# Improved utilization of the radio spectrum respecting physical laws

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## Abstract

In this paper, the problem of improved utilization of the radio spectrum is reduced to a problem of a better arrangement of solids in a generic multidimensional space. The solids should be ‘packed’ tightly together, but not too close because of possible conflicts due to their unintended ‘proximity’ interactions. Major improvement proposals are discussed, those related to technology and those related to regulations.

## 1. Introduction

This paper deals with potential improvements in the utilization of the radio frequency spectrum, a topic discussed around since long time. The starting point is the fact that some segments of the radio spectrum are not used. In this context, improvement means a reduction of the unused segments. The paper reduces the original problem of the spectrum use to a problem of geometry in a generic hyperspace, as explained in Section 2. Without going into details, the used parts of the spectrum are represented by solids in that approach. The smaller the empty spaces between them are, the better the spectrum is used. The hyperspace convention is used also in Section 3, which offers a short review of potential technological improvements. The radio spectrum may be underutilized due to blocking the access to it by regulatory provisions; these aspects are shortly discussed in Section 4. Section 5 summarizes the findings and Section 6 lists the selected literature. The opinions expressed in the paper reflect personal views of the author.

## 2. Radiocommunication hyperspace

We deal with radio links, each transmitting a message from a source to its destination. The message is a continuous function of continuous time, or a sequence of symbols, i.e. a function of discrete time. It is first transformed into electric signal in the transmitter and then radiated as a radio wave traveling along its propagation path to the receiver, and further. The received message differs from the original one due to unpredictable influences. The system keeps their difference within acceptable limits, to assure the required transmission quality. The difference is often expressed as bit error rate or probability, closely related to other system performance measures such as transmission range or speed. The signal transformations at the transmitter involve a number of variables/parameters and concentrate the signal power in specific regions of a multi-dimensional space created by these variables. The signal concentration regions, or solids, can be depicted only by means of their plane projections or cross section cuts, other variables/ parameters fixed, because it is impossible to show more than two variables on a plane. Each pair of independent variables defines a plane (compare with the concepts of signal mask, service area, denied area, etc.). For instance, in the time domain, digital signals appear as disjoint forms that represent individual transmission sessions, or signal blocks (packets, frames), or pulses, and empty spaces – time breaks.

The radio wave looses the power during its propagation (due to absorption, spatial spreading, diffusion, and shadowing). It experiences also other phenomena such as depolarization, scattering or reflection, or the Doppler Effect, if the transmitter, receiver, or reflecting objects are in motion. Because the propagation medium is shared by all the radio links and other constituencies of the environment, all radio waves they radiate add together. Their sum varies due to object movements, switching on/off the radiation sources, etc. That involves additional variables, most of which are of random nature that can be described only by probability distributions. As a result, the signal solid at the receiver input differs from that radiated by the transmitter. The algorithms embedded in the transmitter-receiver hardware and software repair it and recover the original message. The receiver creates a multidimensional ‘window’ (solid) that filters the intended signal, reverses the transformations made at the transmitter, and corrects the transmission errors (compare with the receiver selectivity mask). It involves the signal despreading, demodulation, decoding, etc. The receiver window may consist of a single 'opening' (analog systems) or a series of non-contiguous openings (digital systems) stationary or changing in time.

## 3. Improvement potential: science and technology

One approach makes use of the redundancy that is generated during the signal transmission. It is well known that radio waves reflected by various objects along the propagation path are replicas of the original signal and that they can interfere with it, leading to signal fading and self-interference. In fixed services, such a destructive interference can be avoided by location of the stations in such a way that the reflected waves are e.g. blocked by terrain irregularities. However, the multiple signal replicas can be exploited to enhance the original signal, and various diversity techniques are used for that purpose (e.g. time diversity, frequency diversity, space diversity, polarization diversity). The idea of summation of multiple copies of the same signal is also behind the 'intelligent systems' (e.g. intelligent antennas, single-input-multiple-output SIMO systems, and multiple-input-multiple-output MIMO systems). The same principle is used in single frequency networks (SFN), where two (or more) stations transmitting the same content share a common frequency channel.

