Paper

Trends in Use of RF Spectrum

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Abstract—This paper reviews possible improvements in the use of radio waves for carrying information from an engineering viewpoint. A few new concepts are proposed, which reduce the problem to an arrangement of solids in a multidimensional space.

Keywords—radio communication hyperspace, radio frequency spectrum resources, radio regulations, spectrum engineering, spectrum management.

1. Introduction

This paper deals with the use of the radio waves for information transmission, a problem under discussion since many years. It is also known also as spectrum management, or management of the radio frequency (RF), or RF spectrum resources. (We use interchangeably the terms *radio waves* and *RF spectrum resources*.) There is opinion that these resources are not used as effectively as they should and could be, and various improvements have been proposed. The issue attracts more and more attention as new technologies appear that can change dramatically the way the RF spectrum has been used and managed.

We seek here general trends rather than detailed analysis of specific improvement proposals. We begin with a short summary of the present spectrum management and its improvement proposals. Next, we move to engineering aspects. We generalize classic notions of the signal mask, receiver selectivity, and transmitter coverage and reduce the problem to an arrangement of multidimensional solids that should be "packed" tightly together, but not too close. Then, we discuss some possible improvements due to scientific and technological progress. The paper is based on the presentation prepared for the URSI General Assembly [1]. Opinions expressed here reflect personal views of the author.

2. Radio Regulations

The first radio regulations were created at the 1903 Berlin conference. All those interested gathered there to assure that the uses made of the radio waves will not infringe their vital interests. It was only two years after the first wireless communication across Atlantic astonished the world. Since then, the significance of radio increased enormously. The International Telecommunication Union (ITU) has been created. The Berlin agreement has been replaced by the ITU convention and radio regulations. These are now legally binding in some 190 countries around the world and this section offers their short summary. More details can be found elsewhere, e.g., in [2], [3].

2.1. International Regulations

The ITU regulations represent the collective wisdom of all the ITU members. The radio waves and the geostationary satellite orbit (GSO) (since 1963) are treated as *common heritage of mankind* that must be fairly shared among all countries. On the international arena they can be used freely, without any restrictions, as long as it *"shall not cause harmful interference to, and shall not claim protection from harmful interference"* [3]. If however there is an interference threat, the regulations define principles on how, when, where and under what conditions their use should be allowed or denied. In essence, the radio regulations are a collection of the principles, requirements, procedures, and plans, commonly agreed among all those interested as necessary for the fair shared use of the RF spectrum and geostationary satellite orbit. As that use depends on the progress in science and technology, the ITU regulations are reviewed every few years. Governments and private sector entities work together toward a compromise, and the participation in the work is open to all those interested. For instance, the preparations for the 2007 World Radiocommunication Conference started 5 years before the conference and resulted in a few thousands modification proposals. The proposals were considered by some 3000 experts from 161 countries, gathered in Geneva, Switzerland. The conference documents count some 12000 pages and the final acts alone – 500 pages. These numbers illustrate how the task is important and difficult.

A conflict-free use of any shared resource implies the exchange of information about the actual and planned uses, collaboration and compromise. The ITU procedures and common planning exercises create a practical framework for that. The system makes it possible to use the RF spectrum (and the GSO) in an orderly and transparent way. Additionally, the ITU standardization activities lead to standard transmission methods, which in turn assures a mass market for equipment and facilitates radio services across the globe, making them cheap.

Uses made of the RF spectrum (and the GSO) that require international recognition are to be registered in the ITU databases. Every new proposal is examined in view of potential conflicts with those notified earlier in the database. The system bases on formal declarations, and does not foresee any monitoring by an independent body. The declared use can differ significantly from the actual use, and most often it does differ, which leads to apparent scarcity of free frequency bands and orbital positions. It is a weak point of the ITU system. Finally, we note that the protection of passive services depends totally on administrative regulations.

