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Flexible Spectrum Use and Laws of Physics

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This note refers to flexible-use spectrum rights that would allow the radio frequency spectrum to be traded, aggregated, divided and freely used for a wide range of user-selected services. So far, discussions on that approach have largely focused on economic aspects, without due consideration of physical realizability. We argue here that additional spectrum management rules are required to assure compatible coexistence of radio systems in congested environments.

Background

Various proposals to improve management of the radio frequency spectrum resources have been around since long time[1, 2, 3]. Among these, the flexible spectrum use doctrine has enjoyed particular popularity. Its two rules: "*(1) Transmit within signal power restrictions inside your licensed electrospace region and (2) Keep your signals below 'X' outside that region*"[4] are expected to assure the quality of service and to protect other services nearby. The idea is appealing. It sounds simple and refers to well-known concepts. For instance, when you own or rent a house, you are free in arranging the furniture at will, or in replacing it by new models. The doctrine is supposed to assure similar freedom in using the radio frequency spectrum.

Unfortunately, it is not as simple as it might look at first glance. Discussions on this matter have largely focused so far on economic aspects. Some questions have been left open, without due consideration of physical realizability and inherent constraints. This text aims at filling this gap. The next two sections focus on radio wave propagation and unintended interactions among radio systems. Then, a few open questions are indicated. Finally, we conclude that additional spectrum management rules are necessary to assure

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[1] See e.g. Struzak R: Introduction to International Radio Regulations (ed. by Radicella S); The Abdus Salam International Centre for Theoretical Physics 2003; ISBN 92-95003-23-3

[2] For a review of literature, see e.g. Ting C, Wildman SS, and Bauer JM: Comparing Welfare for Spectrum Property and Spectrum Commons Governance Regimes; Telecommunications Policy 29 (2005) pp. 711-730.

[3] Nekovee N: Dynamic Spectrum Access – concepts and future architectures; BT Technology Journal, Vol. 24, No 2. April 2006, pp.111-116

[4] Matheson RJ: Flexible Spectrum Use Rights. Tutorial. International Symposium on Advance Radio Technologies (ISART) 2005

compatible coexistence of densely packed radio systems. In principle, these rules can be built-in in the device hardware and software.

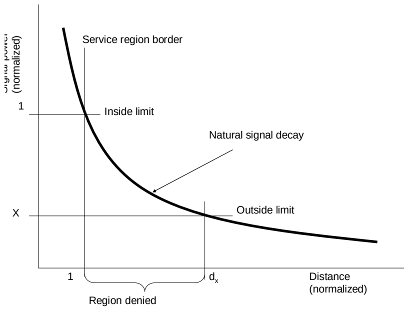

Figure 1**.** Natural signal decay in free space and signal limits inside and outside the licensed (covered) region imply that neighboring service areas must be at some distance one from another. The service extends up to (normalized) distance 1, whereas the area denied to neighboring systems extends up to distance d_x.

Propagation

Rules (1) and (2) mentioned above impose signal limits that are different within the licensed region and outside of it. On one side of the region's border, the signal must be strong (as required by the service offered) whereas on the other side it must be weak (not to disturb services that might be licensed there). However, the radio wave signal propagating in a continuous medium decays gradually and cannot change abruptly, as Figure 1 illustrates.

The power of the radio wave falls naturally below level 'X' at some distance d_x from the transmitter. In case of two systems, d_x determines the range of the region denied to neighbors that can share the same frequency resources in a compatible way. It is known as the frequency reuse distance. (The minimum distance concept can be extended over other dimensions, see the following section.) With such a constraint, only a small part of the space is usable, which evidently limits flexibility in using and managing the radio frequency spectrum resources. The flexible spectrum use doctrine disregards that fact.

Unintended interactions

The service coverage and quality, as well as other features, depend on the intended signals, as well as on unintended interactions among radio systems[5]. Transmission of messages via radio can be considered as a series of mappings in signal hyperspace, see Figure 2.[6,7] The transmitter first maps the original message (m_i) into the radio wave that is radiated in the direction(s) of the intended receiver(s). The propagation-process maps the radiated wave into the incident wave at the receivers (s_{ij}). The propagation process introduces noise, distortions, reflections, latency, fading, Doppler Effect, etc.

