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EVOLUTION OF SPECTRUM MANAGEMENT CONCEPTS

Ryszard Struzak
National Research Institute for Telecommunications, Warsaw, Poland, r.struzak@ieee.org

Abstract: Current problems of spectrum management are discussed: licensing vs. license-exempting, spectrum planning vs. flexible spectrum use, spectrum market vs. free spectrum. Focus is on the impact of new technologies and international aspects.

Keywords: Radio networks, Spectrum engineering, Spectrum management, Access to radio spectrum, Coexistence, Signal hyperspace

1. INTRODUCTION

How the radio frequency spectrum is managed, has a strong impact on radio communications. It is thus no surprise that the current spectrum management practices generate numerous discussions and improvement proposals. My Google browser showed 486'000 items in response to keywords "*spectrum management*". The proposals embrace a wide variety of concepts, from the private spectrum ownership up to a free spectrum commons. I do not intend to address here all of the many issues raised; such an exercise would require far more space than is available. Instead, I will focus on extracting what I believe is important to understand better the problem.

This text bases on an earlier publication [1] and starts with reminding the origins of spectrum management. Then a short discussion of administrative regulation, spectrum market, and open spectrum doctrines is given with due regard to international aspects and impact of new technologies. A new abstract model of the spectrum management process is presented, taking into account an engineering viewpoint. The closing part contains conclusions, acknowledgment and few references.

2. ORIGINS

At the beginning, the radio frequency spectrum was a commons open to all. Everybody had free access to it with no bureaucracy or access fees. Interoperability was the main problem. The open spectrum concept, however, did not continue for long. Primitive status of technology and knowledge of those times could not cope with radio interference that occur when the radio signals of one spectrum user degrade performance of another user's radio. As spectrum use was growing, so did the problem of interference fuelled by competition and greediness.

An interference victim reacted usually by raising the signal power, which initiated a chain reaction and "power race" among the radio users. Of course, the victim could negotiate with the offender, but negotiations are not easy when one of the negotiating parties must accept extra costs and/or efforts. And it is often difficult to agree upon the responsibilities, as numerous interference mechanisms are possible and many factors are involved. Consequently, interference problems must often be solved before court, and litigations are complex, long, and costly.

It was soon realized that the interference prevention *ex ante* is better than the correction of interference effects *ex post* and the open spectrum doctrine was replaced by administrative regulations. According to the new doctrine, the access to, and uses made of, the radio frequency spectrum must be controlled. Military and governmental entities were the first users of radio so it was natural that the state assumed that control. The state set the necessary policies, laws, and regulations, complemented by technical and operational standards and enforcement mechanism. This was the beginning of what is known now as spectrum management. Because radio waves ignore political borders, the issue was soon internationalized. It took only five years after the first trans-Atlantic radio transmission in 1901, when an international radio regulatory conference was called to Berlin.

3. REGULATION

This section discusses briefly administrative regulations, licensing, and log-term planning, with due regard to international aspects and impact of technology.

3.1. Why Regulations?

In addition to avoiding the interference, there are other major reasons to regulate telecommunications. Haucap and Marcus indicate three: (1) to protect society from any abuse of market power, (2) to achieve social objectives such as universal services, and (3) to provide a framework for the management of shared resources (e.g. the spectrum, internet domain names, or telephone numbers) [2]. Peha reminds that the regulations compel the standardization of equipment and transmission methods. This in turn assures a mass market for radio equipment and facilitates radio services across continents [3], which makes radio services cheap and popular. There is also another aspect, often disregarded. Those who already use the spectrum are not interested in loosing their privileged situation and require their investments (and profits) to be protected by regulatory provisions.

3.2. Administrative Regulation

The present spectrum management concept stem from a series of international treaties. The Convention of International Telecommunication Union (ITU) with associated radio regulations and other documents is most important here. It represents consensus reached in the process of continuing negotiations among governments with the participation of private sector. The advantage of consensus decision-making is that it encourages efforts to find the most widely acceptable decision. Main disadvantages include large time required to develop a consensus decision, and the tendency to use ambiguous language on contentious points in final agreements that makes their future interpretation difficult.

