

On Radio-Frequency Spectrum Management

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Abstract—This article review lessons learned from the uses of radio-frequency (RF) spectrum at national and international scales. Its main purpose is to stimulate debate on how to allow new wireless systems to operate, and to reduce the chronic apparent shortage of RF spectrum. The article aims at a better understanding of the mechanisms behind spectrum management and their pertinence to the public interest. The main contributions if the article are:

- Considering RF spectrum management as a construct that structures radio services and, at the same time, distributes wealth and power;
- Highlighting major doctrines of RF spectrum management;
- Promoting spectrum management directly by its users;
- Promoting cooperation and transparency.

The several parts of the paper include the evolution of spectrum exploitation, and a foreseeable future by taking a closer look at major dilemmas and challenges. The paper ends with general comments and conclusions.

1. Introduction

“There is no more spectrum available”.

This was stated by Herbert Hoover, the US Secretary of Commerce, in 1925. Since then, the statement has been heard each time a new wireless service has been proposed. That shortage of spectrum has been felt as a factor delaying the social and economic development of society. Various proposals have been put forward to solve the problem, but no satisfactory solution has yet been found. The laws of physics impose absolute limits. Progress in science and engineering bring us closer to these limits, while administrative means impose additional restrictions. The latter result from our choices, more or less deliberate. Better policy and organization could augment the outcome drawn from what is physically possible. For example, for all communications between fixed points, cables could be used instead of unguided radio waves, which would leave radio waves for mobile applications. Satellite networks could similarly take over from terrestrial networks. Better propagation and system models could lead to more efficient spectrum use. Alternatively, we could replace inefficient signal-coding and data-compression technologies with better technologies. The Regional Radio Conference (RRC) on terrestrial broadcasting, held in Geneva in 2004/2006, is

a good example. The participating countries decided there to move from analog to digital television by June 2015, which freed a significant part of the electromagnetic spectrum for other uses. According to Martin Cooper, a pioneer of mobile radio, large segments of the radio-frequency spectrum are underutilized due to outdated ideas and practices that are still followed [1]. Other professionals have shared his opinion.

Science and engineering make the spectrum potentially usable, but its real use depends on local legal, regulatory, financial, and also perhaps other factors. Diplomats, lawyers, economists, and engineers gather every few years to review and improve the intergovernmental treaties that regulate the uses of radio waves. Traditionally, when doing that they strictly observe the consensus principle. The consensus requirement assures that the majority cannot impose regulations that would harm any vital interests of a single country. As a consequence, with unbalanced representation the conference results might be biased. That could put some spectrum user groups not represented at the conference in an inconvenient situation, which could last for decades. The nearest such event, the World Radio Conference, will be held in Geneva, Switzerland, from November 2 to 27, 2015 [2]. As at such previous conferences, URSI will certainly participate as an observer, i.e., with no voting rights. However, individual URSI scientists can participate and vote if they are members of national delegations.

The target readers of this review are all of those interested in radio and spectrum management mechanisms who do not actively participate in such activities. Because of this, this paper draws heavily from the authors’ earlier publications, lectures, and discussions at spectrum management working groups they chaired in URSI and in other bodies, such as the International Telecommunication Union (ITU). However, the opinions expressed here are the authors’ personal opinions.

2. Spectrum Exploitation

This section deals with key ideas and practices inherited from the past. It starts with the genesis of state intervention, national spectrum management, and intergovernmental collaboration. The USA is taken as an example for national management. The mechanism of international regulations

in the framework of the International Telecommunication Union is then briefly reviewed. The role of scientific research is outlined, as is the cooperation with URSI and other organizations.

2.1. *Unregulated Commons*

Radio is associated with the names of James Clerk Maxwell, Heinrich Hertz, and Alexander Popov. None of these marketed his discovery: they were motivated only by scientific curiosity. The first radio company in the world was the Wireless Telegraph & Signal Company, founded by Guglielmo Marconi in Great Britain, in 1897. It started with wireless telegraphs for navies. Since then, military needs have continued to be the major force behind the technological progress of the wireless sector, the extraordinary success of which continues until today. Marconi marked the birth of a new industry that began transforming the Industrial Society into the future Knowledge Society. We all take part in that process, whether we want to or not, having only minuscule influence on it and a very vague idea of where it will ultimately bring us. The way we use the spectrum can accelerate that process, or can slow it down. Marconi's company offered equipment and services. The spectrum efficiency of his spark-gap transmitters was very low. Their emissions occupied almost the then entire usable radio spectrum over large geographic areas (e.g., some 250 million square kilometers), yet carried only of the order of single bits every few seconds. The Earth's surface could accommodate only a few such transmissions at a time. To avoid interference, the operators invented the rule of "*listen before transmit*", which has been adapted many years later in some local-area wireless computer networking systems, such as Aloha and Wi-Fi. This latter network, which is presently very popular, is based on the Institute of Electrical and Electronics Engineers (IEEE) 802.11 standards. The radio-frequency spectrum was dealt with as a natural "commons" for free use by everybody, just as the air is used for breathing. *Commons* refers to resources that are not privately owned, and are accessible to all members of society. They can include everything from natural resources and common land to computer software. When commonly held property is transformed into private property, this process is known as "*enclosure*" or "*privatization*".

Marconi patented his wireless telegraph to assure him a monopoly, and to block other companies from developing similar devices and services. However, his monopoly did not last long, and new companies appeared in the market. They all chose to compete instead of cooperating, and the competition was fierce. To strengthen his position, Marconi tried various means. He had a good relationship with the ruling class in Italy, as did his spouse in Great Britain. His opponents accused him of bribery of the highest governmental officials to obtain lucrative governmental contracts. The accusations led to political scandal in Great Britain, known widely as the "Marconi scandal", but Marconi did not lose much. It was the first known corruption case in the radio business.

To force people to use his services and devices, Marconi did order his radio operators to ignore messages sent using the competitors' devices, in spite of the fact that in maritime emergencies, the consequences could be tragic. With no regulations, this was quite normal, and in accordance with the concepts of free competition and the Darwinian doctrine of survival of the fittest. One of Marconi's competitors was Karl Ferdinand Braun (who shared the 1909 Nobel Prize in Physics with Marconi). Braun was associated with the German Telefunken Company.

Defending the company's interests, the German government intervened to break down Marconi's monopoly once and forever. The personal experience of a family member of the German Emperor had an effect: his courtesy radio telegram to the US President was rejected by a Marconi operator simply because it was sent from a German-made device. Certainly, there were numerous similar cases, but none directly touched such high personalities. They initiated the international radio regulatory activities that have continued until now. As a consequence of the incident, a preparatory radio conference was called in Berlin in 1903, just six years after Marconi opened his company. The focus was on the maritime services, interconnections, and financial settlements. Interconnectivity does not happen by itself, since it is not in the incumbent's interest to share the income with competitors.

2.2. *First Intergovernmental Agreements*

The proposed regulations included two important obligations. The first was to receive and process emergency radio messages, no matter what their origin. The second was to continuously watch for distress signals. These proposals turned out to be impossible to adopt at the conference, and the delegations decided to come back to them at the next conference, at the same place, three years later. The Berlin 1906 conference (1) allocated two frequency bands (around 0.5 MHz and 1 MHz) for public correspondence, (2) founded the International Radiotelegraph Union (IRU), and (3) signed the International Radiotelegraph Convention. By setting the rules on how the electromagnetic spectrum was to be used, the signatories de facto declared its collective ownership. However, other independent nations could join, acquiring the same rights. Specific spectrum uses were to be registered, and the IRU Bern Office recorded the ship stations in operation (known as the "Bern List").

However, an inherent conflict appeared at the conference between private interests and public interests. Marconi succeeded in ensuring that the governments of Great Britain and Italy opposed the convention, in order to defend his company's interests. The regulations had to wait six more years, until the following conference in London. The losses due to the delay have never been evaluated. It was the only case of direct governmental protection of a specific company at radio conferences [3] that the authors have found in official documents. If similar cases happened, they were made outside of the conference rooms.

International treaties are part of a worldwide game that governments agree to play. Consensus is an inevitable ingredient, as there are few things able to force a state. Conference negotiations aim at balancing conflicting interests, and large companies have a strong say there. The Berlin controversies had to wait until the 1912 London conference. The famous Titanic disaster was not without effect on the approval, which happened just three months before the conference, and could have been avoided if an agreement had been in place. This luxury ship sank with some 1500 passengers, after colliding with an iceberg during her maiden voyage. Distress signals were immediately sent by radio, but none of the ships that responded were near enough to reach her before she sank. However, a nearby ship that could assist, the Californian, failed because her radio operator switched his radio off after the daylong watch, and the message did not get through [4]. The Titanic disaster did directly or indirectly touch many very wealthy and influential people of the time. They were shocked by the story, and so was the general public. Numerous books and films have kept the memory of that tragedy alive until today. Certainly, the disaster contributed to the approval of the regulations proposed six years earlier.

To improve the coordination of the uses made of radio spectrum, the IRU was transformed into the present International Telecommunication Union (ITU), without major changes in the basic philosophy and regulations earlier agreed to. The ITU is the UN Agency for Information and Communication Technologies (ICT), with a total membership of over 190 Member States, and some 700 private companies from around the world. It consists of three Sectors: Radiocommunication, Standardization, and Development. The Radiocommunication Sector (ITU-R) coordinates radio-communication services, and the international management of the radio-frequency spectrum and satellite orbits. It also develops common technical standards and recommendations, and maintains Radio Regulations and the Master International Frequency Register (MIFR). The Radio Regulations are a binding international treaty, setting out the allocation of frequency bands for different radio services. They also set technical parameters to be observed by radio stations, and procedures for the notification and international coordination of specific frequencies assigned to the stations by Administrations, as well as other procedures and operational provisions. Radio Regulations are set and modified by consensus of all the Member countries at radio conferences; more details are given below.

2.3. National Spectrum Management

National spectrum management and international treaties regulating spectrum exploitation were born at about the same time. Since the very beginning, they have been closely interrelated: modifications of one of them in turn induce a series of consequential changes in the other. However, while the international use of spectrum requires collective consensus of all Member States, every State is fully sovereign for regulating its national uses, as long as

it does not touch other country's interests. Consequently, if a station wants its use of radio frequency to be internationally recognized, it must be recorded in the ITU Master International Frequency Register. The notification process includes verification of whether or not the station's parameters agree with the radio regulations and plans in force. ITU only charges for the nominal cost of work. In 1963, the governments extended the concept of spectrum commons to include artificial satellites. Since then, the orbital parameters and frequencies of satellites have been recorded in the Master International Frequency Register.

In practice, the governments translate the Radio Regulations into their national regulations, and assign portions of the spectrum resources among their subjects. Most have introduced the obligatory national spectrum licensing associated with a spectrum-fee system, in spite of the fact that no country pays for the spectrum. Indeed, the fees can be seen as an extra tax imposed on the spectrum users to feed the governmental budget and development plans in sectors that may be far away from telecommunications. Details may differ from country to country. The license offers rights to exploit a specified band of frequencies under specified conditions and for a specified time, which can be – and most often is – extended over the following years. This makes the license quasi-permanent. In some countries, the license is transferable, which makes it not much different from an ownership certificate. The ways in which the licenses have been issued also differ from country to country, and may change with time. By issuing a license, a government can (and often does) control by whom, how, where, and when the spectrum is used, and for what purpose. This is often criticized: we will come back to that in a later section.

Traditionally, the license is awarded on the basis of seniority (the “first come – first served” rule), in comparative hearings, also called “beauty contests” (this could also be done by lottery). The first approach is the simplest to manage, automate, and control. The second approach is based on merit: a jury representing diverse entities considers all the proposals, compares their relative merits, and grants the license to the most-valued proposal. If the process is open to the public with an elected independent jury, the process is known as a “beauty contest”. Otherwise, it is often named the “command and control” approach. This is more complex and more time-consuming than the previous procedure, and the “merits” and “values” are often vaguely defined. However, this is the only way to take into account the social consequences of the licensing decision. Distributing the licenses via lottery has not found supporters. Another approach is privatization or auctioning, discussed in a following section.

2.3.1. The FCC Example

This section deals with the US Federal Communications Commission (FCC), for two reasons. First, the FCC is one of the oldest and most-experienced radio regulatory agencies in the world. Second, a number of countries have drawn heavily from its experience, as did international

spectrum management. World War I accelerated the development of radio technology, and the global center of the radio industry moved to the USA after the war. New services appeared: the service that developed most dynamically was broadcasting. It has proven its usefulness in commerce (advertising) and in politics. It has become a strong force in modern society, often abused to manipulate public opinion. A growing number of transmitters soon resulted in mutual interference, which lowered both the quality of transmissions and profits. In their rivalry for listeners, the operators increased the signal power radiated, which led to a power race, more interference, and more litigation. The era of spectrum plenty ended. A new era of spectrum scarcity began: it was just at that time that Herbert Hoover declared the lack of spectrum, as quoted in the introduction. All those interested agreed that the free market could not solve the problem, and governmental intervention was necessary. In 1926, a special governmental agency, the Federal Radio Commission (FRC), was created to regulate spectrum uses. The FRC was later transformed into the present Federal Communications Commission (FCC), which exists now. It deals with commercial radio, television, wire, satellite, and cable “as the public interest, convenience, or necessity” require.

