An alternative spectrum management strategy

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(Original title: Partager le spectre autrement)

Abstract:

Since many years, the radioelectric spectrum is overcrowded by more and more diverse services. However, ITU find frequencies for more and more systems, as for example the second and third generations of cellular mobile telephone. The present spectrum management techniques are reaching their limits. To cope with that request for more and more frequency allocations, it will be necessary to adopt new spectrum management methods.

This paper present the more promising ways to improve the global spectrum availability: improvement of signals technical parameters, better evaluation of unintentional interference, more realistic interference scenarios, precise estimation of user's needs...

Later, the paper shows how new spectrum management techniques are internally used by the more recently introduced systems. It concludes on the possible ways to extend those new spectrum management techniques to different systems sharing the same frequency band.

A more detailed analysis of the evaluation methods of the new spectrum management strategies will be made in a further paper. An appropriate balance between analytical computations and simulations will be proposed.

Glossary:

- BER: Bit error rate,
- CCIR: Comité Consultatif International des Radiocommunications,
- COFDM: Coherent Orthogonal Frequency Division Modulation,
- DFS: Dynamic frequency Selection,
- GSM: Global System for Mobile communications,
- HATA: Okumura-Hata propagation model,
- ITU: International Telecommunications Union,
- QPSK: Quaternary Phase Shift Keying,
- 16 QAM: 16 states Quadrature Amplitude Modulation,
- RITA: Réseau intégré de transmissions automatiques (The French army tactical network),
- TDMA: Time Division Multiple Access,
- UMTS: Universal Mobile Telecommunication System,
- WCR: World Radiocommunications Conference.

Introduction:

When the present spectrum management methodology was defined by ITU-R, previously CCIR, the telecommunication and RADAR technical background was very different from the present ones. All modulation types, RADAR pulse shaping and receiving signal processing were generated by analogue techniques. When the different ITU services were defined, each one was precisely specified to fit with specific operational needs. Transmitted frequencies were usually fixed or very difficult to modify. Correlatively, the user's number was very low. For those reasons, it was possible to achieve stable frequency allocations for all users.

Now, with the development of digital technology, everything is different. Telecommunication modulations are digital and highly diversified. The recent GSM cellular system use TDMA and, depending on the type of transmitted data, a lot of different error correcting codes. A new system as UMTS is even more complicated and adaptive, use spread spectrum and an advanced power management technique to achieve a wide-band mobile transmission.

Current radars use pulse compression, and sometimes phase arrays antennas or even some kind of digital beam forming in a limited number of elevation angles. Side lobe cancellation reduces the minimum detectable source level. Multitarget tracking improve overall radar performances. In space, many SAR (synthetic Aperture Radar) are in use.

Fortunately, in that new context many things remain the same as at the beginning of the 20th century, for instance: the basic physical laws, the radio-waves propagation mechanism, etc. However, the sensitivity of modern digital systems to propagation perturbations and other user jamming is entirely different. Digital modulation and radar signal processing are less perturbed by multipath propagation and the jamming power resulting from the presence of other users than the previous analogue techniques. Last but not least, similarly to new cellular mobile systems, many systems combine these improvements with a spatial redundancy due to the system design.

In this new environment, the spectrum management objective remained the same: protection of existing user's frequency allocation and reduction of the jamming probability to a minimum level. Obviously those objectives adopted at the international level still remains. However, the new digital techniques allow us to look for an adaptation of the management method defined for analogue systems.

To find the possible means of improvement, we have to analyse how present concepts fit to the optimisation of the spectrum use. Even the most accepted ones have to be analysed and their adoption justified: transmitted frequency bands, channel spacing, jamming signal to noise level, etc.

This analysis needs to estimate global results on generic scenarios defined to compare the results of different technical choices. These scenarios, even those which are different to practical ones, have the tremendous advantage of allowing a fast evaluation of the different parameters' influence and the detection of the major extra-capacity fields.

1 A simple generic scenario:

This scenario has been selected for its ability to show the relative efficiency of the various spectrum management strategies.

1.1 Input data :

This very simple scenario has been adopted for its demonstrative capacity. Its parameters are as follows:

- All emitters are supposed to be uniformly implanted in the field (fig 1).
- The simulated field can be restricted to a circular sector.
- When several frequencies are available for a transmitter, his frequency is randomly selected among the available ones.
- The propagation model is statistically defined (a free space propagation path being able to enter that specific model by cancelling the model's statistical spreading value).