According to the ITU convention, the radio frequency spectrum is a common heritage of humanity, accessible at no cost (for the governments). The way it is used is negotiated at the ITU radio conferences, following the one country – one voice rule. However, each government is sovereign in controlling the access to, and the uses made of, the radio frequency resources over its own territory. At the same time, each government is responsible for discharging of the obligations defined in the convention and in administrative radio regulations annexed to it. All governments – signatories to the ITU convention agreed to allocate different parts of the radio frequency spectrum to different uses or “services” through the famous ITU frequency allocations tables [1].

3.3. Licensing

The governments control the uses made of the radio frequency spectrum by assigning specific its portions to specific users. This is done through an exclusive license issued for each radio station or group of stations, usually for a fee and for a limited period. The license specifies essential characteristics of the station, such as the location, frequency or power level. The governments also impose often obligatory equipment authorization. They also specify the category of material for emission. The assigned portion of the spectrum can be used only for the purpose specified in the license and the license may not be sold or leased to others. Some equipment, such as e.g. short range devices, may be license-exempted. If a license is to be recognized internationally, it must be notified at the ITU.

In some regions and frequency bands, the government has to choose from among a number of licensee candidates. One approach is the priority principle, known as the first-come first-serve rule. Any newcomer has to adapt his proposed services to the pre-existing situation. That concept is still in use at the ITU international notification process. “Beauty contest” relies on comparative hearings. It bases on the value, usually social one, of the proposed usage. The government awards licenses to those it believes best serve the public interest. In recent years, some countries were selling licenses to the highest bidder i.e. to that one who offers the highest price through auctioning (which is a kind of a wealth criterion). However, maximizing revenues is not always in the national interest, as Peha rightly noted [3]. The auctioning of the radio spectrum relieves the government from social obligations, is simpler to apply than the beauty contest, and may be a source of considerable revenues. The auction of licenses for 3G mobile communications in 2000 netted the United Kingdom government US$ 35 billion in revenues. This amount, however, must be paid back by the end users of the services. With a hypothetical company that buys a license in the U.K and in addition makes business say, in South Africa, it would be a hidden subvention of the British government by South-Afrikaners!

3.4. Planning

The radio frequency spectrum is often considered a limited resource because the number of licenses granted is restricted. In fact, the restrictions result from the ways we exploit the radio spectrum and manage it. To assure its effective use, various planning algorithms, methods, and simulation tools have been developed. The ITU spectrum allocation process is a kind of a long-term planning. For some services, the planning goes much further than frequency allocations. For some specific services and frequency bands, detailed plans are set with key technical and operational characteristics of stations defined. Plans for terrestrial broadcasting services in Europe, or regional plans for satellite broadcasting service are examples.

Whereas planning approach is widely accepted on company level, its application at international level is often criticized. The reason lies in the planning horizon. Company plans are usually short-term ones, but international plans reserve frequencies (and/ or orbital positions) long before their use. This is criticized for two reasons. First, with fast changing technology, there is no way to predict with a reasonable precision the future needs, and the reserved frequencies could never be used as originally intended. Second, the planned frequencies are useless as long as they are not put into use. In the meantime, they are blocked which creates additional barriers to innovative projects. On the other hand, advocates of the planning approach indicate that plans offer a precious predictability. Developing countries that are now not yet ready to deploy satellite services are afraid that without such plans there will be no orbital positions/ frequencies available for them in future. Predictability is also valued by investors that are afraid to put money in projects without assurance that only internationally agreed plans could offer.

