to establish laws to foster competition on the market [26].

As already mentioned in Subchapter 4.2.2 Market methods, the possibility of selling, buying back or leasing of spectrum increase the efficiency in use of spectrum bands. Furthermore a liberalized market place offers an easy way to get spectrum bands for new market participants and their applications.

5 Analysis of the RF-spectrum regulation

The last chapters explained in detail the organizations and the theory of spectrum management; who is responsible for what, how should it be done and what is the aim of all these processes.

In this chapter, the spectrum allocation done in the last decades is under investigation. Special examples shall illustrate the development and the practical work of spectrum management. If we have a look on a national or regional frequency table (e.g. the European table of frequency allocation [2]) several questions come up:

- Which bands are used?
- Why is this application allocated in this band?
- What was there before?

These questions need to be considered out of two perspectives. One point of view is the technical aspect of frequency allocation. The advantages and disadvantages of propagation for certain frequencies and the possibility of technical realization need to be considered. At the end of the nineteenth century the VHF band was technical not useable, in the nineteen-eighties the step above 1 GHz was the big cruces. Nowadays, the usage of terahertz radiation is in focus of research. The technical limits are shifted with every year and decade and with it the technical aspects of frequency use and spectrum management. The other point of view is the economical aspect of frequency allocation. Several interests of different groups clash into each other; the stakeholders are the industry, the governments and the end users. Hence, the economical aspect is strongly connected with political interests. To achieve ITU's goal to increase the social benefits through spectrum management, all these aspects, the advantages and disadvantages and the different interests of the stakeholders have to be considered. In the following pages possible answers are given on these big questions. The success and failures of applications and the related spectrum management are pointed out.

The UHF band is taken as example; this frequency range from 300 MHz to 3 GHz is the densest used band nowadays. Mobile telecommunication, TV broadcast and two really import ISM bands are located next to several other applications in this band. What makes this frequency range so interesting for users? The focus of this example is on mobile telecommunication and TV broadcast.

5.1 Mobile telecommunication

The history of mobile communication leads back to the nineteen seventies when Motorola introduced the first mobile phone on the market. Till to the end of the eighties, no one of the big players like Motorola or AT&T were aware of where the market will go to. The first mobile phones were not handy at all and so the market estimation of Motorola and AT&T predict only several hundred thousand subscribers for the year 2000. But with the change from the first analog generation (1G) to the second digital mobile telecommunication generation (2G), an incredible success story started [27]. The development and with it the change of spectrum use for mobile telecommunication is shown with the timetable bellows. The market trends, the change of network subscribers and the growth of occupied bandwidth for mobile phones is shown on the example of Austria.

5.1.1 Timeline

1979 At the World Administrative Radio Conference (WARC), a decision was taken to set aside a block of radio spectrum in the 900 MHz range for land mobile communication systems in Region 1.

1982 The Group Special Mobile (GSM) was established.

1988 Research for 3G starts.

1990 ETSI froze the specifications for the GSM 900 MHz band.

1991 ETSI froze the specifications for the GSM 1800 MHz band.

FCC froze the specifications for the D-AMPS (TDMA) 800 MHz band.

First GSM call done in Finland.

1992 At ITU’s WRC, spectrum bands were allocated for a worldwide uniform next generation mobile telecommunication system (3G). The technical standard is called IMT-2000; the bands are 1885-2025 MHz and 2110-2200 MHz and include terrestrial and satellite communication.

1993 The Public Postal Service Austria (PTT) started his first two base stations for GSM in the central of Vienna and at the Vienna International Airport. The network was called A1 and used a frequency band with 2 x 5.4 MHz in the range of 898 MHz to 904 MHz and 943 MHz to 949 MHz (Figure 16). In December 1993 PTT had installed 400 base stations all over Austria. Till 1996 PTT (now Telekom) was the only operator with 1,242 base stations and 300,000 users.

1994 One million subscribers using GSM worldwide.

1995 The UMTS task force was established.

FCC froze the specifications for the D-AMPS (CDMA) 1900 MHz band.

1996 In Austria the first private license was sold to Maxmobil (now T-Mobile) for 290.7 Mill Euro (2 x 5.4 MHz). Inspired by the license price for Maxmobil, also Telekom had to pay 290.7 Mill Euro for their band.

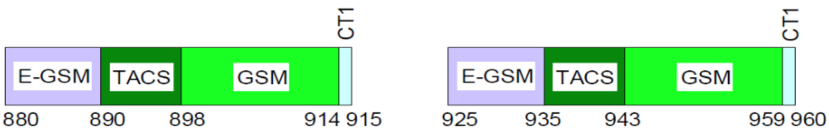

Figure 16: 900 MHz 2G spectrum allocation [28]

1997 ERC implements the ITU specifications for IMT-2000 on European level and allocates frequencies from 1900-1980 MHz and 2010-2025 MHz. The bands from 2110-2170 MHz are used for terrestrial applications, from 1980-2010 MHz for earth to satellite and from 2110-2170 MHz for satellite to earth radio links.

The second private license was issued to Connect Austria (bought by Orange) for 167.2 Mill Euro. Because of an increase of the bandwidth for Maxmobil and Telekom to each 2 x 7.8 MHz, no bands were left for Orange (since 2014 Drei) in the 900 MHz Spectrum. Therefore Orange got the first 2 x 16.8 MHz blocks in the 1.800 MHz band. After a reached coverage of 75% and 300.000 users, also Orange's blocks have been increased to 2 x 22.4 MHz.

1998 The CT1 band was re-farmed for GSM usage.

Third Generation Partnership Project (3GPP) was established.

1999 The third private license was sold to Telering (bought up by T-Mobile in 2007). Telering got 2 x 14.6 MHz in the 1.800 MHz band. In the same year, also Telekom and Maxmobil got their first frequencies in the 1.800 MHz band, but only for regional usage.

2000 The WRC finalizes the extension of the IMT-2000 band (2.5 GHz).

Launch of GPRS.

In Austria 2.1 GHz band UMTS licenses were auctioned for 831.6 million Euros.

2001 First 3G UMTS launched in Japan (WCDMA)

Shut down of the analog mobile phone system TACS.