There are five independent Commissioners of equal power who direct the FCC, which is a rather unique structure: in other agencies, there is typically only one director. Every candidate is proposed by the US President and confirmed by the Congress; the president also nominates the Chair. None of the Commissioners can have a financial interest in any Commission-related business, but each is required to be thoroughly familiar with the radio sector. Only three of them may be members of the same political party. They have to act in a fully transparent manner. Supposedly, the US legislature set all these precautions to assure that FCC decisions are impartial, fair, and free of political or commercial influences. In spite of this, some FCC decisions have been criticized as being biased. Critical voices were also heard when it was disclosed that the FCC Chair nominated in 2013 had earlier worked as a lobbyist for the cable and wireless industry. The FCC alone employs about 1900 persons, and spends some US\$350 million per year. These resources are needed to manage commercial applications of the spectrum. They do not cover the governmental spectrum uses that are managed by the National Telecommunication and Information Agency (NTIA). The FCC homepage also lists the Interdepartmental Radio Advisory Committee, which helps to coordinate all activities related to spectrum use in the country [5].

2.4. Spectrum Management Evolution

2.4.1. Global and Regional Spectrum Management

The two Berlin conferences marked the end of the era of unregulated spectrum commons, and the beginning of spectrum regulation. Garrett Hardin, a prominent American ecologist, showed many years later that any *unregulated*

commons is unsustainable by its very nature [6]. His famous phrase, the “tragedy of commons”, has often been misused in spectrum-related discussions. The spectrum has become the natural public goods (commons) belonging to the whole of humanity, represented by the sovereign governments: parties to the Convention. This was in accordance with the ideas of Henry George, an influential American economist, writer, and politician. George held that people could own and trade what they create, but things found in nature should belong to all. The States have agreed that they are the sole sovereign entities deciding (together) on how the spectrum is to be used. Each state shall have free access to the spectrum. The spectrum shall not be traded, but its uses shall be regulated.

World War I did freeze international cooperation and accelerated the development of radio technology at the same time. The first radio conference after the war was held in Washington, DC, in 1927, just after the FCC was created in the USA. Many famous scientists participated, including Edward V. Appleton, the future laureate of the 1947 Nobel Prize in Physics. The Washington Conference updated the international spectrum-management system. It reviewed the Radio Regulations, defined a number of new radio services, allocated a specific frequency band to each, and extended the regulated frequency range up to 60 MHz. Similarly, World War II again froze the collaboration, and accelerated the development of radio technology. Just after the war, the Allied countries imposed a new international deal, aimed at “lasting international peace, justice, collaboration, and mutual trust”. The United Nations organization was created, and the ITU became straightaway its specialized agency. The 1947 conference held in Atlantic City again extended the amount of regulated spectrum, and introduced new allocations.

Among others milestones, the non-telecommunication use of radio-frequency energy was recognized there. Specific radio bands were reserved for industrial, scientific, medical [ISM], and domestic uses. Since then, the power industry developed enormously. Collecting solar power in outer space and transporting it to the Earth’s surface using microwaves was proposed decades ago. Wireless powering reappeared in relation to the powering of drones, electric cars, and the Internet of Things. The present tiny ISM frequency bands may be insufficient for such new applications, and additional bands may be necessary. In addition, ISM bands have now successfully been used for new telecommunication systems, such as Wi-Fi and similar systems. New powering systems operating in these bands create a serious potential threat to them.

Technology development continued: the subsequent conferences adapted the regulations to the changing reality. The 1959 radio conference accepted the idea of “passive services”. Until then, a service had to transmit radio waves to be qualified as such: those services that only received signals had been outside the purview of the Radio Regulations. For instance, radio astronomy, remote sensing of the Earth, etc., were excluded. The regulations began to differentiate between the *physical use of spectrum*, when a frequency

band and part of space was “filled in” with RF energy, and the *administrative use of spectrum*, when it was reserved for signal reception, or for a future use. The first Conference for Space Communications was held in 1963, just six years after the Soviet Union launched the first artificial satellite around the Earth. This conference extended the ITU-regulated commons over outer space and geostationary satellite orbits. New space services were defined, new spectrum allocations were made, satellite positions were assigned, and Radio Regulations were updated. The Outer Space Treaty entered into force in 1967. It explicitly stated that outer space was “not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means”, like the earlier spectrum. In 1992, spectrum allocations for Global Mobile Personal Communications by Satellite (GMPCS) were made. This opened new possibilities, earlier unimagined and not yet explored in full. This also significantly removed the pressure on the terrestrial spectrum, but increased further disproportions existing among the ITU Member States, at the same time. As previously, the electromagnetic spectrum and satellite orbits were collectively managed by all the ITU Member States on behalf of and for the benefit of all the people of the world. Further information can be found in [7] and on the ITU Internet home page.

The radio conferences are practical means for managing the spectrum. They may be worldwide or regional, general or specialized. The general conferences are authorized to deal with virtually all aspects of spectrum use. The specialized conferences deal with particular services and/or particular portions of the spectrum. The regional conferences are held to solve specific spectrum use problems within particular geographic regions. Some Radiocommunication Conferences are convened to negotiate and agree upon international frequency plans for specific applications, geographical regions, and frequency bands, which are subject to a priori planning. They are organized regularly and when needed. The participants in the conferences are official governmental delegations of the ITU Member Countries, each having one voice. The conferences are also open to inter-governmental organizations and the specialized agencies of the United Nations. Nongovernmental entities authorized by their countries are admitted, too (since 1993).

2.4.2. Worldwide and Regional Radio Conferences

Radio Conferences, worldwide and regional, serve as the foundation of global spectrum management in the framework of the ITU. As they all are similar, we here present only one: the Regional Radio Conference (RRC) Geneva 2004/2006, which opened a new era in global management of spectrum for digital broadcasting. It was called to coordinate the deployment of some 70500 transmitting stations in 118 countries. Two conditions were imposed: (1) no more than 448 MHz of spectrum should be used, and (2) the plan should assure the conflict-free operation of the stations, without causing or suffering unacceptable interference as much as practical. The conference was split

into two sessions, the first held in 2004 and the second in 2006. The preparations took six years. At the first session, the participating countries agreed upon the principles, technical characteristics, and working methods. Each country defined then its requirements during the intersession period. The requirements were submitted to the second session for iterative adjustments, if necessary. Over 1000 delegates worked hard for five weeks at formal sessions, working groups, and private meetings. The success was possible thanks to the good will and high competence of the participants, as well as the exemplary cooperation between the ITU Secretariat, the European Broadcasting Union (EBU), and the European Organization for Nuclear Research (CERN). The iterative planning was largely automated, based on the software developed by the European Broadcasting Union. Two computer networks were used. One was the ITU’s distributed system of some 100 personal computers. The other was the CERN Grid infrastructure, with a few hundred dedicated computers. The outcome was a new treaty replacing the earlier agreements concerning analogue broadcasting plans that existed since 1961 for Europe, and since 1989 for Africa [8]. Figure 1 is a photo of the plan for digital television in the printed version (over 2000 A4 pages), and in the electronically readable version on CD. With this plan, a significant part of the electromagnetic spectrum was made open for other uses, the well-known “Digital Dividend” [9]. Not all countries participated in the conference. Some questioned the spectrum-planning idea in general: see the discussion below for the reasons.



Fig. 1. A photo of the Plan TV GE 06, CD and printed versions (courtesy of the National Institute of Telecommunications, Poland).¹

2.4.3. Radio Regulations Board

Consecutive ITU radio conferences are usually separated by a period of a few years. If an urgent international problem arises in the time between them, it is the Radio Regulations Board (RRB) that decides what to do until the nearest conference. It is the only ITU body authorized to decide which party is right and which party is wrong, in an objective and fully transparent procedure. During the conferences,

¹ See color pictures online at www.nit.eu/publications/journal-jtit

the board members participate in their advisory capacity. This section describes how the Radio Regulations Board has evolved.

Each Radio Conference makes Radio Regulations more detailed, and more difficult to interpret and to implement. From a few pages in 1906, their volume increased to more than 1000 pages, not counting numerous frequency plans and agreements separately published. Probably the largest changes introduced by a single conference took place at the 1947 Atlantic City conference. To assist the Members in practical implementation of these changes, the conference created the International Frequency Registration Board (IFRB), which years later became the present Radio Regulations Board (RRB). It was modeled after the FCC, discussed in a previous section. The board members are elected by all the Member States at the Plenipotentiary Conference. They have to act independently, and serve as “custodians of an international public trust”. They must be “thoroughly qualified by technical training in the field of radio and possessing practical experience in the assignment and utilization of frequencies”. Interestingly, such qualifications are only required in regard to the Board members: the other elected ITU officials can be lawyers, managers, etc., with no technical training at all. The board’s decisions have been ultimate: only the Member States can change them. In spite of several revisions of the ITU’s basic documents, the substance of these provisions has not been changed until now. Traditionally, the board works in full transparency, with the documentation of each case open to all interested ITU Members. However, recently a party requested that its case be considered behind closed doors, referring to its trade secrets, but the board rejected that request.

The board was envisioned “as something of a cross between the Federal Communication Commission and the International Court of Justice” to solve urgent intergovernmental conflicts that appear during the periods between the conferences [10]. In reality, it never achieved any status comparable to the Court of Justice. The major reason was the failure of Member States to allow the board to perform all of its functions as an intergovernmental arbitrator on the frequency uses: it seemingly was not in the best interest of the largest corporations. The 1965 Montreux Plenipotentiary Conference might even have abolished the board completely, had it not been strongly supported by the developing countries, as Codding noted. These countries considered the board as a neutral body, capable of assisting in protecting their interests in conflicts with foreign companies. The board has survived, but its size and importance was reduced, and the pressure of some countries to get rid of it continued. In 1994, the full-time board was replaced by a part-time board and its Secretariat was merged with the CCIR Secretariat into one Radiocommunication Bureau.

2.4.4. CCIR Supporting Studies

The success of the Geneva 2004/2006 conference was possible thanks to earlier careful studies in the European

Broadcasting Union and elsewhere. Indeed, it was realized early that negotiations at the Radio Conferences required a lot of background scientific and engineering knowledge. With this in mind, the 1927 Washington conference created a special organ within the ITU, the International Radio Consultative Committee (CCIR) and its Study Groups. The aim was to facilitate the conferences by separating discussions on the well-defined engineering issues from political and economic negotiations. The Member Countries defined questions to be studied (voluntarily), and the results of these studies were submitted to the conference. They were also independently published in the form of the famous CCIR Green Books, Recommendations, Reports, and Handbooks. The CCIR studies significantly contributed to the diffusion of the progress in radio science and engineering.

The spectrum-scarcity problem had to wait until the CCIR General Assembly New Delhi 1970 created the Study Group on Spectrum Management and Monitoring. The assembly elected the first author (R. S.) as its Vice Chair; he served in that function until he became a CCIR official in 1985. CCIR contributed to the development of spectrum engineering, frequency planning, electromagnetic compatibility, and related disciplines. In 1994, CCIR became a part of the ITU-R Sector and ceased to exist as a separate organ, but the Study Groups and working methods have continued until now. Their publications have enjoyed great popularity, as have computer programs [11], [12]. More recently, in parallel with the Study Groups, the ITU has organized a series of open seminars and conferences devoted to specific problems of current interest, e.g., the Kaleidoscope Events. That collaboration proved to be extremely useful, in spite of some limitations discussed below.

2.4.5. URSI Contributions

The CCIR/ITU Study Groups have drawn heavily from the knowledge voluntarily brought by other organizations and individuals. Richard Kirby, the then CCIR Director, noted [13]:

Even in the earliest days of radio, some of the best scientific minds were challenged by the problem of sharing the radio frequency spectrum among different users.