4. SPECTRUM MARKET

This section deals with economic mechanisms proposed to encourage better uses made of the spectrum. Neo-liberal economists argue that the radio frequency spectrum should be treated in the same way as all other resources. In analogy to land management, they suggest that the spectrum should be privately owned. A spectrum market should be created, in which spectrum parcels could be bought, sold, subdivided and aggregated at will [4, 5]. How these parcels will be used, would remain at the owner's discretion only. Such a flexible use and "the invisible hand of the market" will assure the most efficient use of the resource, according to the proponents. The opponents to that approach underline that it would certainly facilitate the profitable resource use by rich ones, but there is no evidence that it will adequately address social needs, or will not guide to a monopoly. Another major problem with the privatization of the spectrum is inherent difficulties with the precise definition of the property protection rights.

In 1989, New Zealand was the first country to expose its entire telecommunications market to full unlicensed competition since the early days of radio. Evaluating that decision fifteen years later, Haucap and Marcus wrote, "*outright elimination of telecommunications regulation is a bad idea*" [2]. Critics of privatization indicate that even in the land management, places valued by the society, such as public roads or natural reservation parks, are still keep as commons, and, cooperative farms still co-exist with private ones.

One might expect that privatization of the radio spectrum would lead to an international spectrum market. Then, the ITU working arrangements would need to be replaced by the WTO General Agreement on Trade in Services (GATS). Unlike the ITU, the WTO has significant power to enforce its decisions through trade sanctions against those who fail to comply with its decisions. However, WTO treaties have been accused of a partial and unfair bias toward multinational corporations and wealthy nations and the WTO is criticized as being the tool of powerful corporate lobbies.

The idea of making money through selling some rights to radio waves is not new. The ITU chronicles registered, for instance, a proposal to collect "transit fees" for radio waves travelling from one country to another over the territory of a third country. Another proposal suggested "parking fees" to be paid for the right to transmit radio waves from a geostationary satellite orbit. The fees would be collected by the government of the country just below the satellite.

5. SHARING FREQUENCIES

5.1 Single-Frequency Networks

In terrestrial broadcasting, a network of transmitters is usually required for a country-wide coverage. Even if all stations in the network transmit the same programme content, each transmitter operates at a frequency channel that differs from those used by the neighbouring ones. It is known as a multi-frequency network (MFN). To avoid mutual interference, the frequencies, locations, and powers of the stations must carefully be coordinated in MFN networks. In Europe, for instance, broadcasting networks have been coordinated in 1961, at the ITU Stockholm conference. It is surprising that the Stockholm Plan and Agreement has served well since then for so many years. (It is a heavy argument in discussion on merits/ demerits of the planning approach to spectrum management.) Only when digital technology become mature, the signatories of Stockholm Agreement decided to put in place a new agreement and frequency plan for digital broadcasting (DVB-T and T-DAB) in Europe, Africa, the Middle East, and partially in Asia. Extensive work is now underway, culminating in the ITU radio conference scheduled for 2006.

The new plan will use a concept of a single-frequency network (SFN). In such a network, two or more stations transmitting the same contents share a common frequency channel, which offers a significant economy of the radio spectrum. This was impossible earlier, when the Stockholm plan was negotiated, but the progress in radio science and technology made it feasible now. The price to be paid for better use of the spectrum is increased complexity. Each station must run synchronously with the others to avoid interference, and synchronization of multiple signals is difficult. With ideal synchronization, the receiver processes signals from the neighbouring stations and add them to the wanted signal, which can be written as follows:

$$C = B\log_2\left(1+\frac{S_0+\sum_{i=1}^{n}|k_i|S_i}{N+\sum_{i=1}^{n}(1-|k_i|)S_i}\right) \qquad \text{(Eq. 1)}$$

Here, C is the potential channel-capacity, B is the bandwidth of the channel, S is the signal power, N is the noise power, i is the signal number (i = 0 for the wanted signal), k is the correlation coefficient with the wanted signal; n is the total number of signals. Note that for n = 0, the equation reduces to the Shannon formula. With all signals fully correlated (k = 1), the equivalent power of the wanted signal increases; with signals completely uncorrelated (k = 0) - the equivalent noise power increases.

