4. RADIO SPECTRUM

What is the electromagnetic spectrum?

There is not a simple definition of the spectrum. From the technical viewpoint the spectrum is simply the range of electromagnetic waves that can be used to transmit information, but from the practical viewpoint the economic and political aspects, as well as the technology actually used to convey the information by means of these waves, play pivotal roles.
As an example, when Marconi in 1902 first spanned the Atlantic with his "wireless telegraph message", he used the whole spectrum available at the time to send a few bits/s over an area of thousands of square kilometres.
With the spark transmitter used for this achievement that occupied all the frequencies that the existing receivers were able to understand, nobody else could use radio for communications on a radius of some 3500 km from the transmitting station in England. So, if other users wanted to send messages in the same area, they would need to coordinate their transmissions in different "time slots" in order to share the medium. This technique is called "**TDMA**", Time Division Multiple Access.

Users located at distances much greater than 3500 km from Marconi's transmitter could use the spectrum again, since the power of the radio waves decreases as we move farther away from the transmitter. Reusing the spectrum in different geographical areas is called "**SDMA"**, Space Division Multiple Access. Marconi was later able to build a transmitter that could restrict emissions to just a range of frequencies, and a receiver that could be "tuned" to a particular frequency range. Now, many users could transmit simultaneously in the same area (space) and at the same time. **"FDMA"**, Frequency Division Multiple Access was borne. Radio then became a practical means of communications, and the only one that was available to reach a ship in the open seas. The coordination of the frequencies allocated to different users was done by national agencies created to this effect, but since radio waves are not stopped by national borders, international agreements were needed. The international organization that had been created to regulate the transmission of telegrams among different countries was commissioned to allocate the use of the electromagnetic spectrum.

Nowadays, ITU, International Telecommunications Union, is the oldest International Organization, tasked with issuing recommendations about which frequencies to use for which services to its 193 nation members.

The use of the spectrum for military applications raised a new issue; "jamming", the intentional interference introduced by the enemy to impede communication. To avoid jamming, a new technique was developed in which the information to be transmitted was combined with a special mathematical code; only receivers with the knowledge of that particular code could interpret the information. The coded signal was transmitted at low power but using a very wide interval of frequencies to make jamming more difficult.

This technique was later adapted to civilian applications in what is called **"CDMA"**, Code Division Multiple Access, one of the flavours of **spread spectrum communication**, extensively used in modern communications systems. In summary, the spectrum can be shared among many users by assigning different *time slots*, different *frequency intervals*, different *regions of space*, or different *codes*. A combination of these methods is used in the latest cellular systems. Besides issues of sovereignty and its defence, very strong economic and political interests play a determinant role in the management of the spectrum, which also needs to be constantly updated to take advantage of the advances in the communications technology.

Telecommunications engineers keep finding more efficient ways to transmit information using time, frequency and space diversity by means of ever advancing modulation and coding techniques. The goal is to increase the "spectrum efficiency", defined as the amount of bits per second (bit/s) that can be transmitted in each Hz of bandwidth per square kilometre of area. For example, the first attempts to provide mobile telephone services were done by using a powerful transmitter, conveniently located to give coverage to a whole city.

This transmitter (called a **Base Station** in this context), divided the allocated frequency band into say, 30 channels. So only 30 conversations could be held simultaneously in the whole city.

As a consequence, the service was very expensive and only the extremely wealthy could afford it. This situation prevailed for many years, until the advances in electronic technology allowed the implementation of a scheme to take advantage of "Space Diversity".

Instead of using a single powerful transmitter to cover the whole city, the area to be serviced was divided into many "cells", each one served by a low power transmitter. Now cells that are sufficiently apart can utilize the same channels without interference, in what is known as "frequency reuse". With the cellular scheme, the first 10 channels are to use frequency band 1, the second 10 channels frequency band 2 and the remaining 10 channels frequency band 3. This is shown in Figure RS 1, in which the colours correspond to different frequency bands. Notice that the colours repeat only at distances far enough to avoid interference. If we divide the city in say, 50 cells, we can now have 10X50 = 500 simultaneous users in the same city instead of 30. Therefore, by adding cells of smaller dimensions (specified by lower transmission power) we can increase the number of available channels until we reach a limit imposed by the interference.