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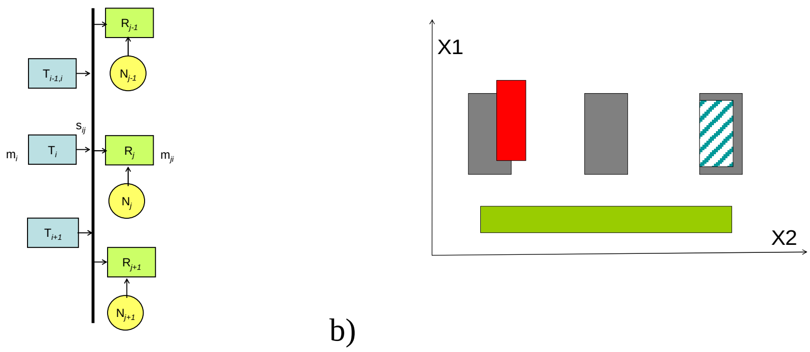
[5] Definition of spectrum use and efficiency of a radio system; REC. ITU-R SM.1046-2; (Question ITU-R 47/1-- 1994-1997-2006).

[6] Struzak R: Evolution of Spectrum Management Concepts; Electromagnetic Compatibility 2006. Proceedings of the Eighteen International Wroclaw Symposium on Electromagnetic Compatibility, June 28-30, 2006, pp. 368-373

[7] Such a hyperspace might be created by any set of orthogonal variables by which one radio signal can be distinguished from another. Frequency, power, polarization, direction, modulation, coding, spreading etc. are examples.



a) b)

Figure 2. a) Schematic diagram of multiple radio links. b) Projection of incident signal hyperspace on plane (x1, x2). The dark rectangles represent the receiver's reaction window.

Many of these effects are uncontrollable. Due to physics of radio wave propagation, the radiated wave is received not only by the intended receiver(s), but also – unintentionally - by a number of other receivers, where it is unwanted. Thus, at each receiver, the incident wave is a combination of the wanted signal, a number of unwanted signals and noise.

The receiver applies communication protocols, algorithms and signal processing to map that wave into the recovered message (m_{ij}). Normally, the recovered wanted message is as close to the original message as required and all unwanted messages carried by radio waves are null and void at the receiver output. In that process, the receiver responds only to those components of the incident wave that fall into its reaction window. Other components e.g. those that appear at wrong time, at wrong frequency, etc. are considered unwanted and are rejected.

Figure 2b is a projection of the signal hyperspace on plane (x1, x2). Variables “x1” and “x2” may be interpreted as e.g. 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 sheet of paper. Note that the receiver reaction window may consist of a single opening (analog systems) or a series of non-contiguous openings (digital systems). For an unwanted signal to be rejected, it must be sufficiently distant from the receiver's reaction window in at least one variable. The “sufficient” distance is system dependent. It might be the geographical distance, frequency-difference, power-difference (as in ultra-wideband systems sharing frequencies with narrow-band systems), time-difference, distance between the spreading functions (in spread-spectrum systems), etc., or their combination

Figure 3 illustrates the effect of environment (computer simulation). The scenario assumes an omnidirectional radio system first operating alone. Then, without any other change, one, two or six identical systems are put into operation nearby in such a way that their original coverage areas touch each other. The outer (blue) line is the border of service coverage in the case when the system operates alone. The inner (red) line is the coverage border when signals from neighboring co-channel transmitters are taken into account. It is easy to notice that each new transmitter in the neighborhood reduces the coverage of our system under consideration. One transmitter added nearby reduces its original coverage area by 35%. Two transmitters result in the coverage loss of 50%, and six -- 75% (the numbers are scenario-specific). Referring back to our household analogy it is as if the house walls were made of a rubber membrane rather than built from rigid materials. Under the neighbors' pressure, its rooms change size and form, so that the owner's flexibility in the furniture arrangement is reduced.