For a shared exploitation of the radio frequency spectrum, the signal solids should be 'packed' tightly together. However, they should not be too close one to another, because of harmful unintended interactions. Crucial is here observation that there are 'holes' in the solids that can be used by other signals. Note at this occasion a crucial role of the signal compression: it decreases the size of the solids and thus increases empty spaces between them. However, the compression issues are not discussed here. For minimal transmission errors, the intended signal must fit the receiver window completely, in all dimensions, and with no spill out. The spilled out signal is not only useless – it creates an interference threat to neighboring radios. By the same reasoning, any part of the receiver window unfilled by the intended signal is not only useless; it is unnecessarily exposed to interference from neighboring transmitters. It is also clear that any unintended signal must lie outside of the receiver window, at a 'safe' distance from it, at least in one dimension. The safe distance is application and technology dependent. It may be geographical separation, code separation, direction separation, etc. In the ultra wide band (UWB) technology, 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.

Filling empty spaces in one signal solid by another signal requires the both signals to be mutually matched and carefully positioned against each other (except for fully randomized systems). The precise positioning requires an appropriate adjustment or access scheme: a scheduled access, an access on-demand, or an access by self-adaptation to the environment. All they rely on a collaborative approach and on a common reference frame. The adaptive approach implies a real-time monitoring of the 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 protocol is copied from the radio amateurs' etiquette, which allows the shared use of the available spectrum without collisions.

The signal sensing is only a step towards flexible systems that adapt themselves fully 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 [1, 2]. Their main functions are monitoring the environment (individually or in a group); sensing the 'spectrum holes'; channel-state estimation and predictive modeling; interference threat analysis; best frequency selection; providing the fair spectrum sharing with other radios in a dynamic manner. The frequency selection may be a tricky issue here because of 'false signals' due to nonlinear effects. 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. In spite of all benefits and advantages of such a solution, the concept has a little chance for its quick and universal introduction. Its high costs and enormous capital investments in older technologies that still work and bring profits are the main obstacles. For some time to come, we will thus continue to live with the present administrative arrangements, discussed shortly in the next section.

Radiocommunications base on the 19th century theory of James Clerk Maxwell (1831–1879). In the meantime, however, physics has progressed enormously. The quantum theory appeared (Max Planck, 1858 –1947); the traditional notion of space, time, and matter was replaced by the interchangeability principle of matter and energy in the four-dimensional spacetime; the relativity theory emerged (Albert Einstein, 1879 –1955). New ideas continue to appear changing our understanding of the world, as for instance the string theory [3]. According to the theory, the electron is no more a material particle or wave function as we thought, but consists of oscillating 'strings'. To make sense, however, the string theory requires the universe of ten dimensions or eleven, and not four, as Einstein told us. To derive tangible results from that progress, a number of practical application-oriented research programs have started opening the unexplored fields beyond the limits of the classical Maxwell's theory.

## 4. Improvement potential: access regulation

Radio has profound and growing impact on the society, on its security and prosperity, and radio regulations are to assure its right use for right purposes. One of international regulations formulates the basic requirement concerning the right use as follows: any radio link can use any frequency under the condition that it "*...shall not cause harmful interference to, and shall not claim protection from harmful interference...*" [4]. That principle dictates the development direction of radio networking discussed in the previous section. In essence, the radio regulations define the safe distances between the neighboring radio systems (in the form of technical and operational requirements). For simplicity, they classify the radio services and detail where, when, and at what frequencies they can safely be deployed. In addition, they compel the standardization of equipment and transmission methods. These in turn assure a mass market for radio equipment and facilitate radio services across the globe, which makes them popular and cheap.

Additional spectrum access rights complement the technical and operational regulations to achieve some political, economic, or social objectives. The universal access and protecting the society from the abuse of market power are two examples of such objectives. The access rights are usually in the form of licensing, and various licensing criteria are in use around the world. The first-come, first-served principle (seniority criterion) is one of the most popular. The licensing influences the use of the radio frequency spectrum by reducing the spectrum demand through imposing specific criteria. That approach is criticized, and various remedies have been proposed.