WiMAX Forum was established.

The rest of the Austrian 1.800 MHz spectrum was awarded as shown in Figure 17. Next to the 1.800 MHz GSM band is the Digital Enhanced Cordless Telecommunication (DECT) allocated. Therefore the last GSM channel is unused as interference protection.

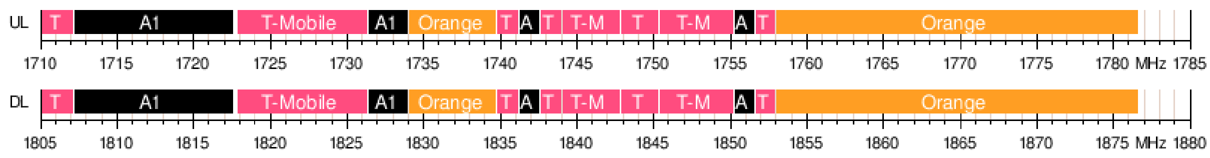

Figure 17: 1800 MHz Band for GSM [29]

2002 First 3G CDMA-2000 launched in South Korea and USA.

ITU announce the 4G vision called IMT-Advanced.

The TACS band was re-farmed for GSM usage.

2003 3G UMTS launched in Europe (WCDMA)

2004 GSM surpasses one billion customers.

First proposals for LTE published in Japan.

In Austria the E-GSM spectrum (880-890 MHz) was sold to Telekom and Orange.

2005 WiMAX standard IEEE 802.16e was approved.

2008 Finalization of LTE standard.

The CT1 band was sold to Orange (Figure 18).

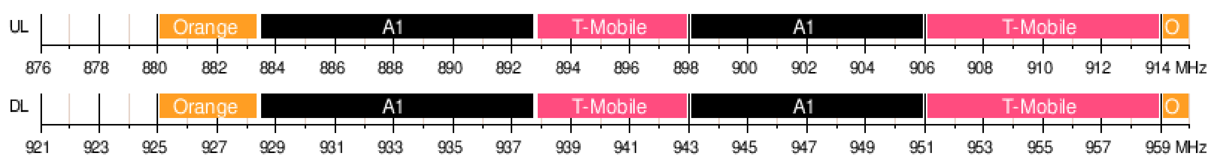

Figure 18: 900 MHz Band for GSM [29]

2009 First LTE network was launched in Stockholm and Oslo.

LTE-Advanced fulfills IMT-Advanced specifications and was submitted to ITU.

The change from analog to digital TV-broadcast created free bands around 800 MHz. All over the world this band (790-862 MHz) was re-farmed for telecom purposes.

2010 ITU recognized LTE and WiMAX as 4G standards and as pre-version of IMT-Advanced.

Four LTE licenses are assigned for the 2.6 GHz band and auctioned for 39.57 million Euros in Austria.

2011 Global mobile connections surpass 6 billion users.

LTE Advanced and WiMAX Advanced were standardized.

2012 The European Parliament announce in Decision No. 243/2012/EU [30] the multiband radio spectrum policy program to harmonize spectrum bands for mobile telecommunications in Europe. Therefore the whole mobile communication spectrum 800, 900 and 1800 MHz spectrum was reorganized (Figure 19).

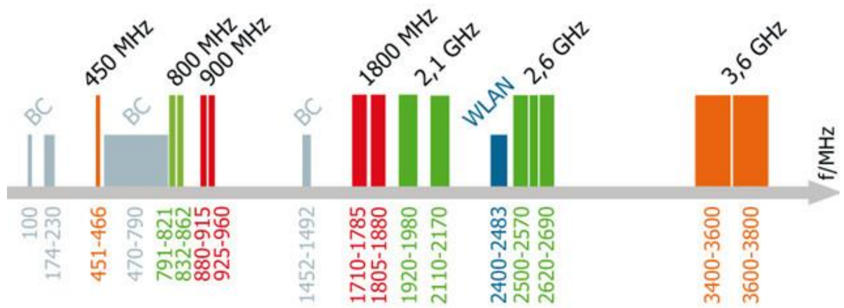

Figure 19: Frequency spectrum for mobile communication in Austria [13]

Frequency band	**Usage**
BC	Broadcast
450 MHz	Mobile communications
800 MHz	Mobile communications LTE
900 MHz	Mobile communications GSM/UMTS/LTE
1800 MHz	Mobile communications GSM/LTE
2.1 GHz	Mobile communications UMTS/LTE
2.4 GHz	ISM band: WLAN
2.6 GHz	Mobile communications LTE
3.6 GHz	Mobile communications WiMAX/LTE

Table 9: Spectrum allocation for mobile communication in Austria [13]

2013 The multiband auction for 800, 900 and 1800 MHz yield 2.014 billion Euros for the Austrian government. Telekom Austria (A1 TA), T-Mobile Austria (TMA) and Drei Hutchison (Drei) bid for the licenses. Because of existing licenses for the 900 and 1800 MHz bands, the re-farming process will take till 2020; the new licenses are valid for 20 years. The bands and the re-farming process are shown in Figure 20.