5.1. Living with ISM interference

The new SFN plan will follow the standard ITU frequency bands that have been allocated to the broadcasting services many years ago. However, there are cases where a frequency band can be shared even in derogation of the ITU table of frequency allocations. Article 4.4 of the radio regulations says that a station can use any frequency under the condition that it "*...shall not cause harmful interference to, and shall not claim protection from harmful interference caused by, a station operating in accordance with the provisions of the Constitution, the Convention and these Regulations"*. This powerful provision is exploited in two distinct ways. One solution is restricted to so-called ISM-frequency bands, where no interference limits exist; we discuss it in the following section. Another one consists in the usage of weak signals, too weak to cause interference, as discussed in the next section.

The ITU radio regulations allocate a few frequency bands for non-communication applications in industry, science, medicine and at home. These are known as ISM applications [6]. No limits are imposed on radiations from the ISM equipment (except for those dictated by the health requirements), and any radio communications must accept ISM interference, no matter how strong. Without any regulatory protection, radio communications in the ISM bands rely solely on the built-in interference immunity of the systems used.

In the ISM bands, most governments resign from individual licensing of radio stations. However, they impose limits on the power radiated (EIRP). Actually, this restricts radio communications to relatively short distances only. In spite of these restrictions, license-exempted radios, such as the Bluetooth, wireless local loop (WLL) of the 802.11 family, and other short-range devices, have enjoyed enormous success. However, the potential benefits of these advanced technologies cannot be exploited in full because of the national spectrum management rules. For instance, an external directive antenna added to a standard WLL device can extend its range up to ten or more kilometres (hundreds-kilometre-records were noted). In regions where no telecommunication infrastructure exists, it would offer the most cost-effective access to the global network. Broadband Internet, voice, video, and data communications would be accessible for a tiny fraction of the cost of alternative solutions. However, the use of such antennas is illegal in most countries, no matter if it actually creates interference or not.

Why the national regulations require the communication equipment to limit the power radiated and at the same time allow unrestricted radiation from the ISM devices is unclear. The avoidance of interference seems an unconvincing reason. Even if it can be accepted as justification in densely-populated (and rich) regions, it seems curious in remote, rural, and poor areas, where only a few radios, if any, may use the ISM bands. The issue deserves a closer examination.

5.2. Hiding in Noise

The Ultra Wide Band (UWB) communication technology offers a different approach to the spectrum sharing. Instead of using signals of high spectral power density and narrow frequency band, it uses signals of low spectral density and wide band.

In the UWB systems, the signal is spread over frequency bands with such a low spectral power density that the UWB signals are hardly noticeable by the conventional narrow-band systems. Various technologies have been developed: the wide-band CDMA, OFDM, or impulse radio are examples. The USA has legalized civilian UWB systems in 2002 and set radiation limits for them that are widely followed in other countries. However, the technology is still in its infancy. One concern is the issue of cumulative effect of potentially large number of UWB users co-existing with licensed spectrum users. Further developments may require the present limits to be revised [11].

6. CONCEPTUALIZATION

The process of spectrum management determines what radio services are to be provided, where, when, and at what conditions. The administrative regulations squeeze the radio users in the allocated frequency band tightly (for efficiency), but not too tightly to cause interference. That system works well as long as no new services (or new technologies) are proposed. It fails when new applications appear, for which no frequency bands have been pre-allocated yet. As a remedy, Matheson proposes the spectrum market and flexible use doctrine, discussed earlier. He associates closely his doctrine with "electrospace". The electrospace is a hyperspace of seven variables: (1) frequency, (2) time, spatial location {geographical longitude (3) and latitude (4) and altitude (5)}, radio wave angle of arrival azimuth (6) and elevation (7).