The International Union of Radio Science (URSI) was one of the first such organizations. The first URSI General Assembly was held in Brussels in July 1922 [14]. URSI was born under the patronage of the Belgian King Leopold II. As the possessor of the Belgian Congo, he was materially interested in having inexpensive communication means with (and within) his colony. At that time, with no satellites, only terrestrial radio could offer such communications, and URSI greatly contributed to progressing radio science and in removing obstacles in the way to global radio services. The second General Assembly of URSI and the ITU radio conference in Washington in 1927 were jointly organized, and URSI took an active part in the creation of the CCIR. Many URSI scientists were involved, contribut-

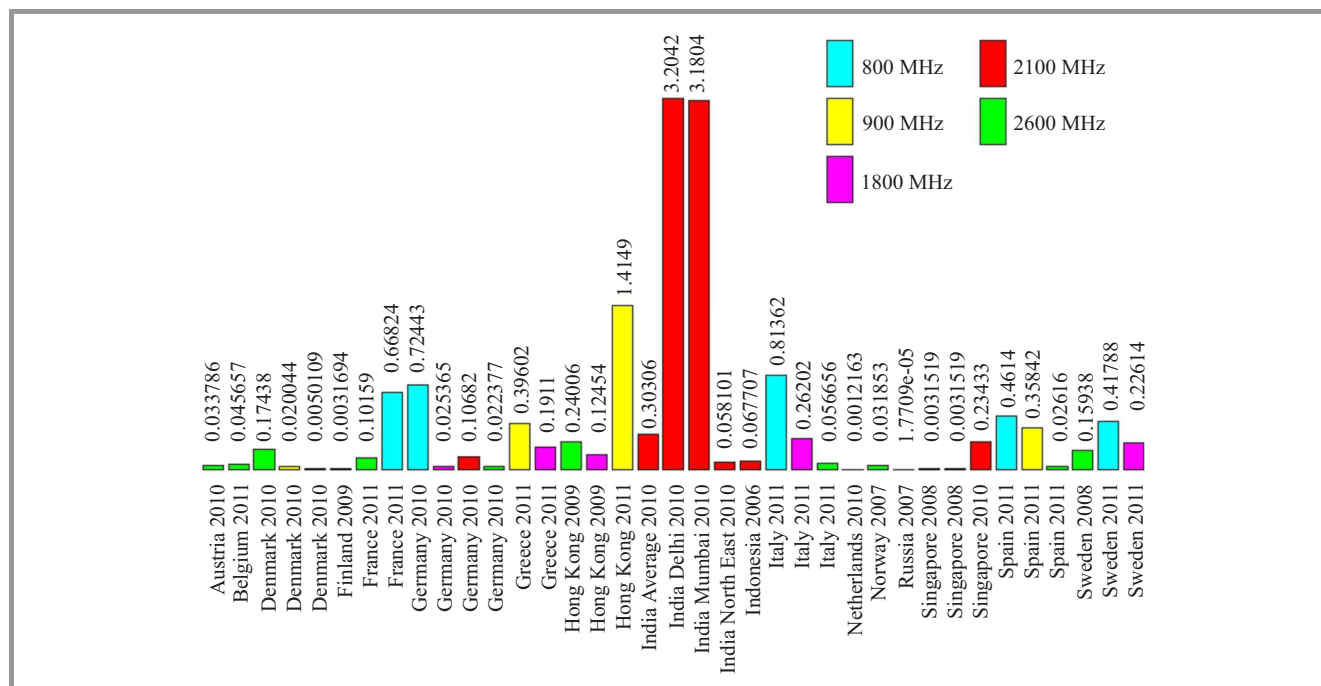


Fig. 2. Auction prices given in Euro/MHz/Population, from [22]. (Note: This is for paired spectrum. The Euro/MHz/Population values were based on historical exchange rates when the different auctions were worked out. When calculating Euro/MHz/Population, the sum of the uplink and downlink bandwidth was taken into account. In auctions where paired/unpaired spectrum was sold in bundles, the amount of paired spectrum was used.)

ing to the development of radio science and its applications, and to strengthening the role of science in intergovernmental agreements. Since then, a number of URSI reports have been approved by CCIR and used by ITU Members without modifications.

The collaboration was most effective when Balthazar Van der Pol, URSI Vice President (1934–1950) and Honorary President (1952–1959), also served as the CCIR Director (1949–1956). The URSI General Assembly in Tel Aviv in 1987, after the CCIR presentation [15], created the Working Group on Spectrum Management in Commission E, with the first author (R. S.) as its first Chair. However, he soon had to withdraw because it “could create potential conflicts” between CCIR and URSI according to ITU legal advisors, as URSI is a non-governmental entity, while CCIR/ITU was an intergovernmental organization. With time, some URSI scientists also lost their initial enthusiasm (except for radio astronomers and remote-sensing specialists), and the group was temporarily inactive. Some wonder if it could be related to changes in the funding mechanism of research projects and in an increased role of big companies, which are more interested in competition and exclusive spectrum use rather than in sharing the spectrum with others. The working group on spectrum was reestablished at the URSI General Assembly in 2005.

2.4.6. Other Contributions

URSI was not alone: numerous scientific and R&D laboratories (governmental and private) from around the world

have supported the CCIR/ITU-R Study Groups. Their contributions to spectrum management cannot be overvalued. They are too many to be all listed here. The Institute of Radio Engineers (IRE), established in 1912, is one of the oldest. In 1963, it transformed into the Institute of Electrical and Electronic Engineers (IEEE), the world’s largest professional association for the advancement of technology, according to their declaration. Among scientists, it is known not only through its numerous publications and conferences, but also through its Fellow program of professional recognition. The first IEEE Fellow was Jonathan Zenneck, a German physicist famous for his work on radiowave propagation over the Earth’s surface in the 1900s. The IRE Professional Group on Communications Systems (PGCS) was organized in 1952. Five years later, the group on Radio Frequency Interference (PGRFI) was created. Later, they became the present IEEE Communication Society (ComSoc) and the IEEE Electromagnetic Compatibility Society (EMC-S), respectively. These are some of the first organizations that called attention to the spectrum-scarcity problems, and have played a major role in shaping spectrum management. Their reports are the definitive works representing the collective wisdom of some of the most distinguished leaders in science and engineering [16]–[18]. Recent IEEE activities in that area are coordinated by the IEEE Dynamic Spectrum Access Networks (DySPAN) Committee, among others. The spectrum-utilization issues were also debated at IEEE sponsored symposia around the globe, e.g., the International Wroclaw Symposia and EMC Zurich Symposia, organized since 1972, currently, the EMC Europe Symposia.

Lots of improvements in spectrum management came as a result of DARPA, MITRE, and NATO projects [19], [20]. In Europe, studies of the European Broadcasting Union (EBU) have been highly valued and often served as the basis for Radio Conferences: this was the case of the Regional Radio Conference Geneva 2004/2006, mentioned earlier. Many saw the UK's Radiocommunication Agency (now OFCOM), with its cooperating R&D university teams, as one of the world leaders in spectrum management and engineering [21]. More recently, the European Commission (EC), with the European Conference of Postal and Telecommunications Administrations (CEPT) and its European Communications Office (ECO), have been successfully working towards improved spectrum use. They have created various groups and committees (e.g., the Radio Spectrum Policy Group, RSPG, and the Radio Spectrum Committee, RSC), and supported specialized symposia and conferences. These studies are in close association with the ITU studies, and most of their results are freely available via the Internet.

2.4.7. National Spectrum Management

Since the nineties, in addition to traditional administrative spectrum licensing, auctions have become a popular national methodology also believed to create incentives for effective utilization of spectrum, as well as revenue for governments. Figure 2 shows the spectrum price (in Euros per MHz per capita) observed at auctions in various countries in the years 2006 to 2011. The amount paid in the auctions was covered in consumer bills, as no company would operate to lose money. It was the highest in India, some three thousand times higher than in the Netherlands: if related to the average income per capita, the difference would be even greater.

2.5. Regulated RF Spectrum

This section is a short summary of the major practical results of common studies and collaborative negotiations within the ITU framework. Historically, the ITU has divided the world into three regions, as shown in Fig. 3, for the purposes of managing the global radio spectrum and in order to avoid harmful interference between systems. Each region has specific allocation plans, by considering regionally harmonized bands, which take into account regional standards and peculiar aspects of the respective markets.

Region 1 comprises Europe, Africa, the Middle East, the former Soviet Union, and Mongolia. Region 2 covers the Americas, Greenland, and some Pacific Islands. Region 3 contains most of non-former-Soviet-Union, Asia, and most of Oceania. The ITU Members have been dealing with the regulated frequency bands as often as they found it useful, according to the above three regions.

Radio Conferences change Radio Regulations, often extending the spectrum limits as shown in Fig. 4. The 2015

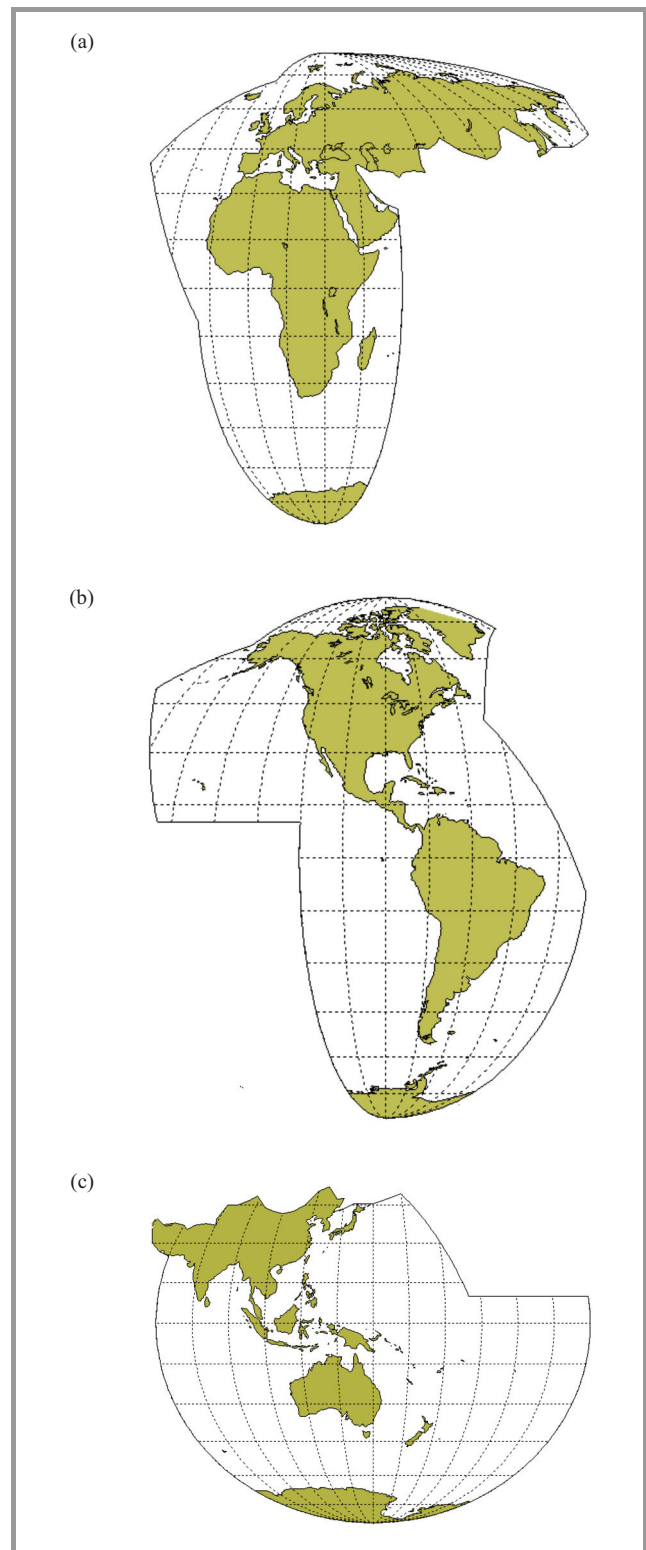


Fig. 3. A map of ITU: (a) Region 1, (b) Region 2, (c) Region 3.

World Radio Conference will discuss possible further extensions.

The total volume of regulated spectrum has been approximately doubling every 30 months or so, as Cooper, quoted earlier, calculated. He added [1]:

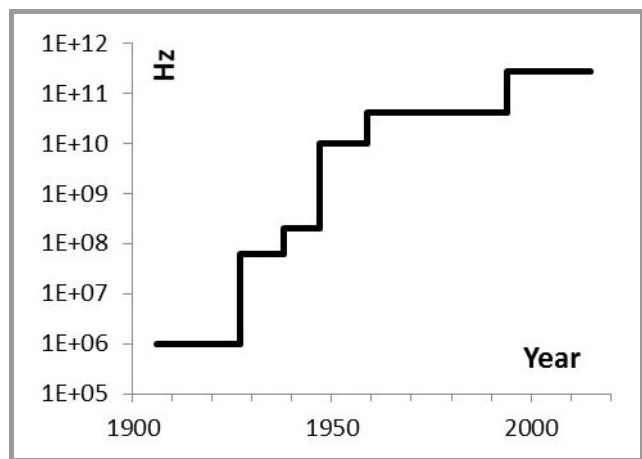


Fig. 4. The maximum frequency allocated in the Radio Regulations by Radio Conferences in the years from 1906 to 2015. (Note: The complete lists of the ITU conferences can be found in [23]).