2.2. National Regulations

The ITU regulations are a part of an international treaty that governments commit to observe. In most countries they are complemented by national regulations. The purpose is to achieve specific political, economic, or social objectives. Assuring universal access and protecting the investments made, are examples of such objectives. Most national regulations introduce licenses and fees for the access to the RF resources. Only minuscule parts of the RF spectrum (so-called ISM frequency bands) are exempted from the licensing obligations. These are allocated for industrial, scientific, medical and domestic applications of RF waves.

Various licensing criteria are in use around the world. One is the seniority or first-come, first-served principle. Another one is the criterion of *merits* determined through comparative hearings, known also as *the beauty contest*. In some countries licensing is treated a source of revenue and licenses are auctioned. The access to the resources is given to those who pay the most, which is a form of the wealth criterion. In reality it is an extra tax, which increases the governmental budget without any effort (an idea popular among politicians). It also augments the price of radio services and detours money that otherwise could directly be invested in the telecommunications.

2.3. Private Spectrum

A number of economists consider privatization as the best way to improve the use of the RF spectrum resources. They request the spectrum should be ruled by market forces only, as it is with the real estate. It should be traded, aggregated, divided and freely used for a wide range of owner-selected services [4]. However, Elinor Ostrom, the 2009 Nobel Prize laureate in Economic Sciences, challenged that view, showing that common resources can be successfully managed without government regulation or privatization. Privatization is not a new approach, as it prevailed in the pre-regulation era. At that time, it resulted in the power race and chaos and was abandoned. In view of their crucial role played in the safety, security, and wealth of nations, doubts are expressed if the privatization of RF resources serves as well the society as its advocates claim. A patchwork of incompatible proprietary solutions can replace the worldwide standards and wipe out all benefits they offer. Analogy to real estate is misleading, as it ignores the electromagnetic interactions [5]. The borders of tradable piece of the spectrum cannot be unambiguously determined as in real estate.

2.4. Spectrum Commons

We mentioned that every nation enjoys free access to the RF spectrum resources as they are considered a common heritage of the humanity. Advocates of the open spectrum doctrine propose that principle to be extended over every citizen. The concept is not new, like the privatization idea. Indeed, before the regulations, radio waves were a commons and were appropriated as needed, without any formalities. The concept of free (unregulated) use was abandoned because of a flood of litigations. At that time, the radio science and technology were too primitive to cope with the spectrum sharing problem. However, knowledge and technology of today make it possible to come back to the idea, at least in some applications. Wireless computer networks based on the IEEE 802.11 standards is the best example. They are extremely successful because their use does not require any license (they operate in ISM – industrial, scientific, and medical frequency bands).

The doctrine does not sweep away the market. It only restricts market forces to the equipment market, leaving aside the radio waves; much like in the sea transport, where ships and harbors are privately owned, but the use of ocean waters is free and open to everybody. With current technology, the open access can offer only the *best effort* level of the quality of service, which decreases as the number of users increases. Instead of denying the access to the latecomers or those less wealthy, it forces all the users to share degradation of the quality of service.

3. Radio Communication Hyperspace

Three signal-related concepts are discussed in this section: signal solid, propagation mapping, and reception window.

3.1. Signal Solids

Message to be transmitted from source to destination is a continuous function of continuous time, or a sequence of symbols, i.e., a function of discrete time. The transmitter maps it into a radio wave signal, using modulation and other operations. Examples are the analog-to-digital conversion, signal compression, and scrambling. That process involves a number of independent variables. For instance, the signal engages four variables: frequency, amplitude, phase, and polarization of the carrier radio wave. The widths of the frequency band and time slots the signal occupies are other variables. These variables create a multidimensional space, in which the transmitter concentrates the signal energy in some specific regions. We call them *signal solid*. It is easy to notice that it is a generalization of the signal mask which, in our convention, is a projection of the signal solid on the plane frequency-energy. A multidimensional solid cannot be shown on a plane sheet without deformations, but it can be depicted in a series of plane projections, or cross section cuts, assuming fixed values of other variables. The same reasoning is applicable to all signal-related concepts such as the station coverage for instance.