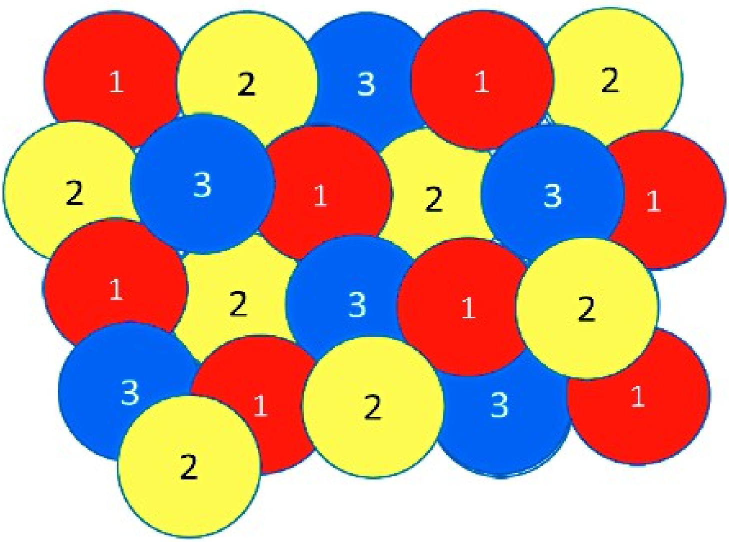

Figure RS 1: Cellular sharing of spectrum

This example shows that a clever use of existing resources can dramatically increase its usefulness. Although the main use of the spectrum is for communication purposes, there are also other uses, like cooking food in microwave ovens, medical applications, garage door openers and so on.

So some frequency bands are allocated for these purposes in what is known as the **ISM** (Industrial, Scientific and Medical) bands.
This spectrum usage is normally for short distance applications.
A breakthrough occurred in 1985 when the FCC (Federal Commission of Communications), the agency that oversees the spectrum in the U.S., allowed the use of this spectrum for communications applications as well, provided that the transmission power was kept to a very low level to minimize interference.
People could freely use these “Unlicensed” bands without previously applying for a permit, provided that the equipment used had been certified by an authorized laboratory that ensured compliance with interference mitigation measures.
Several manufacturers began taking advantage of this opportunity by offering equipment that could be used to communicate between computers without the need for cables, and some wireless data networks covering significant geographic areas were built with them, but the turning point happened after the 1997 approval of the IEEE (Institute of Electrical and Electronics Engineers) 802.11 Standard, the basis of what is known as WiFi.
The existence of a standard that guaranteed the interoperability of equipment produced by different manufacturers fuelled an impressive growth of the market, which in turn drove the competition that fostered a dramatic decrease in the cost of the devices.
In particular, the portion of the ISM band between 2400 and 2483 MHz is nowadays available in most of the world without the need for previously applying for a license and is widely used by laptops, tablets, smart phones and even photographic cameras.
It is important to stress the role of the unlicensed spectrum in the enormous success of WiFi high speed Internet access.
Many airports, hotels and cafes all over the world offer free WiFi Internet access on their premises, and low cost wireless community networks have been built both in rural area and in cities covering considerable geographic areas, thanks to the availability of free spectrum.
Mobile phone operators, who have to pay dearly for frequency licenses to use the spectrum, were quite hostile to this apparently unfair competition.
But when they started offering smart phones, which make very intensive use of the Internet, they pretty soon realized that off-loading the traffic to WiFi was in their best interest, because it relieved the traffic in their distribution network (known as the *backhaul*).

So now they encourage their customers to use WiFi wherever it is available and use the more expensive cellular service only when out of range of any WiFi Access Point.
This is a remarkable example of the usefulness of the unlicensed spectrum even to traditional telecommunications operators who often have lobbied against it.

How is the spectrum adjudicated?

Currently the main methods to gain access to a given spectrum band are auctions and the so called "beauty contest".
The auction method is straightforward; interested parties bid for a given spectrum chunk; whoever commits the higher sum gets the right to use the frequencies.
In theory this method guarantees that the adjudication will be transparent, in practice this has often been circumvented and there have been instances of powerful commercial interests that acquire frequencies only to avoid their use by the competition, with the result of highly valuable spectrum not being used.
Also there is the temptation on the part of governments to use this method as a means to generate revenues and not necessarily in the best public interest.
As an example, in the year 2000 there were auctions in several countries of Europe to adjudicate spectrum for mobile phones, which resulted in a total income of 100 billion (100 000 000 000) euros to the government coffers.