Since 1901, ... spectral efficiency in telephone communications has improved by a factor of about one trillion. Since 1948, it has improved a million times over. And when introduced in 1983, cellular communications immediately offered a ten-fold increase in spectrum capacity – by transmitting in 30 MHz of spectrum what would have taken 300 MHz to transmit with the previous generation of technology. Today's cellular systems are better than 100 times more efficient than the mobile telephones of the 1980s.

It should be noted here that radiowave propagation effects make some frequency bands unsuitable for specific applications. The total regulated spectrum is divided into small pieces, each allocated to a specific service or use, such as terrestrial, or space services; fixed, or mobile services; industrial, medical, domestic, and scientific applications, generally the same in all Regions. Some details may, however, differ from country to country and from region to region, which obstructs the free movement of devices (e.g., mobile phones) and international exchange. For example, Fig. 5 shows the current national allocations for Portugal.

3. Spectrum-Management Trends

This part focuses on foreseeable perspectives of spectrum management. Radio services [24] have increased in popularity. This has been a steady trend since the radio was first invented. This has also been true of the demand for access to radio frequencies. One traditional way of meeting the demand is to use increasingly higher and not-yet-explored radio frequencies, and to develop more-efficient methods for spectrum utilization. The management of the spectrum of these must also be developed,

as described in previous sections. Spectrum management in the future will be a mixture of the current practice of today, with an emphasis on improving efficient spectrum utilization. There are several multidisciplinary factors that play important roles. These comprise the physics of electromagnetic waves and their propagation, technology for spectrum utilization and handling interference, market mechanisms for access to spectrum, and regulatory regimes.

Future spectrum management must take all of these into consideration through a good understanding of physics, technology, and economics in developing the rules for the actors involved. Furthermore, spectrum efficiency must be taken into account, addressing the desired benefit from our collective utilization of the radio spectrum. There is no single metric that can be used in this respect [25]. Technical, economic, and societal judgments therefore apply. In the following, the article is organized in subsections on spectrum management through administrative, trade, and free access to the resources.

3.1. Administrative Assignment

In a way, there must be some administrative rules irrespective of the spectrum-management method used. By assigning exclusive rights to use spectrum at a frequency and in an area, the national spectrum authority gives a user great freedom within the set of constraints that come with the right. No one else can deploy the same spectrum in this area. The rights are often given for many years, to allow sustainable business to be established or continued. Although this describes current spectrum management in many situations, it will most likely continue this way in the foreseeable future for a large part of the spectrum.

Within some services, there is an increasing concern about spectrum scarcity. In particular, mobile data is growing so fast that many operators will be looking for new spectrum resources. Of course, the scarcity also leads to innovation, such that the same amount of spectrum can be used for more traffic and more terminals. Furthermore, many applicants often wish to establish business, and this itself becomes an incentive to make good use of often highly costly access rights. The authorities must look for improved methods of assigning frequency rights. One example is to use graphtheoretic methods in assigning frequency for radio links in popular bands [26], contrasting the usually simplistic methods used today for making assignments. The study indeed indicated a potential for getting noticeably more out of the spectrum, and suggested a closer interdisciplinary collaboration between experts of radiowave propagation and frequency assignments.

Although often all spectrum of interest is already allocated for some service types and even assigned to users, measurements show that only a limited part is utilized at given location and time (see, for example, [27], indicating an overall utilization of 11.2% in Hull, UK, of bands ranging from 180 MHz to 2700 MHz). These types of observa-

Game-theoretical approaches have been suggested to effectively take advantage of the shared-spectrum regimes [36]. Intelligence in next-generation networks, with the concept of equilibrium, will enable fair optimum spectrum utilization. These ideas are still in the early phases, and more research is needed.

An idea of a fully free spectrum utilization for any type of network was suggested for the future mobile and wireless system [37]. The marketplace took over and services were delivered by virtual operators. The value chain consisted of the various elements, such as the spectrum, radio access network, value-added services, and so on, with the different actors and not with a single mobile-network operator.

3.3. Free Access

Wireless local area networks (WLANs) in the form of Wi-Fi have become a great success. A significant part of the broadband traffic from a large number of terminals will go over Wi-Fi for at least part of the route. This happens in spite of the fact that radio systems have no guarantees for satisfactory access to the spectrum at 2.4 GHz or 5 GHz. It is therefore not strange that the so-called “commons” spectrum is thought of as a future solution, and more should be allocated for commons. In commons, specific rules apply, and no management is needed. A rule can simply be just to limit the radiated power to a maximum value. However, as such, it is not really free use, as someone has to set the rules and control the regime [38].

A radical suggestion has been proposed to allow anyone to transit anywhere and anytime, as long as the transmission does not cause interference that cannot be dealt with by the other user [39]. The proposal is to create something called “supercommons”, where technology manages both wanted and unwanted signals, without other management.

4. Challenges and Dilemmas

The ITU’s spectrum management, based on intergovernmental negotiations at radio conferences, has matured since the first meetings in Berlin. Previous sections outlined the way it has evolved and may further evolve. During the century, this has assured the phenomenal progress in all the fields that depend on applications of information and communication technologies, and specifically wireless. The history of radio has proven the ITU radio conferences to be practical: no other field of human activity has noted a comparable rate of progress. The ITU has made it possible to seamlessly communicate around the globe, and to assure the benefits of scale. The mechanism is not ideal, but it has been the only one possible: the only mechanism all the ITU Member Countries could accept. Nevertheless, this mechanism has been criticized by the private sector and by civil society activists, by developed countries and those developing: they all doubt if that mechanism fairly serves all members of society. To complete this review, this

part offers a closer look at some of these critical comments, raised by various parties at various occasions.

For instance, a fundamental issue is the difference in the national and international spectrum treatments. Internationally, spectrum is offered for use for free, with no quotas or licenses, and with only basic operational restrictions imposed on its use globally and regionally. However, nationally it offered as a sellable, rentable, or licensable commodity (except for tiny ISM bands that are license-exempted). The idea of spectrum sharing contradicts the concept of exclusive spectrum use. License exempting negates the licensing. Free competition rules out regulations. Dynamic spectrum management goes against spectrum plans, which in turn excludes ad-hoc spectrum allocations. The idea of transparency negates the trade-secret principle.

All of these ideas seem to follow the Cartesian approach, in which a complex problem is broken down into smaller and simpler bits, each for a specific partial problem separately analyzed. Spectrum scarcity is a complex issue. It cannot be fully understood in terms of its individual component parts, disregarding complex interactions among them and with the rest of the surrounding world. Spectrum scarcity involves a combination of engineering, economic, political, and social issues that cannot be separately solved [40]. A holistic approach is needed, treating the problem as a whole within its full context. There is a striking similarity between the radio-frequency spectrum and environmental problems. The concept of a *supernetwork* may be helpful here. Anna Nagurney [41] defined it as a network that is above and beyond classic networks (informational, financial, social, etc.), including complex interactions among them, both visible and hidden. She classified supernetworks as “*system-optimized*” or “*user-optimized*”. Equally well, they could be termed “*investor-profit-optimized*” and “*customer-benefit-optimized*”.

4.1. Representation

Some private sector representatives note that problems considered at the ITU radio conferences are in reality those of competing companies. Direct negotiations between those interested, without involvement of third parties, would be cheaper, easier, and quicker, and the results would be better for all, they say: governmental interventions distort the competition. On the other hand, some civil society activists accuse governments of representing only the interests of the largest companies. They say such companies have quite different interests from small companies and individuals, which are the weaker parts of society in each country. Similarly, some delegates from developing countries believe their negotiation positions are weaker, and their interests are not taken into account as they should be. At intergovernmental forums, large enterprises lobby national delegations to adopt their views as the country’s position. Small companies and citizens usually lack resources to do so. Often, they are unable to even properly formulate, justify, and convey their views, or to predict all the consequences of the proposals just negotiated. This section sums these up.

4.1.1. Developing Regions

The ITU Member States differ in population, wealth, knowledge, and in many other aspects. Similar disparities among regions and social groups exist in each country. They have different potentials, needs, and lobbying powers [42]. Radio-spectrum negotiations imply a lot of difficult work to be done before and during the negotiations. Documents for consideration may include hundreds and thousands of statements, proposals, and counter-proposals, each being a complex mixture of technical and legal issues. Some of them may require an immediate reaction during the meeting, as even a small oversight may have consequences difficult to correct later. Multiple committees and ad-hoc groups at the conference, often working in parallel, create serious problems for small delegations unable to participate in more than one group at a time. The following excerpt from the Bogota Declaration describes problems seen by some delegates [43]:

The Treaty... cannot be considered as a final answer to the problem of the exploration and use of outer space, even less when the international community is questioning all the terms of international law which were elaborated when the developing countries could not count on adequate scientific advice and were thus not able to observe and evaluate the omissions, contradictions and consequences of the proposals which were prepared with great ability by the industrialized powers for their own benefit.

The declaration, published by a group of a few equatorial states that felt they were being misled, voiced the opinion of a larger group of countries that were only partially familiar with the newest achievements of science and technology, and felt to be outside of the closed “club of rich”. The consensus idea is great under the assumption of a common interest, common understanding, and good will of all the negotiators. Study Groups, mentioned earlier, aim at reaching that, but unfortunately, not all Members can participate in their studies, for various reasons. With this in mind, conference preparatory meetings were long ago proposed [44], [45], where the future delegates could be familiarized well in advance with problems to be negotiated. That makes the preparations for Radio Conferences almost a continuing occupation, which not all companies or even countries can easily bear. Proposals to facilitate this by wider automation of the ITU [46], which would close it to medium access control (MAC) known from computer technology, are not very popular; automates are still too simplistic now. They cannot completely substitute for humans at the negotiations; moreover, they could make some informal deals and secret agreements difficult, if not impossible.

Wireless technologies eliminate the need for expensive cable networks, and their wide use would reduce the disparity among countries and improve connection with social

groups in poor, underdeveloped, or remote regions. Unfortunately, the scarcity of free spectrum is a serious obstacle. The world is now in the midst of a major debate about the public-policy goals. The issue has been discussed at the United Nations, the World Summit on Information Society, the UNESCO-ITU Broadband Commission for Digital Development, and at other forums. They have all set up universal broadband connectivity as an essential element of sustainable development. A series of steps have already been made in order to make these more popular. However, in spite of the progress made, the *digital divide* has not disappeared. Figure 6 shows that it increased from about some 20 percentage points in 2007 up to 70 percentage points in 2014, and that the trend continues.

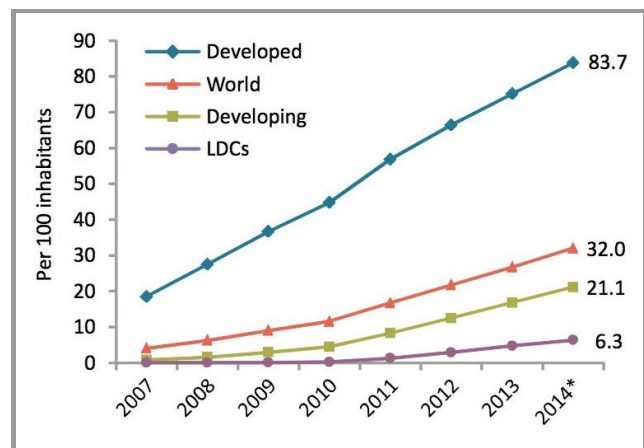


Fig. 6. The active mobile broadband subscriptions by level of development, 2007 to 2014 (* denotes estimate [47]).

Generally, the growth of telecommunication services can be described by logistic functions, which indicate that in some cases the divide cannot be reduced, or could be chaotic [48], [49]. The diverging lines of Figure 6 send a strong message: the goal to eliminate the digital divide is physically unrealizable, or our approach to it is inefficient, and needs a substantial review.

4.1.2. Civil Society

Ideally, a government operates diligently, and represents the interests of all citizens in a just way. Unfortunately, this is not always the case: not every government is seen by all the citizens as trustworthy. To force honesty, civil-society activists demand more transparency. They demand the right to see the documents and negotiations to be sure that there is no difference between what the government publicly declares and what it does behind closed doors, hoping this will limit corruption. In some countries, this has appeared to be impossible, and they do not consent to allowing civil society observers at ITU negotiations. However, recently, under public pressure, the ITU has decided to provide free online access to ITU-R recommendations, and some other documents, to the general public. Providing such access to all input and output documents of all ITU conferences

(postulated since long ago, among others by the first author when he served at the ITU headquarters) was questioned. The argument is that it would cause potential harm to private or public interests, which could outweigh the benefits of accessibility.

Civil society activists also want to bring to the process a variety of views and expertise that relate to ITU activities, such as expansion, development, and adoption of information and communication technologies, sustainable development, access to knowledge, consumer rights, social justice, and human rights. More and more often, one hears from critics that profit-oriented needs dominate those non-profit needs such as health care, education, science, etc., not mentioning the communication costs for ordinary citizens.