3.2. Propagation

The radio wave propagates along its path loosing energy due to the absorption, spatial spreading, diffusion, and shadowing. The reflection and scattering alter it too, as does so the Doppler effect, if the transmitter, receiver, or reflecting objects are moving. The finite velocity of the wave causes the signal latency. In summary, signal solids change dynamically the form, size, and position. Most of these effects have random components that can be described only by their probability distributions. Propagation-related effects distort the signal so that the received message differs from that originally sent. The difference, often expressed as bit error rate, is closely related to system performance measures such as transmission range or speed. The transmitting and receiving stations correct the predictable transmission errors by applying appropriate algorithms and data built-in in their hardware and software. In the anticipation of signal distortions, a multitude of operations are used for that purpose, such as modulation and demodulation, coding and decoding, or spreading and despreading. Clearly, the more the system "knows" about the expected distortions, the more efficient the error correction.

3.3. Reception Window

The receiving station creates a multidimensional "window" that – ideally – is transparent to the intended signal and opaque to all other signals. It is easy to note that this is a generalized selectivity mask of the receiver, whose classic definition is restricted to frequency and energy. In analog systems, the reception window is usually a single opening. In digital systems, it consists of a series of non-contiguous openings, stationary or changing in time. All physically realizable systems have also spurious windows through which unintended signals can penetrate. Normally, the intended signal must fit exactly the receiver window in all dimensions as foreseen by the system design. Any overflow or underflow leads to undesired effects. All signals that do not fit that window in at least in one dimension are to be rejected. Examples of such signals are those that arrive at wrong times, at wrong frequencies, from wrong direction, or with wrong polarization.

4. Technological Improvements

This section presents some comments on possible improvements and on the role of science and technology.

4.1. Electromagnetic Compatibility

Improved use of the RF resources requires improved electromagnetic compatibility (EMC) engineering methods and tools. They are necessary to identify, analyze, predict, prevent, and reduce signal collisions. It involves radio wave propagation because, for instance, shadowing by natural obstacles can efficiently attenuate unwanted signals in terrestrial microwave applications at no extra cost. It is the least expensive reduction method of unwanted signals, but it requires detailed digital models of the terrain irregularities and man-made objects, and careful selection of the station locations.

4.2. Redundancy

There are techniques that improve the spectrum use by optimizing the quantity of information sent per hertz, or by reducing the quantity of spectrum needed to send bits at a specified rate. Signal compression, for instance, removes redundant bits. The radio wave propagation process can do the opposite – can add extra redundancy due to reflections. The received wave is composed of a number of replicas of the original sent. Each replica arrives at a different time, from different direction, and with different polarization, and interferes with the others. The interference can be destructive, when the waves cancel each other, or constructive, when the waves add together. Various techniques exploit it. The diversity reception, intelligent antennas, single-input-multiple-output (SIMO) systems, and multiple-input-multiple-output (MIMO) systems are examples. The idea of signal summation lies also behind the concept of multiple-input-single-output (MISO) systems, as well as of single-frequency networks (SFN), where two (or more) stations transmitting the same content share a common frequency band coverage region.

4.3. Unwanted Signals

The radio wave carries the intended message to its receiver but does not stop there. It continues farther, and can reach other receivers, where it is neither expected nor wanted. Unwanted signals interact with the intended signal and add to the transmission error. As the propagation medium is shared by all the constituencies of the environment, all the radio waves they radiate coexist and the resultant wave follows activities of the individual radiation sources. That introduces additional random factors to the process. If the characteristics of these signals are known or foreseeable, their negative effects can be eliminated or reduced by appropriate system design.