The concept of hyperspace might be useful to explain how technology impacts the spectrum management. However, we believe there should be *no limits* imposed on the number of its dimensions, so that additional variables may be included as technology develops. It might be any set of orthogonal variables by which the radio signals can be distinguish one from another. Power, polarization, modulation, coding, spreading etc. are examples, in addition to the seven variables listed by Matheson.

Let start with a simplified model of a radio communication channel. The transmission of messages via radio can be considered as a series of mappings in an abstract hyperspace. These mappings can be grouped in three categories. First, the transmitter maps the original message into the radio wave radiated by the transmitting antenna.

Second, the propagation-process maps that wave into the radio wave incident at the (distant) receiving antenna. The propagation mapping introduces noise, distortions, reflected and foreign radio waves, Doppler Effect, latency, fading etc. Most of these effects are uncontrollable. The incident radio wave at the receiver is thus composed of the wanted signal and a set of unwanted signals and noise.

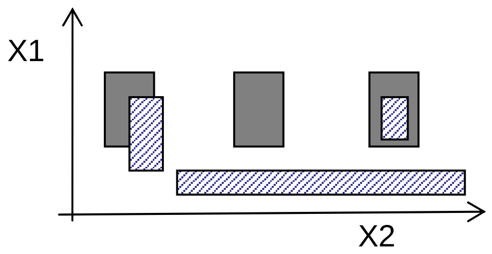

Figure 1. Projection of hyperspace of incident radio wave signals at the receiver on plane (x1, x2). The dark rectangles represent the receiver's reaction window.

Third, the receiver maps the incident composite wave into the recovered message (with an acceptable error). For that purpose, the receiver applies pre-defined signal recovery algorithms and propagation data and responds only to those wave components that fall into its reaction window. It ignores all other components that are uncorrelated with the wanted signal (e.g. those that appear at wrong moments, at wrong frequency bands, etc.). Figure 1 is a projection of the abstract multidimensional space on plane (x1, x2). "x1" and "x2" may be interpreted as frequency and time. Actually, it may be any pair of orthogonal variables used to distinguish the wanted signal from unwanted ones. A projection is used here because it is impossible to show more than two orthogonal variables on a plane sheet. Note that the receiver reaction window may consist of a single opening (analog systems) or a series of non-contiguous openings (digital systems).

The receiver rejects an unwanted signal if it is sufficiently distant from its reaction window in at least one variable; the "sufficient" distance is system/ technology-dependent. That distance might be expressed in frequency-difference as in the multi-frequency networks and FDMA systems. It might be the power-difference, as in the ultra-wideband systems sharing frequencies with narrow-band systems. It might be the time-difference as in the TDMA systems, or the distance between the spreading functions as in spread-spectrum systems. The distance might also be expressed in function of the correlation with the wanted signal. The more dimensions the hyperspace has, the more flexibility in sharing the radio frequency spectrum is achieved.

The spectrum management process relies on the reverse-mapping in that hyperspace: the incident radio-waves at the receiver are reverse-mapped back to the transmitter domain. In that process, the distances at the receiver translate into distances in the transmitter domain (frequency-difference, time guard-bands, geographical distance, power-level difference, etc.). Yet, the reverse-mapping process does not result in a unique solution. A number of transmitter-receiver station pairs, or their deployments, may give the same results as concerns the signal distances at the receiver, although they may differ substantially in other aspects. It is the art of spectrum management that helps in selection the most practical combination.

7. FUTURE SPECTRUM MANAGEMENT

Although we are unable to predict exactly what will happen in the future, we know that the current trends will continue for some time. And we witness three major trends: (1) the spectrum management rules are being built-in in the equipment hardware and software so that they are followed automatically; (2) the competition in the spectrum use is being replaced by a collaborative approach; (3) the competition among the spectrum users is being replaced by competition among the equipment manufacturers.

The software-defined radio (SDR) created a vision of self-organizing radio communication networks, a concept not fully explored yet. Future networks will monitor the environment, communicate among themselves, and reconfigure dynamically, to fulfil their mission in the best possible way, following a common set of policies, algorithms, etc. Such networks will be behaving like an ant colony, where each ant assists any other fellow ant in fulfilling its tasks.