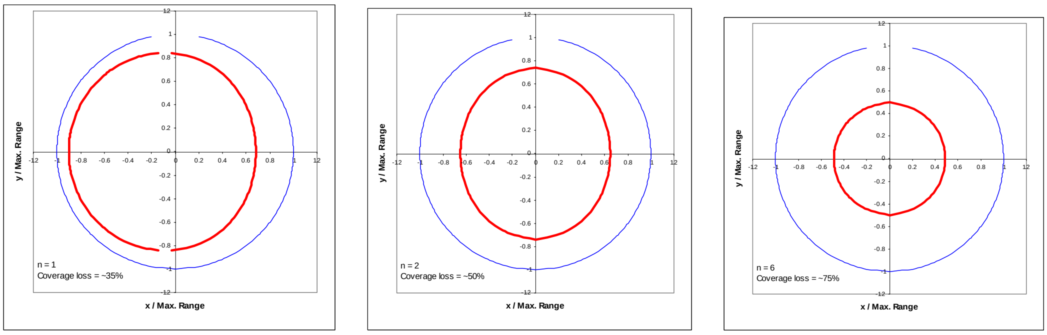


Figure 3. Illustration of environmental impact on the system coverage. Explanations in the body text.

Note that consequences of such influences depend not only on the characteristics of individual systems around, but also on their number and spatial deployment. Unintended electromagnetic interactions play critical role in congested radio environment and their significance increases with the growth of radio.[8] That is the reason why a lot of effort is spent to study these interactions within the ITU-R Study Groups and elsewhere and to set necessary regulations at the ITU Radio Conferences. There exists a multitude of ways and means to control unwanted effects of these interactions. Unfortunately, each of them restricts the flexibility in setting system technical and operational characteristics.

One of popular methods consists in balancing the powers of transmitters operating nearby[9]. Frequency coordination is another method. In the frequency domain, to protect licensed regions against intolerable service degradation, specific constraints are imposed on the frequencies used by neighboring transmitters[10]. In their simplest formulation, the constraints can be written as matrix $[\theta_{ij}]$, where θ is a 'distance', and indexes i and j denote radio systems. If f_i is frequency used by system i, then any two frequencies must be sufficiently distant one from another: $|f_i - f_j| > \theta_{ij}$. Such constraints have been named "binary" as each constraint involves exactly two systems. Other physical interaction processes involve three and more systems and additional constraints. For instance, to eliminate third-order intermodulation effects, frequency combinations $2f_i - f_j \neq f_k$ among any three neighboring systems are forbidden. Similar constraints might be required in the time domain. Mathematical theory of graphs is often useful in solving such interaction problems.

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[8] Delogne P and Baan W: Spectrum Congestion; Modern Radio Science 1999 ed. by M Stuchly; Proceedings of the International Union of Radio Sciences (URSI) General Assembly held in Toronto. ISBN 0-19-856569-0, pp. 309-327

[9] See e.g. Struzak R: Frequency Reuse and Power Control In Wireless Networks; Global Communications – Wireless, Nr 11, 1999, pp.92-104, ISBN 1 902221 27 3

[10] See e.g. Leese R and Hurley S: Methods and Algorithms for Radio Channel Assignmant; Oxford University Press, 2002, ISBN 0 19 850314 8