4.4. Spurious Radiations

Radio equipment produces spurious radiations due to technical imperfections and laws of physics. These do not carry any useful information, but occupy the spectrum. (Man-made ISM emissions fall in that category.) Their reduction increases the equipment cost, which does not translate directly into any tangible benefit for the equipment owner. The beneficiaries are the owner's neighbors. The spurious radiations are thus never completely removed. On the other end, receiving stations have spurious windows that make it possible for unwanted radiations to penetrate and disturb the system operation. Like the unwanted signals from transmitter, they result from technical imperfections and are tolerated because of the cost factor. It is the role of the spectrum managers to keep strict restrictions on such radiations and responses for common benefit. It is not an easy task as it usually requires equipment replacing, which always create an economic loss to someone.

4.5. False Signals

Radio waves interact when applied to a non-linear element. They mix together, and produce a number of false signals at frequencies $F = (nF_1 \pm mF_2)$ in the case of two signals at frequencies F_1 and F_2, where n and m are integers. Such mixing can involve more than two true signals and produce more spurious products. Usually, their amplitudes are much less than the original true signals and decrease as the order of the mixing product $(n+m)$ increases. Although the spurious do not carry any useful information, they can interfere with useful signals as they were true signals from transmitters.

4.6. Signal Separation

It follows from previous sections that any unintended signal at the receiver must lay outside of the receiver window, at a safe distance from it, at least in one dimension. The safe distance is application and technology dependent and is defined by the system design. It may be the frequency separation, code separation, direction separation, etc. In ultra wide band (UWB) systems, for instance, it is the difference in the signal (spectral) power density: the UWB signal has power density much smaller than that of the (intended) narrow-band signals. The signal separation is often realized in terms of station coverage. Traditionally, that coverage is defined as the geographical area within which service from a radio communications facility can be received. In this context, the service and signal are interchangeable. As a consequence, the concept of signal multidimensionality leads us to the idea of multidimensional coverage solids (Fig. 1). Only three variables are shown in the figure: two geographical coordinates and frequency. The cylinders represent the coverage of three omni directional radio communication systems A, B, and C.

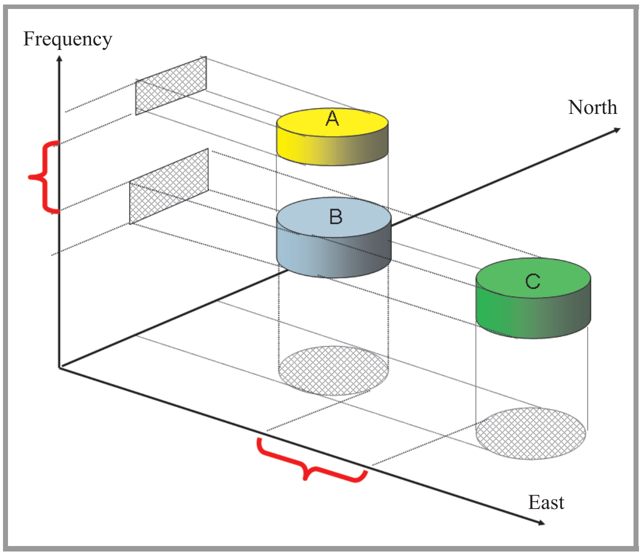

Fig. 1. Separated coverage solids of tree stations A, B, C.

Stations A and B share a common geographical area but are separated in the frequency domain, B and C share a common frequency band but serve separate geographical areas. The coordinate axes may represent also other variables such as time or polarization. This representation applies to all variables, by which one radio signal can be distinguished from others.

The coverage is determined by the energy relations among the desired and unwanted signals and system noise. As a result, the coverage of an isolated station and the coverage of the same station in the presence of neighboring stations can differ significantly (see, Fig. 2). The figure presents results of computer simulation of that effect assuming all stations are identical. In this example, the increase of the number of stations can result in the reduction of the original coverage up to 25% of its original value. To lower the coverage losses, separation distances must be increased. The example shows that the station coverage cannot be determined confidently once for ever. It depends on, and varies with, the signal environment that changes unpredictably. If the station is a part of network, this remark applies to the whole network.