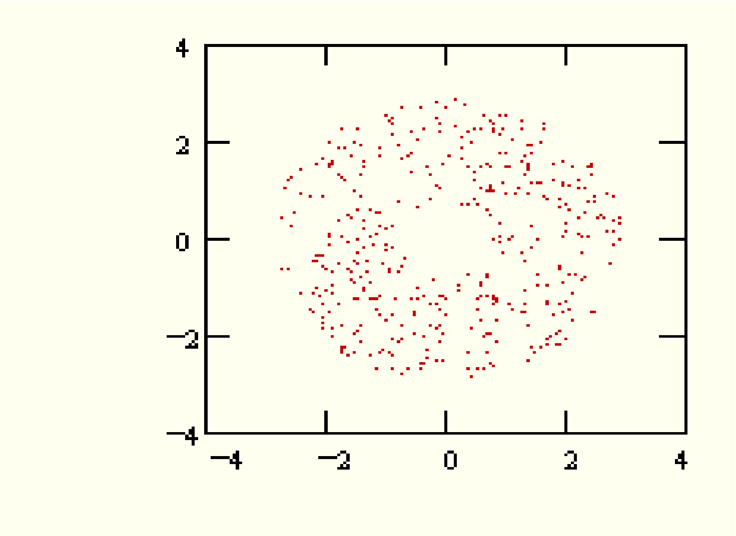

Fig1: Transmitters locations.

As we will see later, the evaluation process based on this type of scenario is unable to assess a real frequency allocation in a specific field. However, it is perfectly able to predict quantitatively the effect of a specific parameter modification.

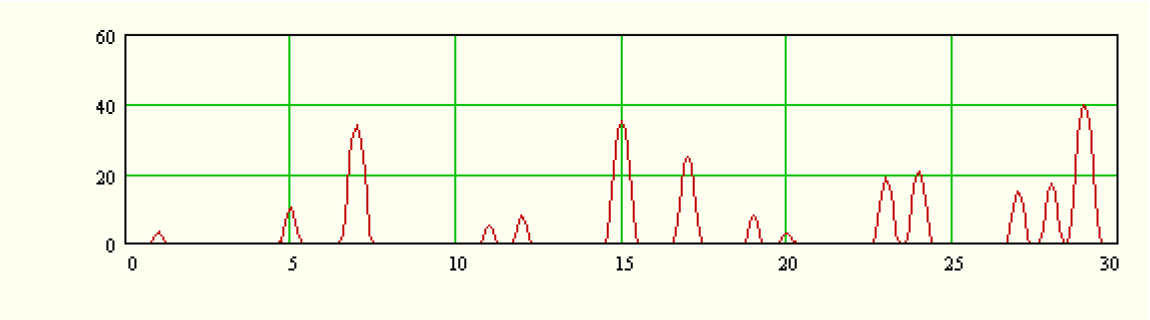

Fig. 2: on-air spectrum.

Instead of analysing the received useful and jamming signals in the air (fig 2), I decided to look at the received power at the output of the receiving filter (fig 3). In those two figures, displayed levels are level in dB above thermal noise level versus frequency in channel numbers.

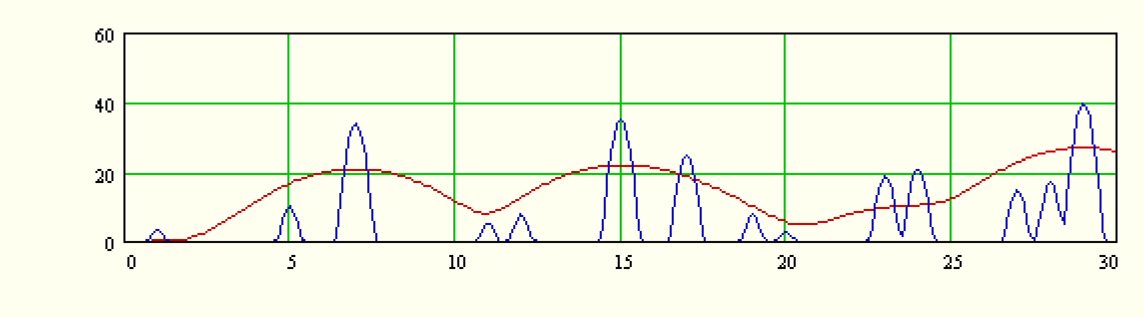

Fig. 3: Received signal.