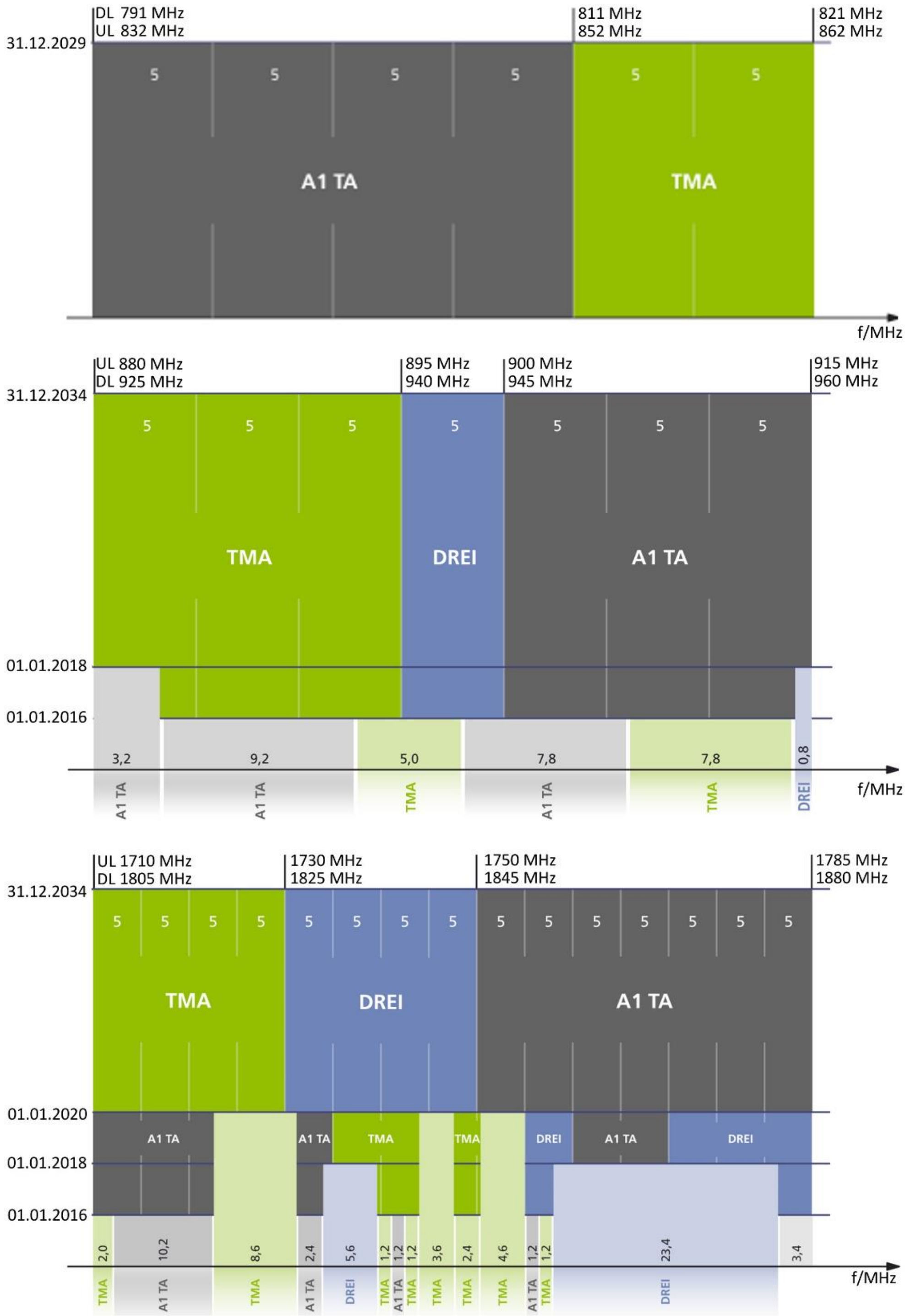

Figure 20: 800, 900 and 1800 MHz allocation in Austria [13]

5.1.2 Main facts

This timeline points out the incredible development of mobile telecommunications in the last 35 years. The main facts are summarized below.

The used bandwidth has been exploding from 48 MHz for 1G plus 2G (Figure 16) in 1990 to 540 MHz for 2G + 3G + 4G (Figure 19) in 2014. With every new generation new spectrum allocations have been necessary. Till now, only the first analog generation was shut down and the band could be re-farmed for other applications. Because of the enormous growth of the second generation of mobile services, it was obvious, that this available spectrum will be used for GSM. With the last multiband auctions for 800, 900 and 1800 MHz all over Europe, the course is set for the future needs of mobile communications. The spectrum bands, which were exclusively used for GSM the last decades, are now available for LTE too. This offers the possibility of a smooth change over to the next generation without another re-allocation.

The number of users has increased from several 100.000 to more than 6.8 billion. In developed countries more mobile phones are in use than citizens live in the country. Figure 21 shows the average relation of mobile phones to citizens for developed and developing countries and worldwide; in average 96 mobile phones are used from 100 inhabitants in the year 2013. Nonetheless, in developed countries every citizen use 1.3 mobile phones, in developing countries a huge potential of market growth is available. Only 90 % using a mobile phone [11].

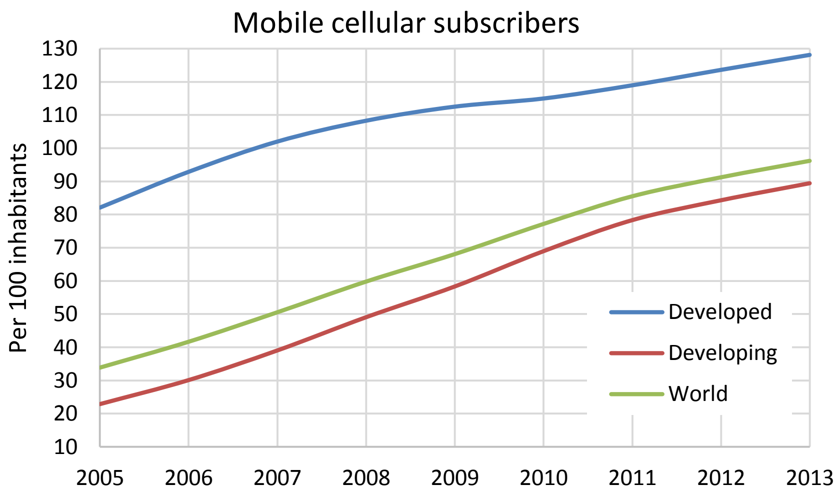

Figure 21: Mobile cellular subscribers [11]

The possibilities of mobile applications expand from simple analog calls (1G) to mobile broadband data communications with a data rate up to 1 Gbit/s (4G).

5.1.3 Analysis

By investigating the development of mobile telecommunications from the last 20 years, some major aspects need to be pointed out; these aspects have been leading to the development status what we are facing nowadays.

First of all, the major aspect is the technical development. In the field of mobile communications a lot of different disciplines of engineering are included. With respect to this thesis's topic only the related issues are mentioned.