4.1.3. Science Interests

Observational radio astronomy explores extremely weak electromagnetic radiations coming from the universe. Space research, remote Earth exploration, and some other sciences do similar exploration. Manmade radiations, no matter whether intentional or spurious, can falsify these observations, or make them useless. Unfortunately, the intensity of manmade radiations increases from year to year. The 1992 UNESCO conference [50] appealed to all inter-governmental organizations to amplify efforts toward protecting the future of such research. One of the ways to do so is to improve the transparency of governmental decisions at all levels, including voting at radio conferences. We mentioned earlier the votes of two delegations at the first Berlin conference, which delayed the solution of communications at high seas until the Titanic disaster. This was the only case the authors found noted in conference documents since the time of Marconi. If there were other such cases, they were outside of the conferences. Unfortunately, bribery has been in the limelight from time to time, and according to Brian Robinson, Chair of the Scientific Committee on Frequency Allocations for Radio Astronomy and Space Science, known by its short designation as IUCAF, the following note was included in his report [51]:

IUCAF members had to evolve from being starry-eyed astronomers as they encountered a world of politics, lobbying, entertainment, threats, espionage, and bribery. On one occasion, an offer (in Geneva) of two million dollars in cash “to shut up” proved no match for dedication to the joys and excitement of twentieth century astrophysics.

The note mirrors relations existing within some countries, rather than characterizing the ITU radio conferences.

4.2. Spectrum Planning

Plans introduce predictability valued by many: the participants in the TV planning conference in Geneva 2004/2006 considered their plan a great success. Planning is also the

only way to reserve a portion of the resource when it cannot be shared after a faster competitor takes it. A position in the geostationary satellite orbit is a good example here, as the total number of such positions is physically limited. However, spectrum planning has been criticized, and this section explains why.

A frequency plan is understood as a table, or generally, a function that assigns appropriate static characteristics to each of the radio stations at hand. Examples are the operating frequency; power radiated; antenna location, height, and radiation pattern; polarization; service area; etc. In frequency plans, specific frequency bands are reserved a priori for particular applications, well in advance of their real use. Individual regions may have various allotment plans for specific services (e.g., broadcasting), within their respective areas.

The plans make a one-time distribution of the spectrum resource on the basis of the expected or declared needs of all interested parties. Critics of the planning approach indicate that it is inflexible and freezes technological progress. Indeed, the progress is very fast, and implementation of the plan may last several years. Technology known at the time of creation of the plan may be obsolete at the time of its implementation. Another difficulty is the impossibility of predicting future requirements with a needed degree of accuracy, and plans based on unrealistic data have no value. Next, radio spectrum is available at no cost at international planning conferences, and there is no mechanism to limit the requirements, except for a general appeal for minimizing its use. There are no accepted or objective criteria for evaluating each country’s stated needs, and there are no quotas on the amount of spectrum assigned to each country. In fact, the individual country itself may have no idea of its needs over the time period for which the plan is to be constructed. It is thus not surprising that each country has an incentive to overstate its requirements, rather than underestimate. Under these circumstances, it is easy to make a case that the plans are not only difficult to construct, but when constructed, will lead to a waste of spectrum and orbit, as noted by Glen O. Robinson of the Virginia School of Law, a former FCC Commissioner [18].

4.2.1. Emergency Communications

The 1912 London Conference resolved the problem of emergency communication at high seas, but left open other problems for more than eighty years. In 1995, Hans Zimmermann of the UN Office for the Coordination of Humanitarian Affairs (OCHA) described the issue as follows [52]:

If anywhere on the ocean a vessel with a crew of one is in distress, all related communications have absolute priority and are free of charge... The necessity for absolute priority of distress signals has been recognized worldwide since the 14 of April 1912, when the “Titanic” hit an iceberg. However when, after earthquake, some 10000 persons are trapped un-

der the debris of buildings and houses, any customs official can prevent the arriving rescue teams from outside the affected country from entering this country with walkie-talkies. And another official might easily prevent the teams from using their communications equipment, unless they first obtain a license from a national telecommunication authority whose building may just have collapsed in the earthquake. Also, if a team is, by chance, nevertheless able to use its satellite terminal, they are three months later presented with telephone bills for tens of thousands of dollars. Such is the sad experience of those who provide international humanitarian assistance in the age of information super highways.

The problem was known for long and its solution was known too. What was missing has been the willingness to make practical steps, or there were insurmountable differences in the hierarchies of values, or in conflicting interests of large corporations. Many tragic disasters had to happen until, under the pressure of the general public, the governments agreed to remove interstate obstacles to quick deployment of communication means during emergencies. The 1986 Chernobyl Nuclear Power Plant disaster was an example. A long time passed until the Convention on the Provision of Telecommunication Resources for Disaster Mitigation and Relief Operations was signed in Tampere, in 1998 [53]. Although the convention has removed major legal obstacles, physical and organizational barriers have remained. Emergency communications are still far away from what are needed and what are technically possible, as indicated in the 2000 OCHA evaluation report [54]. To discharge the OCHA duties, the report proposed a global emergency communication infrastructure accessible to all, from any place at any time. The proposed infrastructure would be based on a constellation of low-orbiting satellites, continuously accessible, like the GPS. In spite of the fifteen years that have passed since its publication, no public discussion about its possible implementation even started.

4.3. Monopoly

Monopoly means a lack of economic competition to produce the good or service, a lack of viable substitute goods, and a high profit. In most countries, monopoly is against the law, except for the state monopoly. However, in many countries, a *legal monopoly* is approved by the state if it is justified by the need to provide an incentive to invest in a risky venture, or for other reasons, e.g., to enrich an interest group. Intellectual property rights (IPR), such as copyrights, trademarks, patents, industrial design rights, and trade secrets, are examples of such government-granted monopolies. This section sums up some comments on the topic.

4.3.1. AT&T Example

While the breaking of Marconi's monopoly took a decade or so, AT&T's monopoly (and that of its subsidiaries, the Bell System) operated in the USA for more than a century: from 1875 until 1984. There were six thousand independent (wired) telephone companies in the US serving three million subscribers. However, subscribers to different companies could not call each other because the competing companies refused connections. The AT&T monopoly solved the problem. AT&T was granted the status of a "regulated natural monopoly", obliged to provide *universal, end-to-end integrated, efficient, and inexpensive telecommunication services*. The doctrine of natural monopoly says that regulation is the most appropriate substitute for the competitive marketplace *provided it is independent, intelligent, considerate, thorough, and just*. Due to economies of scale, grouping of like activities in a single company in many cases could assure better and more efficient service to the public than a number of separate mutually competing companies could offer.

AT&T used its unique position and wealth to create the Bell Laboratories in 1925, which became one of the best and largest telecommunication research laboratories in the world. They developed radio astronomy, the transistor, the laser, the charge-coupled device (CCD), the *UNIX* operating system, the *C*, *S*, and *C++* programming languages, information theory, and many other things. Seven Nobel Prizes were awarded for work completed at Bell Laboratories. Being a regulated monopoly, Bell Labs were largely insulated from market pressures. That allowed them to develop a culture that venerated quality and excellence within a noncompetitive framework of innovation and practicability. In 1984, AT&T ended operation as a monopolist, and most of the former Bell Labs have been scaled down, or shut down entirely. The divestiture was not welcomed by everybody, as one can read in the history of AT&T [55]:

...the global telecommunications industry entered an era of unprecedented chaos and instability – marked by oversupply, fraud, a complicated regulatory environment and nonstop pricing pressures. Combined, these forces led to an industry meltdown in which numerous bankruptcies, defaults and business failures occurred; investors lost billions and countless workers in the communications sector lost their jobs.

Other critics pointed out fragmentation and repetition of efforts, and a lot of energy and resources lost in mutual fights. Another comment underlined that after the divestiture, no company could create and maintain a research laboratory of comparable scale and quality. The reason was high costs and risk of research confronted with smaller income (due to a divided market) and an uncertain future (due to competition). Some one hundred years after breaking Marconi's monopoly, the OECD stated [56]:

Limited spectrum and increasing demand for data services mean that mobile networks will strive to offload traffic to fixed networks. . . The challenge for regulator is that, regardless of the technology used, many parts of the OECD look likely to face monopolies or duopolies for fixed networks. Wireless can provide competition, but spectrum availability will always limit that are not a constraint for fibre.

4.3.2. Intellectual Property Rights

Intellectual property rights (IPR) have two sides. One side is the interest of the owner of the rights. On the other side are the interests of the rest. This helps in protecting a monopoly from competition, with society often paying for it. Consider smartphones, for example. The last few years noted over 140 patent disputes on these alone, with the litigation costs running up to US\$3 million per suit. Just two companies, Apple and Samsung, have disputed over US\$2 billion in patent-related damage compensations [57]–[59]. Armstrong and his colleagues estimated patent royalties on a hypothetical US\$400 smartphone to be in excess of US\$120, which almost equals the cost of the device’s components. The costs of the disputes may reduce the profitability and incentives to invest and compete. Most patent disputes are sterile, and not in the best interest of society. They absorb time and money that could instead be better used improving the products or lowering their price. Intellectual property rights play an important societal role that largely exceeds the commercial interests of a single company. With the present practices, “only lawyers win in patent wars”, as Popelka briefly put it [60].

4.3.3. Spectrum Privatization

Guaranteed exclusivity in the use of a band of spectrum is a form of monopoly. It can be granted through privatization or licensing. The former offers the owner maximum freedom in the use of spectrum. From the access viewpoint, the licensed exclusivity does not differ much from spectrum ownership. The influence of large corporations has been growing, and so has been the pressure to privatize the spectrum and free it from any regulations as much as possible. The ultimate goal is to replace the spectrum commons by private spectrum [61], and licensing by free competition, also known as the *survival-of-the-fittest doctrine*. This doctrine says that the strong should see their wealth and power increase, while the weak should see their wealth and power decrease, disappearing at the end. It implies taking out some form of collective ownership and handing over resources to private owners, if possible. David Bollier, a popular promoter of public interests, compared the private appropriation of collectively owned resources to the movement to enclose common lands in England. The process started there in the XVIth century, and now most of the previously common land belongs to individuals that in total account for less than 0.1% of the popula-

tion [62]–[64]. Its more recent variant is known as *free-market environmentalism*.

More and more countries grant exclusive licenses to the highest bidders, and open the secondary spectrum markets. Seeking the maximum possible return on the investment dollar is a strong motivating force, but it threatens other important values. Not everybody accepts that a rush for profit should be the only, or the most important, driving force in life. Many prophets and philosophers have long since indicated the negative effects of this. Recently, even major economists noticed this problem [65]. If not restricted by rules of tradition, religion, law, ethics, rational moderation, or by other factors, excessive greed may easily destroy the social order, and lead to crime and wars.

4.3.4. Spectrum Ownership Doctrine

Except for radio waves of natural origin, radio frequencies are inherent characteristics of radio devices: the latter cannot exist or operate without the former. The ownership of a device logically extends over the RF waves radiated or received by it. The spectrum-ownership concept interrupts that connection. Named *flexible spectrum use* by Robert Matheson [66], the concept also ignores electromagnetic interactions and the inherent dynamics of the radio-signal environment. The doctrine is based on two simple rules. One assures the owner’s rights: “Transmit within signal power restrictions inside your licensed electro-space region”, while the other protects the neighbor’s rights: “Keep your signals below ‘X’ outside that region”. This exploits an apparent analogy between land ownership and spectrum ownership over the specific service region. When you own a walled garden, you can arrange the garden at will as long as you remain within the walls. However, with spectrum it is not as simple as it might look at first glance, because it is impossible to determine the “walls” of spectrum property with any precision.

One has to realize that the unguided wave-propagation laws do not allow for any abrupt change of signal power. Simple *borderlines* between the inside and outside at the edge of the service region are physically unrealizable in free space: a finite-sized *buffer region* separates neighboring service regions. That buffer region must be sterile. None of the neighbors can extend his/her radio services there, unless special precautions are applied; careful coordination of geographic distance, signal-power density, frequency, time, or coding might be necessary. Second, the flexible-spectrum-use doctrine is static, and neglects the impact of a changing environment, which can change [67], [68] without the owner’s consent or even knowledge.

Without firmly freezing the future signal environment, e.g., through strict spectrum planning, such uncertainties reduce the secondary spectrum marked to nil. That fact calls into question the very concept of private spectrum and its flexible use for active services, not mentioning the more difficult case of the property of frequencies used for passive services. Laws of physics firmly say that in a dense signal environment, no freedom exists in the use of spectrum.

While the idea of privately owned spectrum makes sense in the case of isolated radio systems, it is physically unrealizable where the spectrum is congested. With proper spectrum management, the probability of such interactions is analyzed before issuing the license, and is kept at an acceptable level.