The blue curve shows the received signal with an adapted bandwidth, the red one resulting in the use of a wider receiving filter. The choice of this parameter provides a global signal to noise ratio taking into account not only the propagation losses but the antenna gains and even the spurious responses as far they can be specified in a probabilistic way.

To reduce software complexity, a very simple propagation model, adopted in an ITU study for mobile radios has been selected:

$$A = 128.1 + 37.6 \cdot Log(D)$$

An extra 10db random value is added to take into account the ground to ground propagation statistical dispersion (Fig 4).

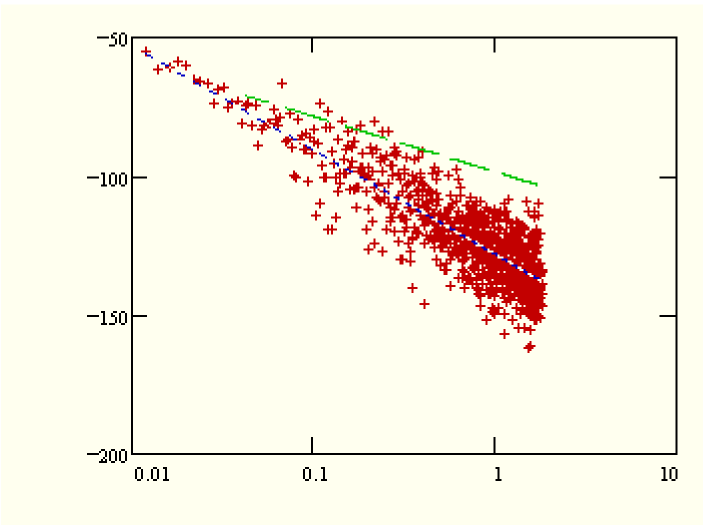

Fig 4: Level in dB versus distance.

For RADAR antenna gains, I selected a typical gain pattern used by IUT studies. The red curve is the specified pattern, and the blue curve a classical sin(x)/x function (fig 5).

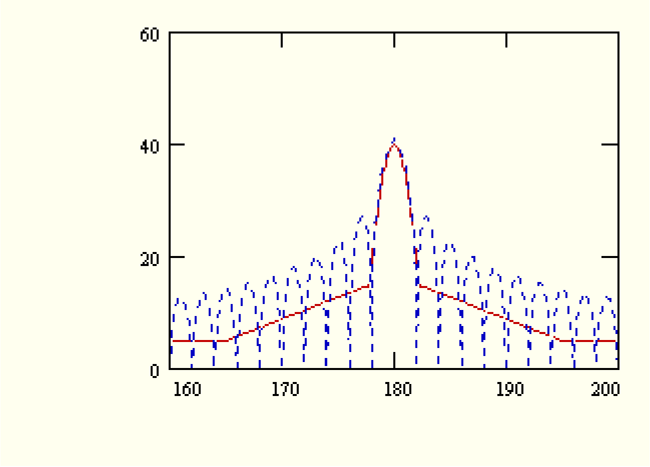

Fig 5: Typical RADAR antenna gain in dB versus azimuth.

The specified antenna pattern is really very close to an apodised aperture function.

1.2 Output data :

Whatever the spectrum management strategy selected, conclusions will be drawn on the base of the received power spectrum, as analysed by the victim receiver. The results are presented in the most synthetic way, by the jamming received power histogram. The two axes are: horizontally the level above thermal noise in dB, vertically the probability of finding a jamming level lower than the selected value on the horizontal axis.

That histogram has been computed for the previous example (fig 6). The red curve is the real spectrum histogram. The blue curve is obtained with a larger filter. The green one is obtained only with the 30 centre frequencies of the channels.