Usable frequencies

With the beginning of mobile communications, the technical possibilities were limited to frequencies with several hundred megahertz. GSM was started with 900 MHz because the techniques for higher frequency equipment was not available. With every year, this boundary could be shifted further. In case of GSM, the next development stage used already 1800 MHz.

Technical equipment

The development of integrated circuits and the increasing power of those ICs has been pushing also the communication sector. Data processing and signal modulation schemes could be improved and implemented in mobile phones. With every generation of mobile communication standards, the throughput could be increased by using the same spectrum bands. The efficiency of the used spectrum has been increasing rapidly.

Wave propagation

As the limitations were not given by the usable frequency or technical equipment anymore, but by the huge amount of users, the different characteristics of frequency propagation had to be considered. The propagation in rural areas with low or urban areas with high user density claims different settings. A mixture of different frequencies and cell sizes is necessary; for mobile communication applications 450, 800, 900, 1800, 2100, 2600 and 3600 MHz are available. Small cells for a high user density in cities or larger cells for rural areas have to be used to cover an entire country with different services.

Spectrum management

The UHF band includes not only allocations for mobile communications applications. Next to the mobile phone systems shown in Figure 19, frequency bands are assigned for fixed mobile systems like defense systems or DECT, satellite applications, the 430 MHz and 2.4 GHz ISM band, amateur radio, broadcasting (terrestrial or satellite TV), aeronautical navigation and radio astronomy. The detailed allocation can be looked up in [2] (pages 78-115). Therefore, spectrum management and in particular interference management is important to reduce harmful interferences to neighbor bands and other applications.

The second aspect is the shutdown of old systems and the re-farming of the released bands. The cornerstone of the modern mobile telecommunication was set with the spectrum allocation of the 900 MHz band in 1979. Even though this band was not commercial usable at this time, this allocation marks the beginning of the development of the first generations. A frequency assignment around 1 GHz was not difficult at this time, because the bands could be hardly used. After the development of technical equipment for those frequencies, the use of these bands increased. With new innovations, old systems got unnecessary and have been shut down. There are several examples in the last years of shut downs and re-farming spectrum bands. The analog mobile phone generation (1G) was replaced by GSM and CDMA (2G), the cordless telephone system CT1 was supplant by DECT. In case of broadcasting services, the analog system got replaced by a digital system and the so called digital dividend could be realized (see 5.2.2).

The third aspect mentioned here is the political aspect. No innovation could become a success story in the dimension as GSM have been, without lobbying and political power. Political decisions are influenced by different groups of interests, in case of technical standards even more than in spectrum management.

GSM was driven by CEPT and after by ETSI, a European project to uniform the mobile telecommunication in Europe. Next to GSM, TDMA and CDMA systems were developed in the US and in Japan. The frequency allocation was different for 2G systems worldwide and roaming was also not possible. This led to dual- or tri-band mobile phones.

For the third mobile telecommunication generation ITU released the IMT-2000 specification. Compliant standards need to fulfil certain criteria for data rate, bandwidth and used spectrum bands. The same approach was chosen for the fourth generation with IMT-Advanced in 2008. These requirements shall guaranty worldwide uniform mobile telecommunication systems, a certain level of quality of service and a worldwide frequency allocation.

The fourth aspect is the economic one. A lot of different markets and with it different stakeholders are connected to the mobile communication. The mobile phone market is one of the fastest growing mass consumption market with global players. The network providers operate on national level, but can be present in several countries or are connected with each other by international contracts. A handful companies produce the base station and backbone systems. And the used resource, the spectrum is sold by the government. All of these branches are necessary for mobile telecommunication. Every industrial sector and every company has his own goals and visions and try to push them to enlarge the own profit. The end user pays for the mobile phone and with the mobile phone network contract for everything else too. All these economic aspects need to be considered for every level of spectrum management and technical standards.

5.2 Television broadcast

Television broadcast is mentioned as a second example. The reason is the development of those systems over the last 70 years and also because of the direct connection of TV broadcast using spectrum to mobile communications. Main facts of analog and digital TV broadcast are pointed out.

5.2.1 Development of TV broadcast

In the nineteen fifties the terrestrial television broadcast got suitable for the mass with the introduction of color TV. 1953 the US system NTSC (National Television System Committee) was adapted for color TV. In France 1961 the Séquentiel couleur à mémoire (SECAM) was proposed. 1967 broadcast with the German PAL system (Phase Alternating Line) started.

With the new millennium, also a new generation of TV broadcast was introduced:

- Digital Video Broadcasting (DVB)
- Advanced Television Systems Committee standards (ATSC)
- Integrated Services Digital Broadcasting (ISDB)
- Digital Terrestrial Multimedia Broadcast (DTMB)

The standards are subdivided corresponding to the transmission media:

- Terrestrial (-T)
- Satellite (-S)
- Cable (-C)
- Handheld (-H)

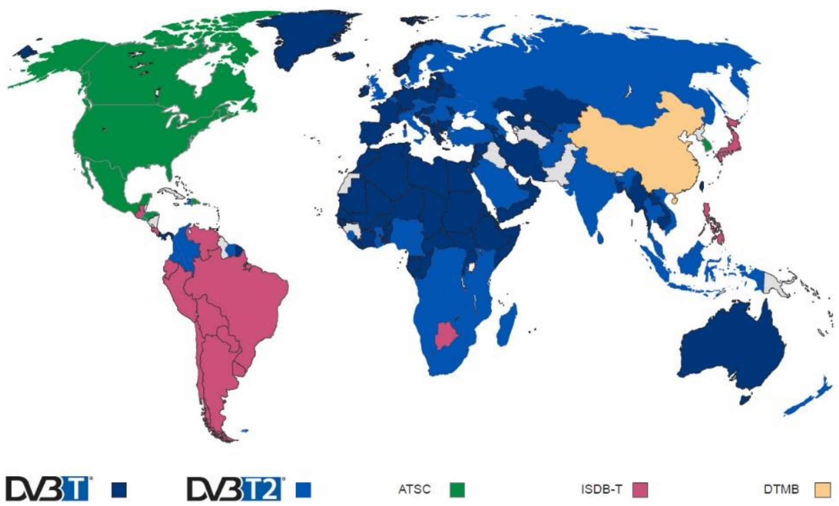

Figure 22: Distribution of digital terrestrial TV broadcast systems [31]

In Figure 22 the digital terrestrial broadcast system distribution is shown. As for mobile telecommunication and other technical applications, a separation of Europe and the US is obvious. In South America the Japanese ISDB system is used. China present his self as another big player in this world and developed his own system DTMB. This landscape underlines one more the different influences, strategies and rivalries of the big players around the world (already mentioned in 4.3.2).