The "beauty contest" method is for the interested parties to submit proposals about how they intend to use the spectrum.
A committee of the spectrum regulating agency then decides which of the proposals better serves the public goals.
This method relies on the objectivity, technical proficiency and honesty of the members of the deciding committee, which is not always guaranteed.
In many countries there are rules for spectrum adjudication that call for the relinquishing of spectrum bands that have been acquired but are not being used; however their enforcement is often lacking due to the strong economic interests affected.

Figure RS 2: A special vehicle for spectrum monitoring in Montevideo, Uruguay.

Figure RS 2 shows a photograph of a spectrum monitoring vehicle in Montevideo, Uruguay and Figure RS 3 that of the same kind of equipment being used in Jakarta, Indonesia.

Figure RS 3: The "spectrum Police" at work in Jakarta

Note that the open spectrum used in the unlicensed bands cannot prevent interference issues, especially in very crowded areas, but nevertheless it has proved a fantastic success for short distance applications in cities and also for long distance applications in rural areas.
It is therefore advisable to investigate new forms of spectrum allocation, taking into consideration the needs of many stakeholders and striking a balance among them.
A dynamic spectrum allocation mechanism seems to be the best choice given the advances in technology that make this viable nowadays.
As an example, the current method of spectrum allocation is similar to the railway system, the railroads can be idle a considerable amount of time, whereas the dynamic spectrum allocation is akin to the freeway system that can be used at all times by different users.

Political issues

The importance of the spectrum as a communications enabler cannot be overstated. Television and radio broadcasting have a strong influence in shaping public perception of any issue, and have been used overtly for political propaganda (It has been said that the election of Kennedy as president of the U.S. was due mainly to his television campaign).
During the cold war, *The Voice of America, Moscow Radio* and *Radio Havana Cuba* were very effective ways to sway a global audience.

More recent examples include the influence of CNN and Al Jazeera in the public interpretation of the Arab Spring. Spectrum used for two way communications has also been subject to government interventions, especially in cases of political unrest. On the other hand, economic interests also play a vital role in broadcasting; the consumer society relies heavily on radio and television to create artificial needs or to veer the consumer towards a particular brand. We can conclude that the electromagnetic spectrum is a natural resource whose usefulness is heavily conditioned by technological, economic and political factors.

Explosion in spectrum demand

As the number of tablets and smart phones grows, telecom operators are trying to get access to new frequency bands, but the traditional way of adjudicating the spectrum is facing a dead end.

Keep in mind that the spectrum is used for radio and television broadcasts, for satellite communications, for airplane traffic control, for geolocalisation (Global Postioning Systems-GPS), as well as for military, police and other governmental purposes. Traditionally, the demand for additional spectrum has been met thanks to the advances of electronics that have permitted the use of higher frequencies at an affordable cost. Higher frequencies are well suited for high speed transmissions, but they have a limited range and are highly attenuated by walls and other obstacles as well as by rain.

This is exemplified by comparing the coverage of an AM radio broadcasting station to that of an FM one: the greatest range of the AM station is due to its use of lower frequencies. On the other hand, FM stations can make use of higher bandwidths and as consequence can offer greater audio quality at the expense of a more limited range.
Current cellular operators use even higher frequencies, usually above 800 MHz. Accordingly, the TV broadcasting frequencies are coveted by the cellular telephone providers, because by using lower frequencies they will need less base stations, with huge savings in deployment, operation and maintenance costs. This is why these frequencies are commonly referred to as “beach front property”.

Techniques for more efficient spectrum usage by means of advanced modulation and coding methods have had the greatest impact in allowing more bits/s per Hz of bandwidth availability. This, in turn, was made possible by the great strides in electronics (fabrication of ever advanced integrated circuits) that now make it economically feasible to implement the required sophisticated modulation and coding techniques.

According to the calculations performed in 1948 by Claude Shannon - the father of modern telecommunications, a typical telephone line could carry up to 30 kbit/s. But this was only achieved in the 90's when integrated circuits implementing the required techniques were actually built. In particular, the transition to digital terrestrial television broadcasting, which is more efficient in spectrum usage compared with analogue transmission, has freed some spectrum in the so called “White Spaces”, the frequencies that had to be left fallow in between analogue television channels to prevent interference.