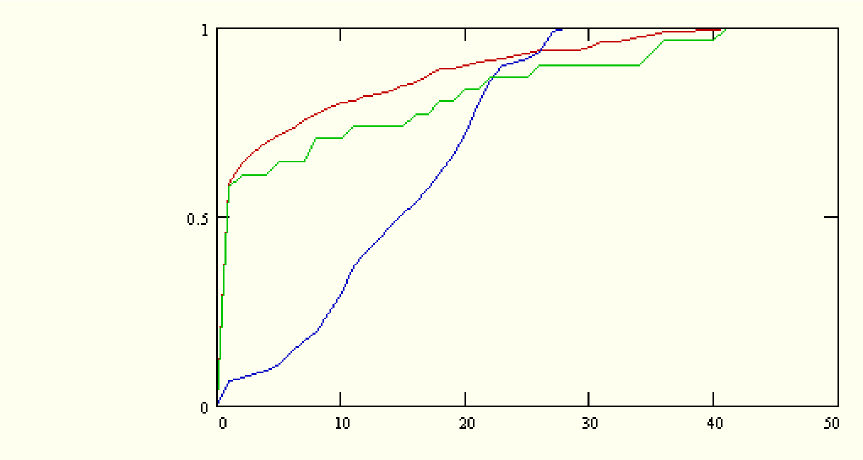

Fig. 6: Received level histogram.

A channel will be free if the jamming level is under a given level. From this example, you can see that the probability to find a free frequency is higher if the frequency is randomly selected than if the choice is limited to the defined channels.

2 Significant parameters identification:

The spectrum congestion is determined by several parameters:

- Technical parameters (including spectrum efficiency of transmitters),
- Waves propagation from transmitters to receivers,
- Type of scenario,
- Spectrum management technique,
- System's parameters.

Let us analyse the influence of each of them in the spectrum congestion.

2.1 Technical parameters :

Present digital systems are highly sophisticated. However, a single model can describe either the telecommunication or the radar signals.

1.1.1 A transmitted signal model :

This common model is described below (fig 7).

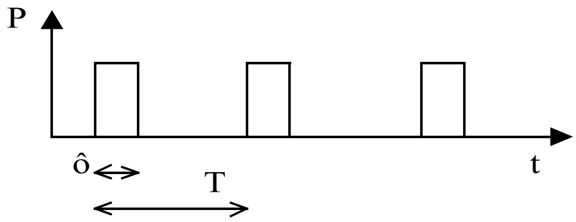

Fig 7: A common signal model.

In the past, telecommunications were using only continuous waves and radar only short pulses. Now, telecommunications use more and more TDMA techniques. Simultaneously Radar uses pulse compression to adapt to the solid state transmitter capacities.

Now both telecommunications and radar signals are similar, even the used technique's names are different: pulse compression or spread spectrum technique,etc.

2.1.2 Modulation and error correcting codes :

For many reasons radar are still widely using chirp modulations. However, as far as the sensitivity to jamming signals is concerned, this modulation is similar to the digital modulations used in telecommunications. Moreover, the associated post processing, error correcting codes or incoherent integration and tracking, are equivalent techniques.

In the telecommunication field, a huge amount of work has been done on modulations and error correcting codes.

The modulation's transmitted spectrums are clearly defined by theoretical limits. For instance, the UMTS specified transmitted power spectrum (blue curve) and the theoretical limit (red curve) are similar (fig 8). The displayed curves are transmitted power density versus frequency offset from the carrier frequency.

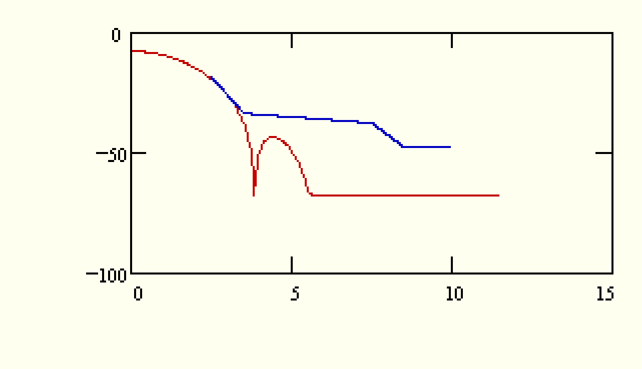

Fig 8: UMTS transmitted spectrum.

All modulation spectrums are similar, except the COFDM spectrum. This one is equivalent to the spectrum of a set of carrier frequencies. The results, with and without amplitude shaping are presented in fig 9.