5.2.2 Digital dividend

The switch over from analog to digital TV broadcast reduced the occupied bandwidth for TV broadcast in the VHF and UHF band. Because of digital compression systems, coding and modulation techniques, six to eight digital TV channels can be transmitted within the bandwidth of one analog TV channel. With the release of the IMT-specifications, ITU propose to identify this nascent spectrum for mobile communication purposes. The relevant spectrum bands vary between the different ITU regions. In Region 1 the band from 790-862 MHz will be available, in Region 2 the band from 698-806 MHz and 806-862 MHz and in Region 3 the relevant bands are 698-790 MHz and790-862 MHz. This leads to a digital dividend of 72 MHz in Region 1 and 164 MHz for Region 2 and Region 3 [1].

The decision making process and the use for mobile communication of those frequencies and with it the whole spectrum management process was driven by political considerations. The re-farmed spectrum and the whole process is called the digital dividend. ITU proposed a valuation between 182.5 Billion Euro and 585 Billion Euro caused by the digital dividend within Europe in the next 15 years [1].

In 2006 the Netherlands was the first country which switched over to digital television transmission. Till 2015 all ITU members should have been started with the process of the digital switch over and assign the spectrum bands for mobile applications.

5.3 Summary of the RF-spectrum regulation analysis

The developments in the broadcasting sector and communication sector have been leading to a huge demand on spectrum bandwidth. Terrestrial and satellite broadcasting and mobile communication became mass products. The increase of users and also the technical requirements especially for communication systems, claim more and more bandwidth. With new generations of mobile communication and developments in signal processing and data transmission techniques, the efficiency of spectrum use could be increased. The new systems replaced old generations and unsuccessful applications got shut down. The available spectrum was re-farmed for modern applications (e.g. digital dividend).

The way of spectrum management have been enhanced too. Based on new challenges, an adaption of spectrum management took place; the strict application based regulations have been broken up and spectrum allocation became more market based orientated. With those changes, an increase of spectrum use efficiency could be achieved. Even though, ITU is working hard on it, one drawback is still the diversity of different developments all over the world; till now, no uniform approach could be achieved for the two important branches mentioned in the subchapters before. ITU try to enhance and uniform the different approaches with standards and regulations. But as for many other concerns too, the humanity and in special several countries and unions are not willed to cooperate and agree on one worldwide uniform approach. The IMT-standards are one first big step to a uniform mobile communication world.

The importance of the communication sector is also visible in the companies operating in this field. In this commercial sector some of the most valuable companies operate in this sector like Google, Apple, Samsung or many more.

6 Regulation of the optical spectrum

The optical radiation is like a white spot on a landscape in case of spectrum management. Applications are existing and they are using these bands with respect to certain standards.

In case of regulation and spectrum management, we have the possibility to start from scratch. With the lessons learned from the last decades in RF-regulation and spectrum management, new regulations and ways of allocations could be established and help to boost the optical wireless communication.

6.1 Spectrum of interest

At the beginning of this thesis in Chapter 1.1 the optical radiation was pointed out as unregulated spectrum. With the growing interest on optical communication systems two questions come up:

- Which wavelengths are interesting for which applications?
- Which wavelengths are already used and will be used in the near future?

6.1.1 Existing systems

Light is in use as transmission media for several decades. Some applications lost their importance again and got replaced by new RF-based applications. Other applications have never been succeeding to break through. Most of the optical based systems are niche products and designed for special purposes. The used electromagnetic spectrum of these systems is covering the whole optical radiation. The most important applications are mentioned.

FSO links

The ideas and the basic characteristics of FSO systems are mentioned in 1.1 Motivation and in 2.2.3 Free space optical communication. The range of applications goes from last mile connections or backup links in LANs to installations for disaster operations or mobile infrastructure to special safety applications where normal RF-links or cables are not allowed. The advantages are small equipment, quick installations and relocation paired with high data rate. The used spectrum is Near-IR and Mid-IR (approx. 800 nm – 10 µm). Because of diverse atmospheric absorptions depending on the wavelength (see Figure 2) only small windows of IR are used.

IrDA links (Infrared Data Association)

Before Bluetooth and WLAN was established in mobile phones, this system was used for short range data communication between mobile phones and other mobile tools. Also for peripheral IT components like moues or keyboards this link was designed and replaced the cables on the desk. The used wavelength is between 850 nm and 900 nm. The stake of IrDA links decreased the last years and with it the importance and distribution of such systems is evanescent low. These connections have been replaced by RF-solutions.

Industrial applications

Optical sensors measure particles in the air, or the composite of liquids. Another industrial use of light are laser using machines for material processing. These applications are not related to communication and mostly encapsulate; the used spectrum depends on the system but can cover the whole optical radiation.

Consumer electronics

Consumer electronics controlled by remote controls with optical transmissions. The used wavelength is located in the near infrared light. In nearly every household one or more remote controls are in use.

Another domain of lasers is for entertainment like laser shows and light projections (visible light) or light barrier (Near-IR). There is no data transmitted, but this systems can interfere optical links.

Optical space observation

Examples for optical space observations are Telescopes like the Very Large Telescope (VLT) or the European Extremely Large Telescope (E-ELT) in Atacama Desert in Chile. Space observatories and Telescopes all over the world are investigating the optical radiation of the deep space. Those applications are passive users of the spectrum. They are only receiving signals on a very low level.

6.1.2 Future applications

With new technologies and in particular with the introduction of LEDs also some new innovations arise. The replacement of light bulbs with LEDs offer the possibility to use electrical lighting also for data transmission. This technology is called VLC. The possibilities go from broadcast to indoor applications, the whole spectrum of wireless communications.