Figure RS 4: Example of TV Channels adjudication in two cities that are close enough that transmissions from one can reach the other. White spaces are kept fallow to minimize interference.

In traditional analogue TV broadcasting, adjacent channels cannot be used at the same time, because the signal from one channel will "spill" over to the two adjacent channels and would cause interference. This is similar to the central reservation used in freeways to separate the two directions of traffic in order to prevent collisions. So a "White Space" must be left between two contiguous analogue TV channels to prevent interference. Digital TV broadcasting is much more efficient in spectrum utilization, and several digital TV channels can be accommodated in the same frequency band formerly used by a single analogue channel without "spillover" into adjacent channels. So, in places where Analog TV is replaced by Digital TV a "digital dividend" is being harvested.
In conclusion, the concept of white spaces can be applied to three different frequency chunks:

- The spectrum that has been assigned to TV broadcasting but it is not currently being used. This applies particularly to developing countries, in which there has been no economic incentive for broadcaster to use every available TV channel.
- The spectrum that must be left free in between two analogous TV channels to prevent interference.
- The spectrum that has been reclaimed as a consequence of the transition to digital terrestrial TV, which is more spectrum efficient. This currently applies to developed countries, but will soon apply to developing countries as well.

In the last 20 years there has been a tremendous growth in the demand for more spectrum for mobile communication services, in which data services are consuming much more bandwidth than voice and the growing use of video is presenting an additional challenge.

Not surprisingly, telecom operators everywhere are trying to get a portion of these "White Spaces" allocated to them to fulfill their needs. Broadcasters, on the other hand, are very reluctant to concede any spectrum at all to what are now their direct competitors.

Spectrum scarcity or spectrum hoarding?

Although the available spectrum is currently totally adjudicated in developed countries, many independent studies have found that the actual simultaneous usage of the spectrum is a tiny fraction of the total. This is caused by the way spectrum was originally adjudicated and also because often spectrum is used intermittently; for instance some TV broadcasting stations do not transmit 24 hours a day.

As a consequence, a radically new way to use the spectrum has been suggested; instead of leasing spectrum to a given organization in an exclusive basis, the new dynamic spectrum management paradigm proposes to use whatever spectrum is available in a certain place at a certain time and switch to another frequency whenever interference is detected in a given band.

An analogy can be made to explain this concept: the current way to allocate the spectrum is similar to a railroad system; the railroads are never used 100% of the time, a more efficient use of the same amount of terrain can be done with a highway in which many different users can share the same path according to their current needs.

Of course to implement dynamic spectrum access requires new technologies and new legislation; many vested interests are fighting it alleging the possibility of interference. The key issue is how to determine when a particular chunk of spectrum is really being used in a particular place and how to move quickly to a new frequency band when an existing user with higher priority is detected. The technology to accomplish this feat has already being demonstrated and implemented in the new IEEE 802.22 standard recently approved, as well as in others currently being considered.

IEE 802.22

Stimulated by the impressive success of WiFi (due mostly to the use of unlicensed, open spectrum), the IEEE created a working group to address the requirements of a Wireless Regional Area Network. The challenge was to develop a technology suitable for long distance transmission that could be deployed in different countries (with quite different spectrum allocations), so they focused on the spectrum currently allocated to TV broadcasting which spans approximately from 50 to 800 MHz. Nowhere is this spectrum being used in its entirety all the time, so there are "White Spaces", fallow regions that could be "re-farmed" and put to use for bidirectional communications. In rural areas all over the world, but specially in developing countries there are large portions of spectrum currently under utilised. It is expected that IEEE 802.22 will enable dynamic spectrum access in a similar way to IEEE 802.11 (WiFi), allowing access to open spectrum. Of course not all the spectrum can be liberated at once, a gradual process is required as the many technical, legal, economic and political hurdles are solved, but there is no doubt that this is the trend and that IEE 802.22 paves the way to the future of spectrum allocation. In order to assess the availability of a given frequency channel at a given time two methods are being considered: channel sensing and a database of primary users in a given geographic location at a given time.

Channel sensing means that prior to an attempt to use a channel, the base stations will listen to the channel; if it is being used it will try another one, repeating the procedure until a free channel is found. This procedure is repeated at regular intervals to account for the possibility of stations coming alive at any time. This method should suffice, nevertheless current spectrum holders have successfully lobbied the regulators to enforce the implementation of the second method, which is much more complicated and imposes additional complexity and costs in the consumer equipment.