4.4. Spectrum Market

The spectrum market is not a new idea. The thought of selling spectrum rights was put forward for the first time at the 1906 Berlin conference. The Russian delegation suggested a kind of transit fees for radio waves propagating over the country's territory. Some fifty years later, in 1959 Ronald Coase of the FCC suggested property rights and spectrum market as a more efficient method of allocating the spectrum to users. (He was the laureate of the 1991 Nobel Prize in Economic Sciences, for his work on transaction costs and property rights). Then Equatorial countries, in their *Bogota Declaration*, mentioned earlier, claimed that the satellites located above their territories should pay a kind of *parking fee*. In 1995, Richard Butler, then the ITU Secretary General, put forward that positions of orbiting satellites be traded, and the income be used to finance the activities of the ITU. He did that when some ITU Member States failed to pay their contributions: with no cash, he would have been forced to close operations and fire the staff. The Member States rather preferred to pay the contributions than to rent orbital positions or shut down the ITU. None of the privatization ideas have been accepted until now at the international forum. The majority of ITU Member States firmly supported the common character of the radio spectrum and satellite orbits.

Spectrum auctioning has been practiced in a number of countries. For governments, it has become attractive because it solves the access rights to spectrum in cases where too many are interested, and also provides money inflow to the budget. However, the FCC Commissioners, like many other experts, long opposed the idea of a spectrum market, so it had to wait some thirty years for its first implementation. Interestingly, it did happen in New Zealand and not in the USA, as one could expect. New Zealand introduced spectrum auctions for tradable leases up to 20 years in 1989. However, many are against spectrum auctions. Earl Holliman, the US Army Spectrum Manager, wrote:

We hear a lot about auctions. The auction approach does not stimulate technology towards more efficient frequency uses. It lets a successful bidder only get richer and pushes the smaller operator back.

For companies, auctions involve large uncertainties and high risks: the expected and needed profits for planned operations might never come true. For customers, they may mean an increase in the price of services. Huge amounts have been paid for frequency bands that were never used [69], [70]. Some auctions are seemingly used to block competitors rather than to put the spectrum into

use. Auctions have been claimed to be corruption-immune, but several scandals have shown the opposite. The 2010 spectrum scam in India, quoted earlier, was an example. Some economists do not believe in the efficiency of the free market. For instance, Joseph Stiglitz, the laureate of the 2001 Nobel Prize in Economic Sciences, says it is only under exceptional circumstances the markets can be efficient. He wrote [71]:

For more than 20 years, economists were enthralled by so-called 'rational expectations' models which assumed that all participants have the same (if not perfect) information and act perfectly rationally, that markets are perfectly efficient, that unemployment never exists... and where there is never any credit rationing. That such models prevailed, especially in America's graduate schools, despite evidence to the contrary, bears testimony to a triumph of ideology over science. Unfortunately, students of these graduate programmes now act as policymakers in many countries, and are trying to implement programmes based on the ideas that have come to be called market fundamentalism.

Numerous other authors are of similar opinions, such as, e.g., Eli M. Noam, Samuel A. Simon, Joseph H. Weber, and Yohai Benkler. Most surprisingly, George Soros, a famous billionaire, joined other critics, writing [72]:

Although I have made a fortune in the financial markets, I now fear that the untrammelled intensification of laissez-faire capitalism and the spread of market values into all areas of life is endangering our open and democratic society.

The UN has called a special summit to consider, among other problems, the "Fundamental Defects of the Free Market System" [73]. The 2011 Washington Declaration on intellectual property and the public interest clearly stated [74]:

Markets alone cannot be relied upon to achieve a just allocation of information goods – that is, one that promotes the full range of human values at stake in intellectual property systems. This is clear, for example, from recent experiences in the areas of public health and education, where intellectual property has complicated progress toward meeting these basic public needs.

This would indicate that practices protecting intellectual property rights should be seen from a wider socio-economic viewpoint, taking into account society as a whole: not only those who benefit now, but also those who pay or loose in a longer perspective.

Many worry that privatization, if widely introduced, would be incapable of assuring balanced sustainable socio-economic development; that government and corporate

surveillance would increase without limits; that the free flow of content we are now proud of would stop; and that intellectual property rights would extend into the interminable past. The uncertainty results from our dilemmas on the hierarchy of values. Erich Fromm, a German philosopher, put it briefly: “to have, or to be?” – a basic question to which everybody has their own answer. Spectrum trading also offers opportunities to the benefit of both operators and the society served, when spectrum can be more effectively utilized in an area or a market.

4.4.1. Competition

In the opinion of many experts, the progress in mobile and broadband communications, and generally in the radio applications we enjoy today, would not have developed at the pace we have seen if there were no competition. It may not be so easy to prove generally, but for many, the cost of communication services has not increased in the latest decades. Rather, the opposite has occurred relative to daily spending for living, and such services have become much more affordable [75]. Furthermore, information and communication technology services have become much more important, highly beneficial, and even absolute necessary for a well-functioning society.

However, other cases show that competition may not serve society well, as illustrated by the following example. When serving in the ITU headquarters, the first author organized the CCIR library of spectrum-management software freely offered by ITU Members. The software could be copied and used at no cost by all those interested. This was functioning well, but a problem appeared when the program for practical planning of low-power (local) TV stations was offered [76]. It was then one of few programs using digital terrain models and inexpensive personal computers. It generated great interest among small and medium enterprises, in both developed and developing countries. Its user interface was in Polish, and it was proposed to translate it into English and other ITU official languages, which would make it more useful in many countries. However, a few delegates representing private business were against this, arguing that “it would kill our business”. As no required consensus was reached, the proposal was not approved. In addition, as a consequence, there is no such free software provided by ITU today.

With the consensus rule, a single company can easily block other enterprises, but opposite cases also happened. For instance, one can learn from the FCC home page that Edwin Armstrong, an American inventor, proposed his frequency-modulation system in 1935. However, companies in the United States, afraid that it would reduce their profits, blocked it for some twenty-five years, until the 1960s. Similarly, for more than a decade, civilian applications of spread-spectrum technology were blocked. More recently, the promising low-Earth orbit (LEO) [77] and high-altitude platform (HAP) [78] technologies were blocked. The majority blamed the general crisis for that, but some suspected the competing companies of significantly contributing to

that. More recently, the FCC stated that it had to protect consumers from mobile-broadband providers’ commercial practices masquerading as “reasonable network management”. Working hand in hand with citizens, the FCC is setting “strong rules that protect consumers from past and future tactics that threaten the Open Internet” and promote “more broadband, better broadband, and open broadband networks”. The providers hold all the tools necessary to deceive consumers, degrade content, or disfavor the content that they don’t like. Some companies make practical use of these tools, keeping third-party applications within a carrier-controlled “walled garden”, as in the early days of electrical communications. That practice ended when the Internet protocol (IP) created the opportunity to leap the wall, but the FCC has continued to hear concerns about other broadband-provider practices involving blocking or degrading third-party applications.

4.5. Spectrum Sharing

Privatization pressure provoked countermovement and the revival of interest in spectrum commons and cooperatives. One of the most respected researchers in that area was Elinor Ostrom, a US economist and the only woman who won the Nobel Prize in Economic Sciences (in 2009), for “her analysis of economic governance, especially the commons”. Her studies have indicated that the commons are sustainable if they are well managed, best done by their owners, themselves. Interestingly, that principle has intuitively been practiced on the global scale by ITU Members since 1906, well before Ostrom’s studies. More recently, the principle was extended over the users of Wi-Fi and similar technologies, which became the most popular use of spectrum commons. For instance, in 2013, more Internet traffic was carried over Wi-Fi than via any other path, resulting in some US\$222 billion in value added to the US economy alone [79]. That evidences the practicality of spectrum sharing and the numerous benefits in comparison with the exclusive (private or licensed) spectrum, including lower access cost. Note that there has always been a part of the wealth kept in common, examples being public roads and parks. Since the very beginning, spectrum access has been free for each and any government: what many civil society activists expect is an extension of that practice over individual spectrum users, without any governmental brokerage.

The US President’s Council of Advisors on Science and Technology (PCAST) suggested a three-tier “dynamic sharing” Spectrum Access System (SAS), making spectrum sharing the norm. Under the Spectrum Access System, Federal primary systems would receive the highest priority and protection from harmful interference. Secondary licensees would register deployments and receive some quality-of-service protections, possibly in exchange for fees. General Authorized-Access users would be allowed opportunistic access to unoccupied spectrum (when no Primary or Secondary Access users were using a given frequency band in a specific geographical area or time period) [80]. The

National Telecommunication and Information Agency has already identified a total of 960 MHz of federal spectrum as candidates for sharing using that approach. The European Commission is considering similar sharing possibilities, based on contracts between the users. This is seen as a natural extension of the previous spectrum policies: licensed access allowing operators to offer a predicted quality of service, and license-exempt access fostering widespread contributions to innovation and fast-paced investment in emerging technologies [81]. However, incumbent commercial or government users may be reluctant to give up their exclusive rights to individual spectrum bands, concerned about already made or planned long-term investments in communication networks, including access to spectrum. And yet, technology is being developed and deployed to allow for such sharing by new entrants without risking interference to the incumbents' systems. A number of countries have pursued regulations or trials that enable license-exempt, Wi-Fi-like devices to access vacant spectrum in the television broadcast bands ("white spaces"). These are expected to improve Internet access, facilitate the delivery of government services, establish communication channels in the wake of earthquakes, typhoons, etc.

4.6. Other Issues

Since the very beginning, scientists have worked on issues that have extended our knowledge about the universe, and made our lives easier, safer, and richer. There is a wealth of literature on the benefits radio waves have brought to humanity. However, that progress has also brought negative effects. The perception of electromagnetic waves has been changing. From an abstract concept, it morphed to a tradable commodity, and from a scientific curiosity, to an apparatus of indoctrination, a weapon in physical conflicts, and a tool for criminals. In addition to the unknown long-term biological side effects of man-generated electromagnetic waves, there are also other sources of worry. Like health, they only indirectly relate to spectrum use. Discussing them in detail clearly exceeds the scope of this article, so we only mention some here, which we believe are needed to better understand the role and complexity of spectrum management.

4.6.1. Orbital Debris

Since 1957, after the launch of the first Earth-orbiting artificial satellite, the near-Earth environment has served as a gigantic rubbish collector. Orbital debris (also called space debris) is a collection of man-made objects launched into space and left there with no purpose after their mission ended. They are dead satellites and their fragments, upper stages of rockets and their fragments, and other abandoned objects. The total number of these objects is counted in the millions of pieces. It increases with every new launch of a space object and with each new satellite explosion, and with accidental fragmentation or due to anti-satellite tests in outer space. These objects are all orbiting with hyper

velocities of a few to dozens of kilometers per second, and can damage operating satellites and space vehicles. For comparison, the velocity of a bullet fired from the famous AK 101 Kalashnikov rifle is less than one kilometer per second. The threat of impact damage is a growing concern. Medium-size objects (0.1 cm to 10 cm in diameter) are the greatest challenge, because they are not easily tracked, and have a kinetic energy high enough to cause catastrophic damage. For instance, a particle with a mass of 10 g moving 10 km/s has a kinetic energy comparable to a one-ton car running on a highway at a speed of 100 km/h. Penetration of even a small particle through a critical component, such as a flight computer or propellant tank, can result in loss of a spacecraft. If a 10 cm object of 1 kg mass collided with a typical spacecraft bus, over one million fragments of 1 mm in size and larger could be created, according to NASA. Such a collision would result in the formation of a debris cloud, which poses a magnified impact risk to any other spacecraft in the orbital vicinity. Mutual collisions can further multiply the numbers. Encounters with clouds of smaller particles can also be devastating for future missions. For instance, the solar panels of the Hubble Space Telescope (launched in 1990 and remaining in operation) have been replaced several times because of damage caused by tiny objects. Such objects may also efficiently block scientific observations of some regions in the sky.

A few countries do radar, optical, and infrared surveillance of space for security reasons. The smallest traceable objects are about 10 cm in diameter at low altitudes, and about 1 m in diameter at geostationary orbit. Some space debris could escape towards other celestial bodies, burn in the atmosphere, or fall on the Earth. However, to do so their velocity must change. What slows them and forces them to fall down is air drag, but this decreases with altitude. At high altitudes, it is negligible, which implies a long time for orbiting in space. Table 1 lists the expected orbital lifetimes for selected circular orbits.

Table 1
The lifetimes of circular orbits [82]

Orbital Altitude [km]	Lifetime
200	1–4 days
600	25–30 years
1000	2000 years
2000	20 000 years
36 000 (GSO)	Indefinite

At geostationary (GSO) altitude, no effective natural removal mechanism exists, except for solar-radiation pressure. From a practical standpoint, objects located in geostationary orbit would indefinitely remain in that vicinity, if not moved at the end of a mission. Orbital debris is a good illustration of the CC-PP (communize costs – privatize profits) behavior of satellite companies first described by Hardin, mentioned earlier. Some of the ob-

jects launched are sent back to the Earth, especially after the invention of re-useable space vehicles, but the creation rate of debris has outpaced the removal rate. Maintaining the current design and operational practices could ultimately render some regions in space useless, and even dangerous.