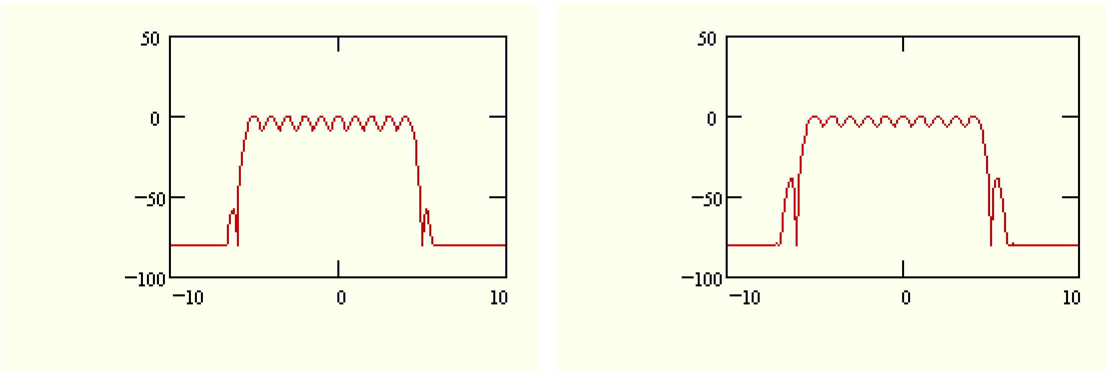

Fig 9: COFDM transmitted spectral power density.

The practical modulation efficiencies can also be predicted. The next chart (fig 10) shows in red the theoretical bit error rate of QPSK, in blue a corrected value to take into account the intersymbol interference, and in black the value obtained by simulation of a real hardware. All values are related to the energy received for each information bit compared to the thermal noise level (E/N_0).

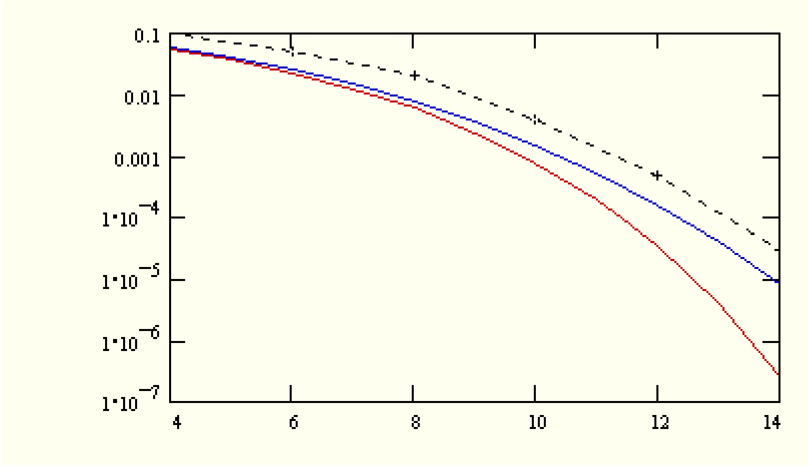

Fig 10: QPSK modulation BER versus E/N_0.

A scientist designed a huge quantity of error correcting codes. A system such as GSM, the European mobile radio system, uses several tenths of such codes adapted to each particular transmission case.

Fortunately, their global performances are close to a theoretical limit and can be predicted. It is possible to compute, for each code length, the needed redundancy to reduce the link error rate to any user specified bit or block error rate requested value (fig 11).

On this chart, you can see an example of errors correcting codes theoretical efficiency for a single code length and several errors correcting capacities.

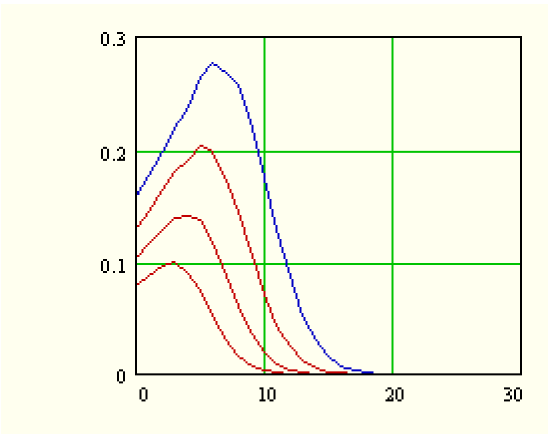

Fig 11: Output error rate versus code error correction capacity.

For a given code length, those curves computed for different input error rates display the final error rate after correction versus the code correction capability.

The same results can be presented as relations between input and output bit error rate (fig12).