With a single radio link, the only possible way to optimize the spectrum use consists in the adaptation of the link variables (characteristics) to the environment. Along that line, even today, most of WLL networks require a station to listen before sending, or to decrease power radiated (in order to not cause interference), or to change the operating frequency (to avoid interference). Such a cooperative behaviour contrasts strongly with the ruthless competition of the early years of radio. New business models of cooperative "open networks" are appearing [12]. The spectrum of radio waves is a shared medium and cooperation among its users offers significant benefits: the more of cooperation, the less of interference. Ideally, every radio station should facilitate the operation of all other stations, like social insects do it. A wider application of cooperative networks and real-time sensing would eliminate major drawbacks of the present spectrum management.

First, they would get rid of exclusive and fixed frequency rights that make a licensed frequency band inaccessible even if it is actually not used. This would be an alternative way of the implementation of the "flexible use" doctrine without touching the controversial issue of spectrum privatization. For the time being, however, the fixed frequency allocations/ assignment and exclusive frequency rights make it impossible.

Second, they would solve the problem of lacking real data on the radio channel propagation and traffic. Real-time monitoring of local environment will produce the real-world data to replace approximate models and assumptions that are used today.

Third, they would communicate among themselves, negotiate their coexistence mode, and exchange necessary data for optimization. Such a dynamic cooperation does not exist now. Separate radio networks are unaware of the policies and protocols of the other users of the radio spectrum and no rational usage of the radio spectrum is possible without the users' full cooperation. Real-world, real-time data on communication channel and cooperation combined with optimized algorithms, would assure a rational use of the spectrum resources. When all this became popular, the need for human involvement in spectrum management will drastically be reduced.

8. CONCLUDING REMARKS

We discussed the evolution of spectrum management system, its major drawbacks, and some improvement proposals. Economists believe that market mechanism will solve all problems; that is strongly opposed by the proponents of the open spectrum doctrine that believe in technological solutions. The success of services in the license-exempted ISM bands has generated a great interest in possible coming back to the open spectrum concept with new technology [7, 8, 9, 10]. For many, the open, free access to the spectrum is superior over the present administrative approach and over the proposed market-based approach. Indeed, the phenomenal success of radio in recent years has been only due to the application of smart technology, and not due to changed administrative regulations, or improved licensing, or spectrum auctions, or due to spectrum ownership. In this respect, Matheson considers that different regulatory models will coexist; it would be a bad idea to place all the spectrum under a single set of rules, for the same reasons that different types of land rules are needed to serve various land uses.

The abstract hyperspace model of the spectrum use may prove useful because of its simplicity. An increase in the number of the hyperspace dimensions results in a greater flexibility in spectrum management.

More and more spectrum management rules are built-in in the equipment hardware and software. One day, self-organizing radio networks will make most of the current spectrum management practices redundant. However, this probably will not take place sooner than the massive investments already made in radio pay off and interests of the present spectrum users are duly accounted for.

Technology is ideology-neutral. The SDR, quantum electronics and nanotechnology will work as well with the spectrum-market, as under the open-spectrum doctrine. Technology may help in solving the spectrum management problems, but is unable to solve it alone. The society is composed of various groups, each with its individual interests, goals and world views. Those, whose needs have been satisfied, are against any change, as any modification would threaten their acquired benefits. Newcomers, with no access to the spectrum resources press for changes. What is the best for one group is not necessarily good for another. The spectrum management practices not only reflect the status of technology, but also the relative balance of powers of the competing interest groups in the society.

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Ryszard Struzak, former Vice-Chairman of the Radio Regulations Board of the ITU and former Co-Chairman of the URSI working group on the spectrum utilization and management, has been a full professor at the National Research Institute for Telecommunications, Poland, and the Co-Director of the School on Wireless Networking at the ICTP, Italy. www.ryszard.struzak.com