4.6.2. Issues to Watch

The future of radio applications may not be as wonderful as it could be, and as most people would like it to be. Technological progress is often driven by military programs that aim at improving ways enemies are destroyed, or allies are protected. However, many byproducts of these programs find later civilian applications, making our life easier, healthier, and pleasanter. Unfortunately, a military invention might also become accessible to criminals, or a government might use it against their own citizens: the latter practice ends often in a government overthrow or revolution.

4.6.2.1. Propaganda

Radio as a wartime propaganda tool become popular during World War II (it later was supplemented by television). Wireless can bring all the persuasive power to millions of people at relatively low cost, ignoring national borders and front lines. However, its power was demonstrated earlier, in 1938, in the USA, after the airing of *The War of the Worlds*, an innocent episode of a radio drama series. Orson Wells presented it so realistically that the radio transmission was taken as real news, and caused mass panic, difficult to manage. Since then, radio and television have become major advertising means. However, they also serve as efficient *propaganda* and *brainwashing* tools in political/ideological campaigns. More recently, mobile phones, SMS (short messaging service) and online social-networking services such as *Twitter* and *Facebook* have similarly affected the social lives and activities of people, starting from the election campaigns in the USA to social protests such as Occupy Wall Street or the Arab Spring of 2010. The unprecedented ease and scale of wirelessly manipulating public opinion worries many. The Arab Spring protests transformed into revolutions that overthrew a few governments. It explains why so many other governments want to control the access to radio waves and to the information they carry.

4.6.2.2. Espionage, Cyber Attacks, and Jamming

The fear of war, criminal acts, or losing power pushes governments not only to license access to spectrum, but to also develop intelligence, eavesdropping, and surveillance, which is relatively easy in the case of wireless communications. However, these may also be used against the citizens' right to privacy. Some years ago, the European Parliament initiated an investigation into the ECHELON system [83], created to monitor the military and diplomatic communi-

cations of the Soviet Union and its allies during the Cold War. With time, it had evolved, allegedly becoming a global system for the interception of any communications over the globe, including private and commercial communications. Another worrying issue is massive surveying of people. According to the press, there is one surveillance camera for every eleven people in Great Britain. An even more worrying issue is the use of radio waves for criminal attacks and secret wars in cyberspace [84]. Real data from that area are rarely published, but the scale of the issue can be judged from the expenses incurred. According to the press, the defense cyberspace budget for 2015 includes US\$5 billion in the USA alone; other countries may spend proportionally.

Jamming was widely used during World War II and the Cold War. Later, unintended interference was often noted. For instance, deliberate jamming of telecommunications satellites was observed and increased between 2009 and 2012. In several circumstances, France raised this issue to the Radio Regulations Board. Several European countries also submitted a proposal to WRC-12 on this issue, which led to an evolution of the Radio Regulations that gave more weight to the issue of deliberate interference.

4.6.3. Power from Space

New, cheap, and environmentally friendly energy sources are now sought in several countries. The world's population is expected to reach 10 billion people by the year 2050, and the present energy sources will be insufficient to satisfy their needs, according to current projections. Among various ideas, the space solar power (SSP) concept has been studied. In 2007, URSI published a comprehensive report on the topic [85]. Among additional possible solar-power satellite (SPS) applications, the report listed sending energy from spacecraft to spacecraft, bringing energy to remote areas on the globe that are difficult to otherwise access, or providing energy to the dark side of the moon. The report stressed that URSI did not unanimously advocate solar-power satellites. Within URSI, there are both advocates of solar-power satellites, and voices of concern and severe reservation.

The solar-power satellite studies started in the USA, during the oil crisis of the seventies, aimed at limiting the dependence of the national economy on foreign oil. In 1974, a patent was granted for a solar power satellite to collect power from the sun in space, and then transmit it down using a microwave beam to the Earth for use. One of the more recent solar-power satellite systems considered huge ($\sim 10 \text{ km}^2$) arrays of photovoltaic cells placed in an Earth orbit, or on the moon to convert the sunlight into electricity. Such arrays would be unaffected by cloud cover, atmospheric dust, or by the Earth's twelve-hour day-night cycle. To reduce the necessary area of costly solar arrays, sunlight could be additionally concentrated using giant mirrors. The incident solar radiation would be converted into electricity using the photovoltaic process. Another part that would manifest itself as heat could also be converted into elec-

tricity using thermoelectric devices. These would serve as thermal pumps, removing heat from the photovoltaic panels and lowering their temperature.

The electricity would then be converted to microwaves, and beamed by a composite space antenna ($\sim 6 \text{ km}^2$) towards a huge Earth antenna ($\sim 12 \text{ km}^2$). The space antenna would assure a pointing accuracy of about 0.0005° , which would mean about a $\sim 300 \text{ m}$ pointing error on the Earth's surface. The terrestrial antenna would contain a large number of receiving antennas combined with rectifiers and filters (called a rectenna), which would convert the microwave power into electrical current, injected into the power network. To limit the health danger, the receiving antenna would be located in the desert, or in mountains far away from densely populated areas. The size of the microwave beam could be large enough to keep the power density within safe limits.

A space solar-power system using today's technology could generate energy at a higher cost than the current market price. One estimate was that it would take 15 to 25 years of further research to overcome that difference. In 2001, Japan announced that they plan to launch a giant solar-power station by 2040. Preparatory studies are also being undertaken in the European Union and in the United States. There are many questions to be solved. For instance, the URSI report quoted earlier lists the following:

What is the impact of SPS electromagnetic emissions – both intended and unwanted (harmonics of the microwave frequency, unexpected and harmful radiation resulting from malfunctions) at microwave frequencies and other related frequencies – on telecommunications, remote sensing, navigation satellite systems, and radio-astronomical observations? What actions can be taken to suppress this unwanted emission? Constraints imposed by the Radio Regulations of the International Telecommunication Union must be taken into account.

However, more important questions remain to be solved before solar-power satellites could operate, e.g., health and environmental problems not yet solved. Others have indicated that it is potentially a double application technology: a solar-power satellite station could easily be converted into a dangerous weapon. Space weapons using solar energy are not a new idea. In World War II, some German scientists were speculating on the use of gigantic mirrors that could concentrate solar energy to set fire to an enemy's cities, manufacturing, crop fields, etc., during wartime. High-power microwave beams could cause similar damage. Between the wars, the solar-power satellite mirrors could be used to control local weather conditions over a selected region. The size, complexity, environmental hazards, and cost of a space solar power undertaking are daunting challenges.

5. Concluding Remarks

This paper has reviewed basic issues of radiofrequency spectrum use. It has shown how deeply our current concepts are rooted in the past, and how often they are dictated by the short-term benefits of the few. It has summarized arguments and lessons learned since the invention of radio, which could be usable in current debates on how to reduce the chronic apparent shortage of RF spectrum. It has highlighted major doctrines focusing on a better understanding of how the spectrum-management mechanisms are associated with the public interest and distribution of information, knowledge, wealth, and power. It pointed up similarities between spectrum conservation and environmental protection. The paper is intended to promote cooperation, transparency, and direct involvement of spectrum users into its management process. It focused on issues that could be improved through good will, negotiations, and consensus without in principle requiring extra resources.

The fundamental question of whether it is better to privatize the spectrum or to keep it as a regulated commons, to sell it, or to distribute it freely, will probably be open for decades. Many have hoped for a long time that science and engineering will solve the spectrum-scarcity problem. Science and engineering are universal – independent of nationality, ideological convictions, or political orientation – which makes joint efforts much easier than in any other field. However, history shows the opposite: spectrum scarcity increases with the progress made in science and engineering. Many have anticipated such an approach to spectrum management could be as useful as it has been found to be in the military. However, negotiations and lobbying will probably continue as the basis for spectrum management for a long time. Human motivations and ways of thinking have not changed much since the invention of radio, and most probably will not change in the foreseeable future, shaping spectrum use. The reason is that society is not uniform. It is composed of groups, each having different world views, interests, needs, and powers. What is best for one group is not necessarily good for the others. The dominant group usually tries to use all possible means and ways to keep the benefits it acquired as long as possible.

The ITU negotiation system has evolved during 150 years and each radio conference makes it better, but it is still not ideal: some of its weaknesses were indicated in the above sections. Notwithstanding this, the history of radio has evidenced that in spite of the threat of supporting some particular interests [22], it has been serving humanity well, not to mention that it has been the only acceptable mechanism. That is an optimistic view. An even more optimistic remark is that the ITU system is not static: it is a dynamic and self-healing system (even if it now recommends static spectrum allocations). The more people understand better spectrum-management mechanisms, the more chances the system will be improved at a future conference. Various forums exist within and outside of the ITU to discuss and understand better problems accompanying the uses of

the radio spectrum, not only the positive uses but also the negative uses; not only seen from a narrow engineering or economic viewpoint, but also from a wider perspective. These forums try to call attention to the need for limiting the negative effects before they develop in full. Should the voice of radio scientists be heard there? ITU has not yet definitely solved the spectrum-scarcity problem, just as the whole of humanity has not solved problems of hunger, health, and many others. According to Hardin, quoted earlier, the scarcity problem cannot be ultimately solved only by technical means, without involving the system of human values and ideas. Mahatma Gandhi, the famous Indian leader, put it briefly as follows:

There is enough on the Earth to meet everybody's need but not sufficient to meet anybody's greed.