Next to the use of visible light, current research shifts the limits of IR further and trend to 10 µm FSO systems. This FSO technology could be also applied for longer distance links e.g. line of sight optical relay links or satellite uplinks.

6.2 Safety regulations and restrictions

Several standards exist for safety reason. These standards are not related to spectrum management and therefore are not considering any related aspects.

6.2.1 Existing regulations

International operating standard setting bodies also offer standards for optical radiation based systems. National guide lines, industrial safety regulations and power limits base on those standards. The most important international bodies are ITU, ISO and IEC.

ITU Recommendations

ITU-R and ITU-T investigated several aspects of FSO links and published several Recommendations on this topic. These Recommendations imply technical and design guide lines [32].

ISO Standards

The International Organization for Standardization (ISO) provides also laser related standards. The main focus is on laser processing machines and industrial safety.

IEC Standards

The International Electrotechnical Commission (IEC) was founded in 1906 and is the world's leading organization for international standards in the field of electrical, electronic and related technologies.

The IEC 60825 – Safety of laser products standard consists of 17 parts. This standard is the basis for every national standard specification related to lasers and laser products. The most important parts for optical wireless communications are:

- **Part 1**: Equipment classification and requirements
- **Part 8**: Guidelines for the safe use of laser beams on humans
- **Part 12**: Safety of free space optical communication systems used for transmission of information
- **Part 13**: Measurements for classification of laser products

6.2.2 Laser safety

Even though the spectrum for FSO systems is not regulated, some restrictions need to be considered regarding safety issues. Safety is the main content of the standards mentioned before.

Eye safety

The human eye is the most vulnerable organ in case of optical radiation. The impacts depend on the wavelength and the related penetration as shown in Figure 23.

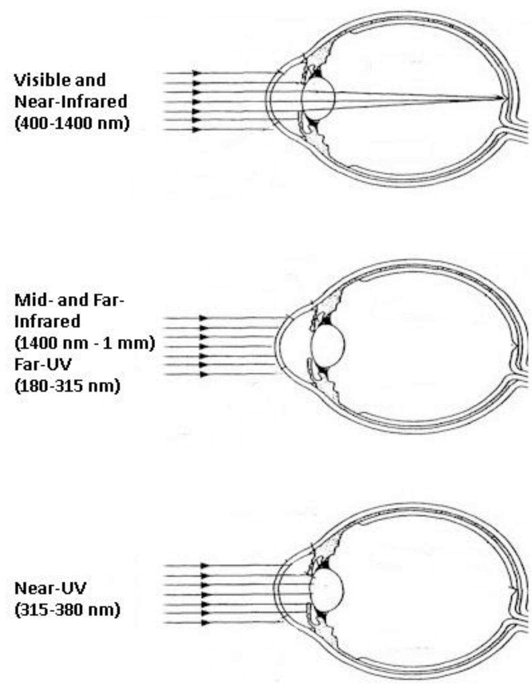

Figure 23: Ocular absorption for optical radiation [33]

The absorption for a certain wavelength and the caused grade of injury is related to the tissue. Hence certain power levels and laser classes are defined for different wavelengths to ensure a safe use of lasers.

Laser classes

Laser sources are graded in seven laser classes. The hazards and warning statements for the different laser classes are summarized in Table 10.

Class	Hazard	Warning statement
1	Safe under reasonably foreseeable conditions (Note: Class 1 lasers include high-power lasers that are fully enclosed, such that potentially hazardous radiation is not accessible during use).	-
1M	Safe for the naked eye except if magnifying optics are used.	Do not view directly with optical instruments.
2	Safe for short exposures (less than 0.25 s). The eye is protected by the blink reflex.	Do not stare into the beam.
2M	Same as Class 2 except if magnifying optics are used.	Do not stare into the beam of view directly with optical instruments.
3R	Safe if handled with care, may be dangerous if mishandled. Risk is limited by the blink reflex and natural response to heating of the cornea for IR radiation.	Avoid direct eye exposure.
3B	Direct viewing is hazardous. Protective eyewear is necessary if the beam is accessible. Safety interlocks are required to prevent access to hazardous laser radiation.	Avoid exposure to beam.
4	Can bur the skin and cause permanent eye damage. Class 4 lasers can also present a fire hazard. Safety interlocks with manual reset are required to prevent access to hazardous laser radiation.	Avoid eye or skin exposure to direct or scattered radiation.

Table 10: IEC 60825-1 laser classes [34]

The maximum radiation power is specified for each class depending on the wavelength as seen in Figure 24. Class 1 and 2 are divided in a standard class and a 1M and 2M class in case of magnifying instruments are used. Class 2 contains only lasers within visible light. The highest laser class 4 contains all lasers above 0.5 W radiation power.