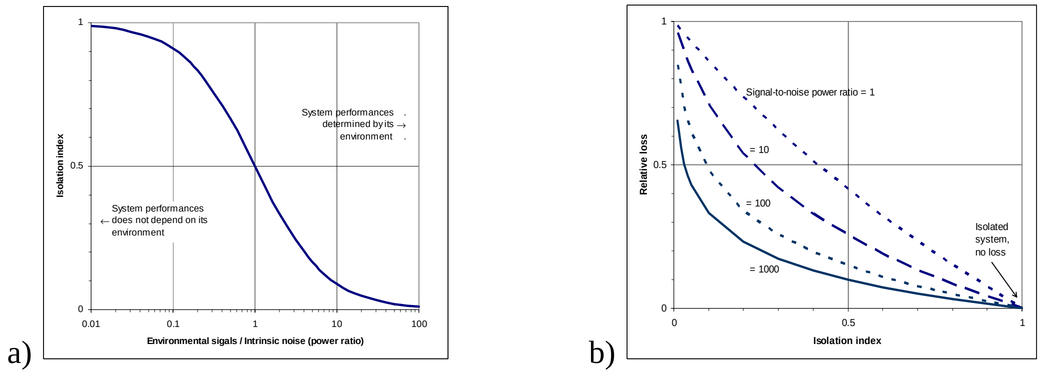

Figure 4. a) Isolation index vs. unintended signal-to-noise ratio. ‘1’ represents perfect isolation. b) System capacity loss vs. isolation index for various wanted-signal-to-noise ratios.

To allow quantitative examination of unintended interactions in a general way, “isolation index” has been proposed[11]. That index is the power ratio of the system noise and all the unwanted signals and does not depend on the technology used. Its value is confined between one and zero (Figure 4a) with ‘1’ representing a hypothetical autonomous system whose features are environment-independent. Zero represents the opposite situation, when system performances are determined by unwanted signals (and the wanted signal, of course). All practical cases fall between these two extremes. Figure 4b shows the relation between the system capacity and isolation index. The capacity falls down if the system is insufficiently isolated from the environment. All practical cases fall between zero loss, when system performances are determined by the system noise, and one, when they are limited by unwanted signals. Other system features show similar tendencies.[12]

Open questions

Consequences of unintended interactions indicated above may be significant. Imagine, for instance, a paid radio service. With the service users uniformly distributed, the income of the service provider is proportional to the service coverage area. As the coverage decreases with each new transmitter added, so does the provider’s income (Figure 3). Similar decrease may happen when the technical or operational characteristics of the systems nearby change. Should that decrease be quietly accepted or should compensation be demanded for the income loss? Will this depreciate the market value of the business? Will this influence the investment decisions? It seems that so far such questions have not been suitably clarified, which leads to uncertainties in contractual rights and responsibilities at the secondary spectrum marked, should it be introduced. Another problem arises with the necessary protection of passive services, where natural phenomena impose unavoidable constraints (e.g. in radio astronomy service)?

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[11] Struzak R: Spectrum Congestion – a Voice in Discussion. The Radio Science Bulletin 291, December 1999 pp. 6-7; March 2000 p. 3-4; June 2000 p.3.

[12] Struzak R: On Spectrum Congestion and Capacity of Radio Links; Annals of Operations Research 107, 2001 (2002), pp. 339-347

Conclusions

We have reviewed some aspects of the coexistence of radio systems. Except for the case of isolated systems, the service coverage, range, and other system features, depend on interactions among the systems. These interactions are ruled by laws of physics and are not negotiable, do we like it or not. They do not depend on spectrum management regime and are the same when the spectrum resources are treated a private property or as a commons.

When a number of radio systems co-exist, they mutually interact and behave as linked together into a common network. In the network, the operation of neighboring systems must be coordinated to avoid problems indicated in previous sections. Until now, such coordination has been ruled by the radio regulations, enforced by local and national spectrum managers and sanctioned by bilateral agreements and the ITU radio conferences. Once the system operation is coordinated within the network, a little flexibility exists, if any, to modify it.

New ‘intelligent’ radio systems offer an elegant solution to the problem. These systems have the policy, coordination, negotiation and regulations rules built-in (in the system hardware and software). They monitor the signal environment and apply these rules to coordinate their operations as needed. In such a way, they automatically ensure compatible co-existence with the neighbors, in a dynamic signal environment. It seems that only such systems can offer a real flexibility in the use of the radio frequency spectrum resources. However, enormous investments in the existing ‘classic’ systems may postpone their mass introduction for a number of years.

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