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References

- [1] M. Cooper, "The Myth of Spectrum Scarcity", <http://dynallc.com/2010/03/the-myth-of-spectrum-scarcity-position-paperby-martin-cooper-march-2010/>, March 2010 (accessed September 2015).
- [2] ITU-R, "World Radiocommunication Conference 2015 (WRC15)", <http://www.itu.int/en/ITU-R/conferences/wrc/2015/Pages/default.aspx>, (accessed September 2015).
- [3] F. Donaldson, "The Marconi Scandal", Bloomsbury Reader, 2013, ISBN: 9781448205851.
- [4] G. Havoc, "The Titanic's Role in Radio Reform", *IEEE Spectrum*, April 15, 2012, pp. 4–6.
- [5] National Telecommunications & Information Administration (NTIA), United States Department of Commerce, Spectrum Management, <http://www.ntia.doc.gov/category/spectrummanagement> (accessed April 2015).
- [6] Garrett Hardin, "The Tragedy of the Commons", *Science*, 162, December 1968, pp. 1243–1248.
- [7] S. Radicella, "Introduction to International Radio Regulations", ICTP 2003, ISBN 92-95003-23-3, <http://publications.ictp.it/lns/vol16.html>
- [8] T. O'Leary, E. Puigrefagut and W. Sami, "GE 06 – Overview of the Second Session (RRC-06)", EBU Technical Review, https://tech.ebu.ch/docs/techreview/trev_308-rrc-06.pdf, October 2006, pp. 1–20 (accessed November 2014).
- [9] E. Pietrosemoli and M. Zennaro, "TV White Spaces – A Pragmatic Approach", ICTP 2013, ISBN 978-9295003-50-7, <http://wireless.ictp.it/tvws/book/> (accessed September 21, 2014).
- [10] G. A. Coddling Jr., "International Constraints on the Use of Telecommunications", in L. Lewin (ed.), *Telecommunications – An Interdisciplinary Text*, Norwood, MA, Artech House, ISBN 0-89006-140-8, 1984.
- [11] R. Struzak, "Software for Radio Frequency Spectrum Engineering", *Radio Science Bulletin*, No. 262, September 1992, pp. 41–48.
- [12] R. Struzak and K. Olms, "Frequency Management and Software for Spectrum Engineering for Personal Computers", *Telecommunication Journal*, April 1993, pp. 168–174.
- [13] W. Rotkiewicz, *Electromagnetic Compatibility in Radio Engineering*, New York, Elsevier, 1982, ISBN 0-444-99722-9.
- [14] URSI, "History of URSI", http://www.ursi.org/en/ursi_history.asp, (accessed September 2015).
- [15] R. Struzak and R. C. Kirby, "On Radio Spectrum, Competition and Collaboration", *Proceedings of the 17th General Assembly of URSI*, (ITU/CCIR presentation), Tel-Aviv, September 24 October 2, 1987.
- [16] JTAC IRE - RTMA, *Radio Spectrum Conservation*, Report of the JTAC IRE - RTMA, New York, McGraw-Hill Book Co., 1952, Library of Congress Nr. 52-9444.
- [17] JTAC IEEE and EIA, *Spectrum Engineering – The Key to Progress*, Report of the JTAC IEEE and EIA, New York, IEEE, 1968, Library of Congress Nr. 68-8567.
- [18] F. Matos, *Spectrum Management and Engineering*, New York, IEEE Press, 1985, ISBN 0-87942-189-4.
- [19] W. G. Duff, "Electromagnetic Compatibility in Telecommunications", *Interference Control Technologies*, 1988, ISBN 0-944916-07-4.
- [20] J. A. Stine and D. L. Portigal, "Spectrum 101 – An Introduction to Spectrum Management", MITRE Technical Report, March 2004.
- [21] R. Leese and S. Hurley, *Methods and Algorithms for Radio Channel Assignment*, Oxford, Oxford University Press, 2002, ISBN 0 19 850314 8.
- [22] T. Tjelta and R. Struzak, "Spectrum Management Overview", *URSI Radio Science Bulletin*, No. 340, September 2012, pp. 25–28.
- [23] ITU, History of ITU Portal, "Complete List of Radio Conferences", <http://www.itu.int/en/history/Pages/CompleteListOfRadio-Conferences.aspx> (accessed May 2015).
- [24] ITU, "Radio Regulations", Edition of 2012, <http://www.itu.int/dms-pub/itu-s/oth/02/02/S02020000244501PDFE.PDF> (accessed September 2015).
- [25] P. Rysavy, "Challenges and Considerations in Defining Spectrum Efficiency", *Proceedings of the IEEE*, 102, 3, March 2014, pp. 386–392.
- [26] I. Flood and M. Allen, "Equipment Selection Heuristic for Microwave Fixed Links", *Radio Science*, 49, August 2014, pp. 630–64.
- [27] M. Mehdawi, N. Riley, K. Paulson, A. Fanan, and M. Ammar, "Spectrum Occupancy Survey in Hull-UK for Cognitive Radio Applications: Measurement & Analysis", *International Journal of Scientific & Technology Research*, 2, 4, April 2013, pp. 231–236.
- [28] European Commission, "Promoting the Shared Use of Radio Spectrum Resources in the Internal Market", Communication from the Commission to the European parliament, the Council, the European Economic and Social Committee and the Committee of the regions, COM(2012) 478 final, Brussels, September 3, 2012.
- [29] J. M. Chapin and W. H. Lehr, "The Path to Market Success for Dynamic Spectrum Access Technology", *IEEE Communications Magazine*, May 2007, pp. 96–103.
- [30] W. Lehr (chair), "Towards More Efficient Spectrum Management", MIT Communications Futures Program White Paper, March 2014.
- [31] M. Falch and R. Tadayoni, "Economic Versus Technical Approaches to Frequency Management", *Telecommunications Policy*, 28, 2004, pp. 197–211.
- [32] R. H. Coase, "The Federal Communication Commission", *Law & Economics*, II, October 1959, pp. 1–40.
- [33] P. Cramton, "Spectrum Auction Design", *Review of Industrial Organization*, 42, 2, March 2013, pp. 161–190.
- [34] A. S. De Vany, R. E. Eckert, C. J. Meyers, D. J. O'Hara and R. C. Scott, "A Property System for Market Allocation of the Electromagnetic Spectrum: A Legal-Economic-Engineering Study", *Stanford Law Review*, 21, 6, June 1969, pp. 1499–1561.
- [35] R. MacKenzie, K. Briggs, P. Grønsund, P. H. Lehne, "Spectrum Micro-Trading for Mobile Operators", *IEEE Wireless Communications*, December 2013, pp. 6–13.
- [36] Z. Ji and K. J. R. Liu, "Dynamic Spectrum Sharing: A Game Theoretical Overview", *IEEE Communications Magazine*, May 2014, pp. 88–94.

- [37] L. Doyle, J. Kibilda, T. K. Forde and L. Da Silva, "Spectrum Without Bounds, Networks Without Borders", *Proceedings of the IEEE*, 102, 3, March 2014, pp. 351–365.
- [38] J. Brito, "The Spectrum Commons in Theory and Practice", *Stan. Tech. L. Rev.*, 1, 2007.
- [39] K. Werbach, "Supercommons: Toward a Unified Theory of Wireless Communication", *Texas Law Review*, 82, 2004, pp. 863–963.
- [40] R. Struzak, "Spectrum Management: Key Issues", *Pacific Telecommunications Review*, September 1996, No. 1 pp. 2–11.
- [41] A. Nagurny, "Supernetworks", in M.G.C. Resende and P. M. Pardalos (eds.), *Handbook of Optimization in Telecommunications*, Berlin, Springer, 2006, ISBN-10: 0-387-30662-5, pp. 1073–1119.
- [42] T. Harbert, "Internet Giants Adopt New Lobbying Tactics", *IEEE Spectrum*, October 2012, <http://spectrum.ieee.org/telecom/internet/internet-giants-adopt-new-lobbying-tactics> (accessed March 2013).
- [43] "Bogota Declaration of 1976: Declaration of the First Meeting of Equatorial Countries", http://www.jaxa.jp/library/space_law/chapter_2/2-2-1-2.e.html
- [44] R. Struzak, "CCIR Preparations for WARC'92", *URSI Radio Science Bulletin*, No. 259, December 1991, pp. 50–57.
- [45] R. Struzak, M. Hunt and A. Nalbandian, "CCIR Preparations for World Administrative Radio Conference WARC '92", *Telecommunication Journal*, February 1992, pp. 56–59.
- [46] R. Struzak, "On Future Information System for Management of Radio Frequency Spectrum Resource", *Telecommunication Journal*, November 1993, pp. 429–437.
- [47] ITU, "Executive Summary", *Measuring the Information Society Report 2014*, 2014.
- [48] R. Struzak, "Broadband Internet in EU Countries: Limits to Growth", *IEEE Communications Magazine*, 48, 4, April 2010, pp. 52–55.
- [49] R. Struzak, "Diffusion of Broadband Services: An Empirical Study", *IEEE Communications Magazine*, 50, 8, 2012, pp. 128–134.
- [50] D. McNally, "The Vanishing Universe", Cambridge, Cambridge University Press, 1994, ISBN 0 521 450209.
- [51] B. Robinson, "Frequency Allocations - The First Forty Years", *Annual Review of Astronomy and Astrophysics*, 37, 1999, pp. 65–96.
- [52] H. Zimmermann, "The Vital Role of Telecommunications in Disaster Relief and Mitigation", *Emergency Telecommunications DHA Issues*, Focus Series No. 2, United Nations, 1995, pp. 3–5.
- [53] A. Rahrig, "Love Thy Neighbor: The Tampere Convention as Global Legislation", *Indiana Journal of Global Legal Studies*, 17, 2, January 2010.
- [54] R. Struzak, "Evaluation of the OCHA (DRB) Project on Emergency Telecommunications with and in the Field, Rev. 1", New York and Geneva, United Nations, July 2000, September 2000.
- [55] AT&T, "A Brief History: The Bell System", <http://www.corp.att.com/history/history3.html> (accessed February 2013).
- [56] OECD, "Report OECD Communications Outlook 2013", DOI: 10.1787/comms_outlook-2013-en, http://www.keepeek.com/Digital-Asset-Management/oecd/science-and-technology/oecd-communications-outlook-2013_comms_outlook-2013en
- [57] C. Guglielmo, "The Apple vs. Samsung Patent Dispute: 20-Talking Points", <http://www.forbes.com/sites/connieguglielmo/2012/08/21/the-apple-vs-samsung-patentdispute-20-talking-points/>
- [58] J. P. Kesan and G. G. Ball, "How Are Patent Cases Resolved? An Empirical Examination of the Adjudication and Settlement of Patent Disputes", *Washington University Law Review* 2006, 84, 2, pp. 237–312.
- [59] A. Armstrong, J. J. Mueller and T. D. Syrett, "The Smartphone Royalty Stack", http://www.wilmerhale.com/uploadedFiles/Shared_Content/Editorial/Publications/Documents/TheSmartphone-Royalty-Stack-Armstrong-Mueller-Syrett.pdf (accessed July 2014).
- [60] L. Popelka, "Only Lawyers Win in Patent Wars", <http://www.businessweek.com/articles/2012-04-24/patent-wars-lawyersare-the-only-winners> (accessed December 2014).
- [61] B. Marcus, "The Spectrum Should be Private Property: The Economics, History and Future of Wireless Technology", *Mises Daily*, Ludvig von Mises Institute, 2004.
- [62] D. Bollier, "Reclaiming the Commons. Why We Need to Protect Our Public Resources from Private Encroachment", <http://bostonreview.net/BR27.3/bollier.html#> (accessed May 2013).
- [63] D. Bollier, "Silent Theft: The Private Plunder of Our Common Wealth", New York Routledge, 2002.
- [64] S. Fairlie, "A Short History of Enclosure in Britain", *The Land*, Issue 7, summer 2009, <http://www.thelandmagazine.org.uk/articles/short-history-enclosure-britain> (accessed June 2014).
- [65] J. Helliwell, R. Layard and J. Sachs, "World Happiness Report 2013."
- [66] R. J. Matheson, "Flexible Spectrum Use Rights. Tutorial", *International Symposium on Advance Radio Technologies (ISART) 2005*.
- [67] R. Struzak, "Flexible Spectrum Use and Laws of Physics", *ITU-FUB Workshop: Market Mechanisms for Spectrum Management*, Geneva, January 22-23, 2007.
- [68] R. Struzak, "On Spectrum Congestion and Capacity of Radio Links", *Annals of Operation Research* 2001, 107, 2001, pp. 339–347.
- [69] BBC News, December 19, 2002, <http://news.bbc.co.uk/2/hi/business/2591993.stm>, (accessed May 2015).
- [70] D. Daniel Sokol, "The European Mobile 3G UMTS Process: Lessons from the Spectrum Auctions and Beauty Contests", *Virginia Journal of Law and Technology*, University of Virginia, Fall 2001, VA. J.L. & TECH. 17, <http://www.vjolt.net/vol6/issue3/v6i3-a17-Sokol.html> (accessed May 2015).
- [71] J. Stiglitz, *The Price of Inequality: How Today's Divided Society Endangers Our Future*, New York, W. W. Norton & Co., 2013, ISBN-10: 0393345068.
- [72] G. Soros, "The Capitalist Threat", *The Atlantic Monthly*, February 1997, pp. 45–58.
- [73] United Nations Conference on the World Financial and Economic Crisis and Its Impact on Development, Abu Dhabi, United Arab Emirates, July 8-11, 2013.
- [74] The Washington Declaration on Intellectual Property and the Public Interest Adopted at American University Washington College of Law, Washington DC, August 27, 2011.
- [75] ITU, "ICT Services Getting More Affordable Worldwide", *ITU Newsroom*, Press Release, https://www.itu.int/net/pressoffice/press_releases/2011/15.aspx#.VVBSO901aQ (accessed May 2015).
- [76] R. Struzak, "Microcomputer Modeling, Analysis and Planning in Terrestrial Television Broadcasting", *Telecommunication Journal*, 59-X, 1992, pp. 453, 459-492 (see also: <http://www.piastr.edu.pl/>).
- [77] R. Struzak, "Internet in the Sky: T1 Tests have Started...", *ITU News*, Nr. 6/98, pp. 22-26.
- [78] R. Struzak, "Mobile Telecommunications via Stratosphere", *Intercomms – International Communications Project*, 2003, <http://www.intercomms.net/AUG03/docs/features.php> (accessed November 2014).
- [79] S. Forge, C. Blackman and R. Horwitz, "Perspectives on the Value of Shared Spectrum Access", *Final Report for the European Commission, SCF Associates, DTI, GNKS-Consult, ICEGEC and RAND Europe*, 2012.
- [80] M. Gorenberg, "A Modern Approach to Maximizing Spectrum Utility and Economic Value", in N. Kroes (ed.), *Digital Minds for a New Europe*, http://ec.europa.eu/commission_2010-2014/kroes/en/content/digital-minds-new-europe, (accessed November 2014).
- [81] Radio Spectrum Policy Group, "Report on Collective Use of Spectrum (CUS) and Other Spectrum Sharing Approaches", *RSPG11-392 Final*, November 2011.
- [82] W. Flury, "The Space Debris Environment of the Earth", in D. McNally, *The Vanishing Universe*, Cambridge, Cambridge University Press, 1994.
- [83] G. Schmid, "On the Existence of a Global System for the Interception of Private and Commercial Communications - ECHELON Interception System", *European Parliament: Temporary Committee on the ECHELON Interception System*, 2001/2098(INI).

- [84] S. Rehman, "Estonia's Lessons in Cyberwarfare", US News, January 14, 2013.
- [85] URSI, "White Paper on Solar Power Satellite (SPS) Systems", Report of the URSI Inter-Commission Working Group on SPS, <http://www.rish.kyoto-u.ac.jp/SPS/WPReportStd.pdf>, (accessed May 2015).
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