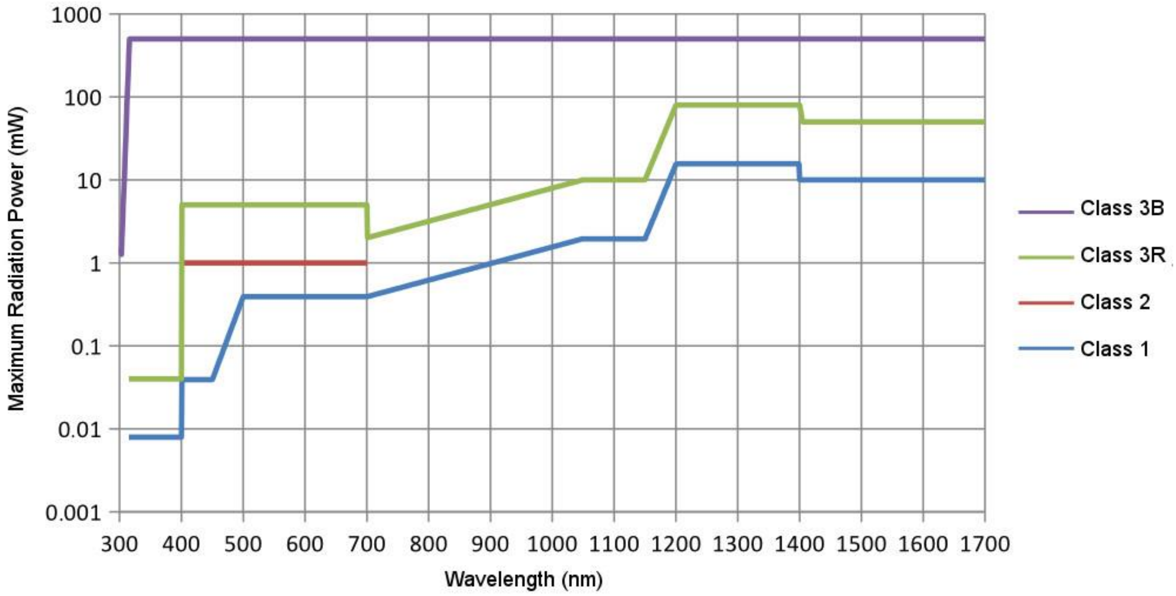

Figure 24: Power limits for laser classes [35]

6.3 Regulation aspects

For optical radiation the same issues may be considered as for RF-allocations. The requirements will vary in some aspects, because of different characteristics between RF and light.

6.3.1 Technical aspects

The technical aspects vary the most between RF and optical radiation, simply because of the higher frequency; light have to be handled completely different. The major aspects are pointed out.

Interference

FSO links can be compared with directional radio links, but the beam divergence is significantly smaller. Therefore the possibility of interference for FSO links is quite low but under certain conditions may occur [32]:

- The systems use the same or very close wavelengths.
- The links operate at the same time within geographically close separation.

The risk of interference for indoor or VLC applications especially for consumer products is many times higher. The mentioned conditions arise in every office or household and may cause harmful interference. Right now, the use of those systems is quite low and the interferences negligible. If one of those new technologies become at a fraction as successful as for example GSM, the consequence would be a very dense use of certain wavelengths as it is in the UHF bands right now. The spectrum management issues would be the same for light as for RF; harmful interferences would appear in the corresponding bands.

Propagation

The major drawback of optical radiation is the line of sight condition for communication links. Light cannot penetrate objects like a several gigahertz signal used for commercial radio equipment (e.g. WLAN, Bluetooth, etc.). For transparent materials like glass a penetration is possible with a certain attenuation and other optical effects like refraction and diffusion.

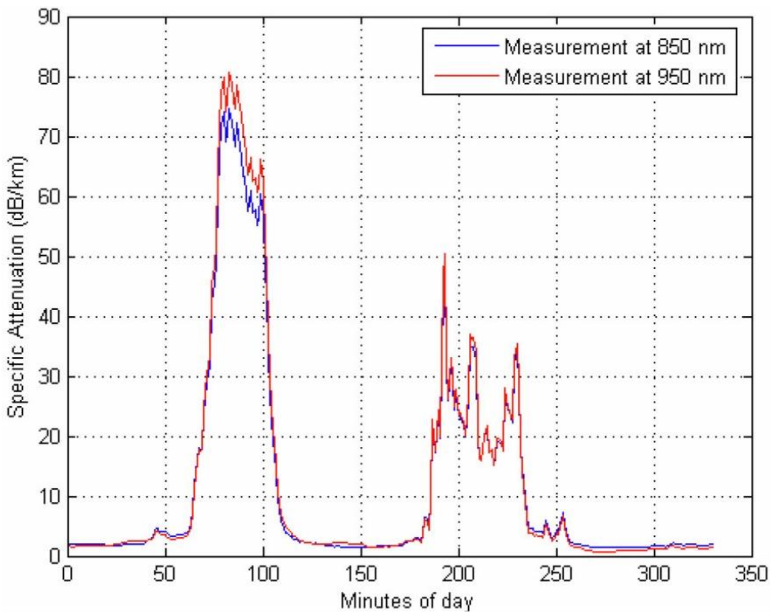

Figure 25: Specific fog attenuation for 850 and 950 nm link [36]

For FSO links the atmospheric conditions have to be considered too. The main atmospheric influences are caused by fog, rain and snowfall, but especially fog attenuates the link the most. Several research institutes all over the world investigate the propagation of light in the atmosphere. In Figure 25 the specific attenuation caused by fog is shown for two different wavelengths. The measurements were done over a whole day and show 2 fog events in Graz, Austria in 2006. These measurements point out the high attenuation of fog for Near-IR.

Equipment

An optical transmitter (Tx) contains LEDs or Laser diodes (LD), optical instruments (e.g. lens) and electrical control units. Such transmitter units can be built up really small. Some LDs are available with integrated control IC and integrated lenses in a package size of only several millimeters.

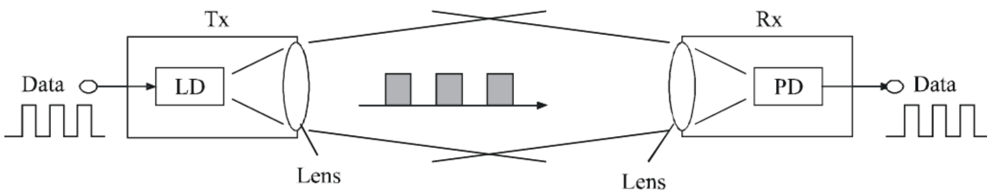

Figure 26: Basic configuration of an FSO link [32]

The optical receiver (Rx) contains the same as a transmitter with the difference of the photo diode (PD) or avalanche photo diode (APD) is used instead of the LEDs or LDs. The unit itself can be as small as the transmitting unit (see Figure 26). The Rx optics are most of the time larger than the Tx optics to focus as much transmitted radiation on the PD as possible.

The $\lambda/2$ or $\lambda/4$ large antennas used for RF links are replaced by the LD or PD in combination with the lenses. This is the main reason for a compact equipment size.

Standards

The existing standards and technical guide lines for optical devices are focusing on safety aspects (see 6.2 Safety regulations and restrictions). This is the main difference to RF related standards for spectrum engineering mentioned in 4.4.1 where the main intention is on interference prevention.

6.3.2 Economic aspects

The most important question in case of economic aspects and one of ITU's principles is: Would increase a spectrum allocation for optical radiation the value for end users?