The second method consists in the building of a database of all the existing incumbent transmission stations, with their position and respective coverage area in order to establish an "off limit" zone in a given channel.

A new station wishing to transmit must first determine its exact position (so it must have a GPS receiver or other means to determine its geographic location) and then interrogate the database to ascertain that its present location is not in the forbidden zone of the channel it is attempting to use.

To interrogate the database, it must have Internet access by some other means (ADSL-Asymmetrical Digital Subscriber Loop, Cable, Satellite, or Cellular), besides the 802.22 radio (which cannot be used until the channel is confirmed as usable), so this adds a considerable additional burden to the station hardware which translates into additional cost, beside the cost of building and maintaining the database.

In the US the FCC (Federal Communications Commission, the spectrum regulatory agency) has been promoting the building of the database of registered users and have authorised 10 different private enterprises to build, operate and maintain such repositories.

Furthermore, field trials of the standard are been conducted. In the UK, OFCOM (the spectrum regulator) is also conducting IEE 802.22 trials and concentrating on the database method having ruled out the spectrum sensing method for interference mitigation. Although IEEE 802.22 is the formally approved standard that has received the most publicity, there are several competing candidates that are being explored to leverage the TV White Spaces to provide two-way communication services, among them:

IEEE 802.11af

This amendment takes advantage of the enormous success of IEEE 802.11 by adapting the same technology to work in the frequency bands allocated to TV transmission, thus relieving the spectrum crowding of the 2.4 GHz band and offering greater range due to the use of lower transmission frequencies. Its details are still being discussed by the corresponding IEEE 802.11 working group.

IEEE 802.16h

This amendment of the 802.16 standard was ratified in 2010 and describes the mechanism for implementing the protocol in uncoordinated operation, licensed or license exempt applications. Although most deployments have been in the 5 GHz band, it can also be applied to the TV band frequencies and can profit from the significant deployments of WiMAX (Wireless Microwave Access) systems in many countries.

Developing countries advantage

It is noteworthy that in developing countries the spectrum allocated to broadcast television is only partially used. This presents a magnificent opportunity to introduce wireless data networking services in the channels that are not currently allocated, and to start reaping the benefits of 802.22 in a more benign environment, where the spectrum sensing and agile frequency changing required to share the crowded spectrum in developed countries can be dispensed with. The usefulness of the lower frequencies for two-way data communications has been proved by the the successful deployment of CDMA (Code Division Modulation Access) cellular systems in the 450 MHz band, right in the middle of the TV allocated frequencies, in rural areas like the Argentinian Patagonian, currently served by "Cooperativa Telefonica de Calafate-COTECAL". COTECAL offer voice and data services to customers at distances up to 50 km from the Base Station, in the beautiful area shown in the figure below:

Figure RS 5: Region served with voice and data services by COTECAL, in Calafate and El Chalten, Argentina.

So there is an opportunity for stakeholders to lobby for the introduction of TV Band Device based solutions at an early stage, while the issues of the digital transition are being considered. This will help ensure that commercial interests of a few do not prevail over the interests of society at large. Activists/lobbyists should emphasize the need for transparency in the frequency allocation process and for accountability of the administration of spectrum in their country or region.

Also it is important that those who wish to deploy networks gain an understanding of the real spectrum usage by spectrum holders in each region of their country. The monitoring of the spectrum requires expensive instruments with a steep learning curve to use them, but recently an affordable and easy to use device has become available that permits analysis of the frequency band between 240 MHz and 960 MHz, which encompasses the higher part of the TV band. Details of this open hardware based RF Explorer Spectrum Analyzer for the upper TV band are at:
http://www.seeedstudio.com/depot/rf-explorer-model-wsub1g-p-922.html
Figure RS 6 shows the RF Explorer for the 2.4 GHz band being used to test an antenna built by participants of the 2012 ICTP Wireless training workshop in Trieste, Italy.

Figure RS 6: Participants from Albania, Nepal, Malawi and Italy testing an antenna with the RF Explorer Spectrum Analyzer in Trieste, February 2012.

This low cost instrument paves the way for a wide involvement of people in the measurement of the real spectrum usage on their own country which hopefully can lead to a better spectrum management.
For additional information see:
http://www.apc.org/en/faq/citizens -guide-airwaves