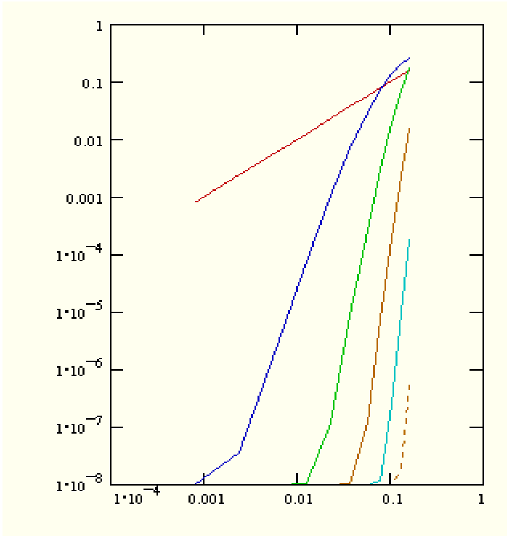

Fig 12: Output BER versus input BER.

Each curve computed for a given correction capability, displays the output's BER versus the input's BER.

The coding gain is independent of the code type but can be slightly lower if the code distance isn't maximal. The only significant parameter is the code length, limited by the processing power of the receiver.

Unfortunately, the use of error correction is not free of charge. Even the maximal code distance needs an extra channel capacity, and correlatively an extra transmitted power.

It is possible to summarise all the results on the modulation and coding techniques in a summary chart (fig 13) showing the needed spectrum versus power efficiency E/N_0.

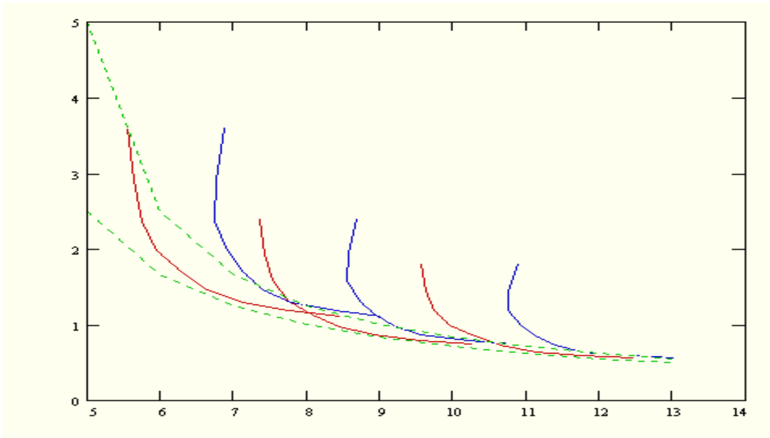

Fig 13: Modulation and coding efficiency.

The X-axis is the E/N_0 needed value. Th Y-axis is the relative needed channel bandwidth. The blue and the red curves show results for 200 and 500 bits codes. For each code length the results for QPSK, 8PSK and 16QAM are displayed.

This shows a very important result. Whatever the precise selected modulation scheme, the modulation and coding spectral efficiency is limited by a theoretical value approximated by the green curves. It is only function of the code length accepted.

2.1.3 Technical parameters influence :

We have seen that most of the technical transmitter and receiver parameters can be easily predicted using only theoretical results. We have also observed that the modulation and coding efficiency cannot be greatly improved in the future.

The spectral efficiency of present digital devices will not be significantly improved in the future.

2.2 Waves propagation :

Radioelectric wave propagation is a widely studied topic. When the number of transmitters and receivers is low, as in radio relay networks, it is possible to use deterministic models taking into account the real terrain. In other cases such as mobile systems or licence free equipment, only statistical models can be used.

There are a lot of such models, more or less limited to a given type of link or environment. Here are some of them (fig 14).

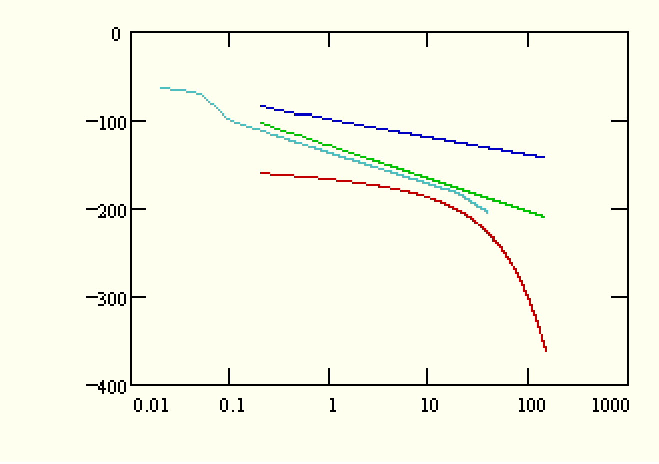

Fig 14: Propagation models: forecast level versus distance.