The economic aspects do not vary with the frequency; governments could gain additional incomes out of spectrum licensing. The basis for assessment would need to be different, because of the high bandwidth. In comparison to RF licenses, the price should be for example per nanometer of wavelength than in e.g. per megahertz.

The licensing process would be only one part of the spectrum management effort, which would be needed for optical radiation. Also all other key functions of spectrum management would have to be considered (see Chapter 4 Spectrum management). To handle the additional effort, resources like manpower and equipment would have to be necessary; these would bring additional costs for spectrum management.

How the end user would profit from a frequency allocation in these bands is hard to estimate. A proposal is given in Subchapter 6.4 Wavelength regulation and allocation .

6.4 Wavelength regulation and allocation

Thirty to forty years ago it was not possible to forecast in what way and in what dimension the mobile telecommunication market would expand. Nowadays, in the same way it is very difficult to do this for the optical communication sector. The growing demand for broadband communication asks for new technologies, but in which relation this will be satisfied by optical based wireless application is hard to predict.

Out of the presented facts, the lessons learned from RF frequency allocations and the objectives of spectrum management a proposal for a frequency allocation and management for optical wireless communication is given here.

6.4.1 Regulation

The key functions of spectrum management bases on three objectives (see 4.1 Objectives of spectrum management). The essence of these objectives is the efficient use of the resource electromagnetic spectrum and the aim to gain a highest possible benefit for end users. The priority of new regulations have to be a fulfillment of these objectives.

In near future with a constant distribution of optical based systems and as long as optical broadband links are not used for consumer electronics, a spectrum regulation would not effects the end user. With an increase of wireless optical communication systems, a regulation would help to deal with harmful interferences and would provide clear guidelines for those systems. A better availability of communication systems would generate a value for end users. But as a coin has always two sides, also regulations have not only advantages. An overregulation restricts creativity, handicaps developments and kills markets.

In a nutshell, spectrum management related regulations for optical radiation should base on

- safety related standards,
- include interference related issues,
- include propagation related issues, and
- cover stakeholder's positions.

6.4.2 Allocation

An expansion of the spectrum allocation table above 3 THz would bring the same consequences for the optical radiation as it is for radio frequencies nowadays. Any assignment should base on regulations mentioned before. The big difference to RF would be, that for all allocations the output power need to be restricted for safety reasons. A change of an existing system brings always advantages and disadvantages with it. The pros and cons of a spectrum allocation for the optical radiation are pointed out.

Advantages:

- A wavelength allocation could help to treat with interference related issues.
- Governments could gain additional incomes out of spectrum licensing.
- The right policy objectives could emphasis the use of optical radiation.
- New broadband applications would increase the benefit for end users.

Disadvantages:

- High license costs are the biggest drawback of RF bands. The free available optical bands attract companies for new developments. With high prices for optical licenses, the interests on those bands and with it the will of investments and research could be curbed.
- If a license and with it an entry in national allocation tables is necessary and fees are charged for the licenses, the costs of the licenses would be passed on the consumer products and shifted to the end users.
- Additional spectrum allocations cause additional effort for every key function of spectrum management. The planning, engineering, authorization and monitoring would have to be adapted for optical radiation. The necessary resources would generate additional costs for the spectrum authorities.

The existing management approaches can be used for an optical radiation allocation (for detail explanations of management approaches see Subchapter 4.2) as follows:

- **Administrative method**: Certain wavelengths could be exclusively assigned for scientific purposes (e.g. optical space observation). The allocation could be coupled with a regional restriction for other applications.
- **Market methods**: If a spectrum allocation for certain wavelengths is necessary, because of harmful interference between commercial applications or because of national interests, these bands should be traded with market based methods.
- **Unlicensed spectrum**: The majority of the optical radiation and especially the interesting spectrum bands for wireless communications should be handled like ISM bands. The example WiFi is showing how successful a technology can be within an unlicensed band.

7 Conclusions

In this thesis the spectrum management was under investigation. Out of the analysis results from RF allocations, possibilities of spectrum management for the optical radiation were proposed. The advantages and disadvantages of a change from a not regulated spectrum to a regulation and allocation of certain spectrum bands were pointed out. By introducing all related aspects of spectrum management starting with the electromagnetic spectrum, the related managing organizations and their principles of operation, up to changes and examples of successful allocations in the last decades, a broad overview on spectrum management was provided.

7.1 Results

Nowadays consumer electronics and the whole wireless communication market depend on high data rates. The high demand on wireless broadband communications can hardly satisfied by radio frequency based applications only. The used UHF and VHF bands cannot provide the amount of bandwidth which would be necessary. This leads to an increasing interest on optical radiation and optical wireless communication systems.

The experience of around 100 years in spectrum management and especially the knowledge of the UHF allocations in the last decade can be used to establish a regulation for optical radiation. The requirement for a regulation would be a tremendous growth of the use of optical radiation for wireless communication. This would lead to a dense use of certain frequencies in the visible light and Near-IR and Mid-IR like in the UHF band and would cause harmful interferences. Should be this the case, spectrum regulations and allocations could help to deal with these problems.

Existing standards like the IEC 60825 – Safety of laser products standard concentrate on safety related issues. For a spectrum regulation, those safety issues have to be included and the safety standards can provide a good base for the regulation standards. Next to the safety aspects, also the differential technical aspects between RF and light have to be considered. The problems with interferences, the equipment and also the behavior of propagation are completely different to radio or microwave links and yield in new challenges for spectrum management.

The spectrum management approaches and methods could be transferred to the optical radiation with slightly modifications.

7.2 Outlook

An exact estimation how the communication market will grow and what technologies will play a leading role is hard to give. In the next decade the main standards in mobile communications will still use RF based links. Developments will help to confirm the domination of such standards and the radio technologies.

In the same way, new ideas and developments will help the optical systems to expand. It is only a matter of time, till the enormous potential in optical radiation will be used for consumer products and optical links ill operate equally next to RF-links. To be prepared for this moment, a discussion need to be inspired about how optical radiation can be used in the most efficient way and how far regulations should be established.

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