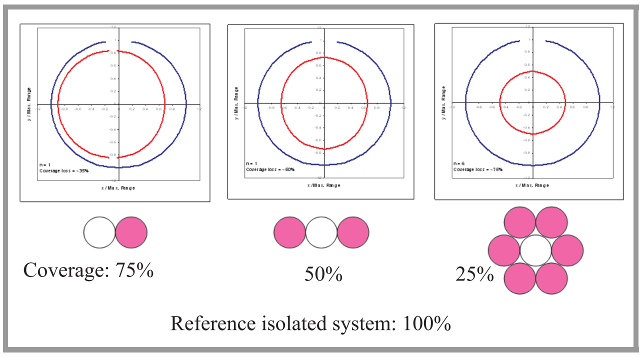

Fig. 2. Station coverage depends on signal environment.

4.7. Filling Holes

Digital signals appear in the time domain as disjoint forms: pulses, or groups of pulses (packets), separated by empty spaces. Time-division multiplex access (TDMA) uses these spaces to transfer two or more bit streams in the same (shared) frequency band. Band-limited signals are similarly represented by disjoint figures in the frequency domain. Empty spaces (*spectrum holes*) can be used to allow multiple users to transmit at the same (shared) time period. Frequency-division multiple access (FDMA) systems base on that principle. The same principle applies to systems that use directional antennas to fill in geographical coverage holes.

4.8. Packing Solids

To avoid harmful interactions, the signal solids must be separated by safe distances. On the other hand, they should be packed tightly together, to leave more space to other signals. Keeping the solids closely, but not too close, requires the signal sizes, forms, and positions to be precisely matched against each other (except for randomized systems). A common reference frame, such as the frequency and time standards, synchronization and harmonized access coordination schemes are crucial here.

4.9. Collaboration

In our hyperspace convention, the engineering task consists in the best arrangement of solids in a hyperspace. That is not possible without collaboration. Activities of ITU and other organizations have served that purpose since many years. Special techniques have been developed to optimize the frequency planning, coverage coordination, and communication protocols.

In modern systems, many of the common ITU collaborative coexistence rules are embedded in the equipment hardware and software. Neighbor-friendly medium access protocols, such as the scheduled access, access on-demand, or self-adaptive access are examples.

The adaptive approach implies a real-time monitoring of the signal environment. For instance, the carrier-sense multiple access (CSMA) systems verify the absence of other signals before transmitting. If a signal is sensed, the transmitter waits for the transmission in progress to finish before initiating its own transmission. Such a friendly approach is not new. It has been invented many years ago with primitive technology, in not-for-profit applications and passed a practical test of life in the radio amateur services.

4.10. More Variables

The signal frequency is one of physical variables, or dimensions, that decide on how the radio medium is used. It decides on propagation effects, on antenna performances and on the system cost, to a large degree. For that reason it first focused engineering efforts since the very beginning. The vital role of time became clear later, after the digital technology was developed. The number of signal dimensions is not fixed in advance for any specific radio system, as it depends on the technology applied by the system. Any physical variable by which radio signals can be distinguished one from another, can be exploited. The more dimensions used, the more degrees of freedom in the radio spectrum utilization, with potentially significant impact on the system costs. Future systems are expected to make wider use of greater number of these variables, which creates new research challenges.

4.11. Optimization

The geometrical abstractions proposed here may help in designing improved use of RF resources by future systems. The problem is related to mathematical optimization problems such as the tessellation, packing, or knapsack problem. A two-dimensional tessellation is a collection of plane figures that fills the plane with no overlaps and no gaps. In a packing problem, given objects are to be packed tightly into a container with minimal gaps.

In a knapsack problem, a collection of objects is to be selected from a given set in such a way that their total value is as large as possible. Also the development of the communication robots and intelligent networks is a challenge, where the mathematical game theory can be helpful. Appropriate mathematical models and optimization tools can facilitate the engineering task enormously.