Recently, more and more often, the auctioning of licenses replaces the other criteria. Here, the access to the radio spectrum is given to those who pay the most (wealth criterion). This is the preferred solution for politicians, as it offers the easiest way to augment the governmental budget without any effort. However, the auctioning results in increasing the price paid for radio services. It also deprives money that otherwise would be invested in the telecommunication infrastructure. Other, more radical proposals request that the administrative regulations to be completely abandoned, the radio spectrum to become a private property, and its use to be ruled by market forces only. The radio spectrum is to be traded, aggregated, divided and freely used for a wide range of owner-selected services [5]. No wide experience exists yet with that approach, and there is a conceptual problem. The 'size' of the spectrum traded cannot be determined and fixed confidently because it depends strongly on, and varies with, the environment that is constantly changing and is out of control. It is as if the walls of the house you own were made of a rubber membrane rather than from rigid materials and its volume diminishes under the external pressure. With each new neighbor settled, the pressure increases, and the hose get smaller and smaller, which evidently depreciates its market value [6]. Even the UWB systems can substantially reduce the service area of a neighboring narrow band system when they are concentrated in large numbers, in spite of the fact that operating separately each one does not increase the ambient noise 'temperature' noticeably (e.g. by less that 1%).

One of the improvement proposals, the open spectrum doctrine, follows the 'Internet spirit'. It should be reminded here that all the international treaties dealing with radio issues consider the radio frequency spectrum as a common heritage of all people around the world, with every nation enjoying an equal and free access to it. The advocates of the doctrine suggest the spectrum to be similarly open for every citizen. The open spectrum doctrine has proved its practical utility enjoying an enormous success in some frequency bands (so called ISM bands), in popular short-distance wireless local loop (WLL) computer networks. Here, the collaborative coexistence rules necessary for the system to coexist have been embedded in the equipment hardware and software, in the form of neighbor-friendly medium access control (MAC) protocols mentioned earlier. Such a collaborative approach is not new. It has passed a practical test of life (with much more primitive technology) in the radio amateur services, as mentioned in the previous section. The open spectrum doctrine and free spectrum access do not sweep away the market completely; it only restricts the market forces to the equipment (terminal) market, leaving aside the radio spectrum (transport medium); much like in the sea transport, where ships and harbors can be privately owned, but the use of ocean waters is free and open to everybody. The improvement in the spectrum use is here due to exploiting the idle breaks in transmissions. Instead of denying the access to the latecomers or those less wealthy, all the spectrum users squeeze themselves and share the congestion inconveniences collectively. The smart systems can differentiate services, and their prioritization schemes can offer special preferences to selected users, according to a criterion. The criterion may be the urgency, merits, wealth, etc. The open spectrum proponents underline also that their approach is the only one, which really encourages technical innovations.

## 5. Concluding remarks

The way the radio spectrum is used reflects the status of science and technology, the relative balance of powers of the competing interest groups, and earlier investments in the infrastructure ('inertia'). The legal, regulatory, business and financial opportunities are determined to these factors, to a great degree. In the paper, we have reviewed some potential improvements through technology and through regulations. However, it is very difficult, if possible at all, to say which one of the improvement proposals is the best. The reason is simple: the problem involves social aspects, and there are no universally accepted criteria in dealing with social issues. The qualification 'better' or 'worse' engages the system of values and preferences that in turn is deeply rooted in the past experience. The society is composed of various groups, each with its own world-views, goals, and interests, often conflicting. What is the best for one group is not necessarily good for the others. Those, whose needs have been satisfied, are against changes, as any modification would threaten their acquired benefits. Newcomers, unhappy with the available access to the radio spectrum, press for changes.

We noted that the frequency is only one of numerous physical variables deciding on how the radio medium is used. To deal with the problem, we introduced a multidimensional space generated by these variables. We do not fix its dimensionality in advance, as it depends on the technology applied. Any physical variable, by which radio signals can be distinguished one from another, can be included. The more dimensions used, the more degrees of freedom in the radio spectrum utilization. That geometrical interpretation leads us to the well-known 'knapsack' problem of combinatorial optimization, in which a collection of objects is to be selected in such a way that their total value is as large as possible, under specific restrictions imposed. We also noted that the technical complexity of the problem is defined only by physical interactions between radio systems. It does not depend on the spectrum access regulations: they do not change when the spectrum is treated as private property or as commons.

The title of the paper includes the word 'physics'; we have to note that the science of physics did not say its last word yet, and we witness attempts to put its recent achievements into practical uses. When and how will they affect the use of the radio frequency spectrum? Nobody is able to answer that question today. With the future, the only sure thing is that it will surprise us...

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