4.12. Communication Robots

Signal sensing mentioned earlier is only a step towards flexible systems that adapt themselves to the changing environment and a number of concepts have been proposed. The software-defined radio, agile-radio, policy-defined-radio, dynamic spectrum access, and cognitive radios are examples [6], [7]. They monitor the environment (individually or in a group), sense the spectrum holes and estimate the channel-state. They use predictive modeling and interference threat analysis and select the best signal parameters, providing dynamic and fair spectrum sharing with other radios. They can also follow the local regulatory restrictions, if these and location information is stored in their memories.

This leads us to the concept of *intelligent communication robots* that work together and negotiate to assure the best possible use of the radio frequency spectrum according to given criteria. A further step is a network of such robots. Future self-organizing and self-learning networks, to which today's wireless ad hoc mesh networks evolve, have capacity to overpass all what we imagine today. This is possible thanks to *swarm intelligence*, based on the collective actions of the component systems. The individual robots will collaborate and exchange real-time information about the traffic and radio environment, like ants or bees, much better and much faster than spectrum mangers can. Signals will flow in three planes: data plane, control plane and knowledge plane.

4.13. Science and Technology

Today radio communication technologies base on the James Clerk Maxwell's (1831–1879) theory. However, physics has progressed enormously since the 19th century. Max Planck (1858–1947) introduced quantum theory. Albert Einstein (1879–1955) replaced the traditional notion of space, time, energy and matter by the interchangeability principle of matter and energy in four-dimensional space-time.

New ideas continue to appear changing our understanding of the world, as, for instance, the concept of the dark matter, or string theory. According to the theory, the electron is no more a material particle or wave function as we were taught, but consists of oscillating "strings". And string theory requires the universe of ten dimensions or eleven, and not four, as Einstein told us [8]. To derive tangible results from that progress, a number of practical application-oriented research programs have started, among which the quest for quantum computer is probably most popular.

5. Concluding Remarks

"There is no more spectrum available" – declared Herbert Hoover, then the US Secretary of Commerce, in 1925. As a matter of fact, it never was sufficient. At the Hoover's times, the new radio regulations were expected to solve the spectrum scarcity problem. Later, spectrum engineering was expected to do the same [9]. Today, some economists propose market forces as universal medicine to solve the spectrum scarcity problem. However, the scarcity relates to physical processes that do not change when the spectrum is public, or is privately owned. Economic mechanisms (and administrative rules) deal only with the way the RF spectrum is accessed, i.e., who has the right to use it and for what purpose. How efficient is that use decides the technology applied.

Radio technologies in use are determined by the status of science, by investment opportunities and business inertia, and by the balance between competing interests. The society is composed of various groups, each with its own world-views, deeply rooted in the past experience. Their interests and goals are often conflicting. What is the best for one group is not necessarily good for the others. Those, whose needs have been satisfied, are against any change that would threaten their acquired benefits. Newcomers, with no access to the radio spectrum, press for changes. Engaged are systems of values and preferences and there are no universally accepted criteria in dealing with such issues.

We have discussed here some technological improvements possible in the use of RF spectrum. In spite of all their advantages, the new technologies have a little chance for quick and universal introduction. Their high costs and enormous investments in old technologies, which still work and bring profits, are the main obstacles. For some time to come, we will thus continue to live with the present regulatory arrangements, most likely mixed with other approaches.

In spite of the spectrum shortage claimed since the beginning of radio, radio applications have developed enormously. It has been possible thanks to the progress in science and technology that did not say the last word yet. Not so long ago, in 2007, the first nano-radio has been built [10]. It is a single carbon nanotube, one ten-thousandth the diameter of a human hair that requires only a battery and earphones to tune in to a radio station. To what degree will quantum physics and nanotechnology impact the use of the RF spectrum resources? Nobody can answer such questions today. With the future, the only sure thing is that it will surprise us…

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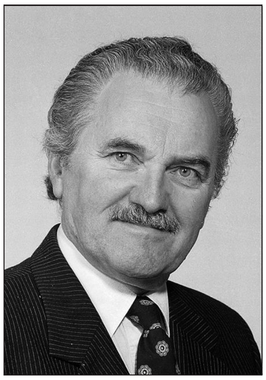

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