The blue curve is free space model, the green one the model selected for demonstration purpose, the cyan one the HATA model and the red one the spherical diffraction model. Apart from the free space model, these models include an additive random dispersion due to ground level fluctuation.

We should not forget that, in the case of ground-to-ground propagation, the range is variable from link to link in a ratio of more than ten.

In the case of some frequency management methods, a better knowledge of the radioelectric waves propagation would have a direct influence on the effective spectrum efficiency. In some other cases, only a better knowledge of the propagation statistical values is really necessary to assess the jamming probability or the channel availability.

2.3 Scenarios :

Scenarios are essential, even though their role is often underestimated.

2.3.1 Spatial parameters:

Usually, a scenario describes how the system's transmitters are set in the field (or in space). Depending on the system use, we have to consider several types:

- Deterministic scenarios: Those scenarios are used to describe fixed systems like radio-relay networks. All transmitters are supposed to be in permanent use. This type of scenario is implicitly adopted by current frequency allocation methods.

- Partially random scenarios: those scenarios are able to simulate sets of fixed stations, transmitting in a sporadic way. Its use can be extended to the base stations of cellular networks, and to some extent, to the associated mobile stations.

- Random scenarios: In this case, transmitter's locations and spatial density are unknown. Many consumer's products belong to that set: wireless phones, mobile radios, hiperlans,etc.

2.3.2 Service related parameters:

A scenario is not really adequate to determine the optimal frequency allocation if the following data are not provided:

- The transmission mode: permanent emission, regular vacations, sporadic transmissions...
- Real-time requirements: permanent availability, transmission within a specified time, low priority data, etc.
- Quality of service: fixed, variable with the system activity like internet, compatible with a given service like in a radar track refreshing system, etc.
- Acceptable burst-type high level interference.

When all telecommunication systems were analogue, this type of interference had to be strictly eliminated. With the current digitaltechnology, it is possible, within reasonable limits, to design a system to cope with this type of interference.

ITU proposed for radar protection to fix the acceptable interference level to –6 dB under thermal noise level or even –10 dB under that level for radar used for security purpose.

In fig 15 the sensitivity reduction created by this type of increase in a telecommunication receiver noise level has been plotted (red curve: without interfering noise, blue dotted line: -10db noise, green dotted line: -6 dB noise). All curves are error rate versus E/N_0.

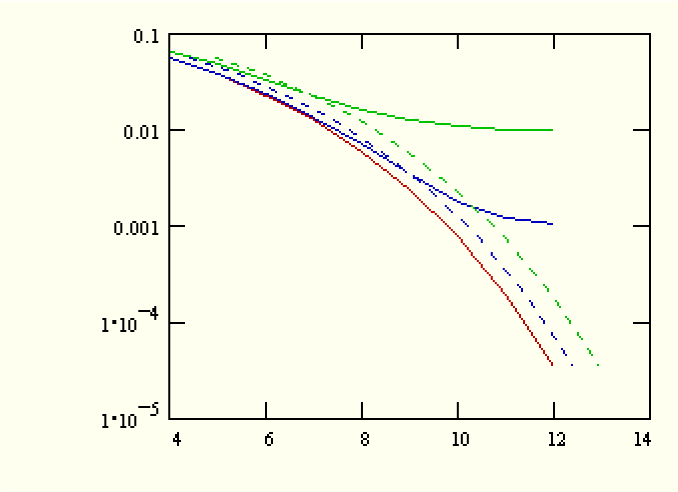

Fig 15: Relative influence of continuous and burst noise.

The results for a 1% and 0.1% added error rate are the blue and green lines. For the usual BER before error correction, the influence of these two types of interference are comparable. Those results show that a limited number of high level pulses could be accepted by specially designed telecommunication systems.

This service-related part of the scenario parameters is very important. As it has been said earlier, the frequency allocation process is defined in order to protect previously accepted user transmissions. If these service parameters are not specified, authorities will be obliged to suppose they are the most difficult to achieve, i.e. permanent emission and high service quality.

3 Evaluation of management strategies :

A frequency allocation strategy can be evaluated on the basis of simulation results, or analytical computations. This second method, generally possible in the case of generic scenarios, yields more precise results (fig 16).

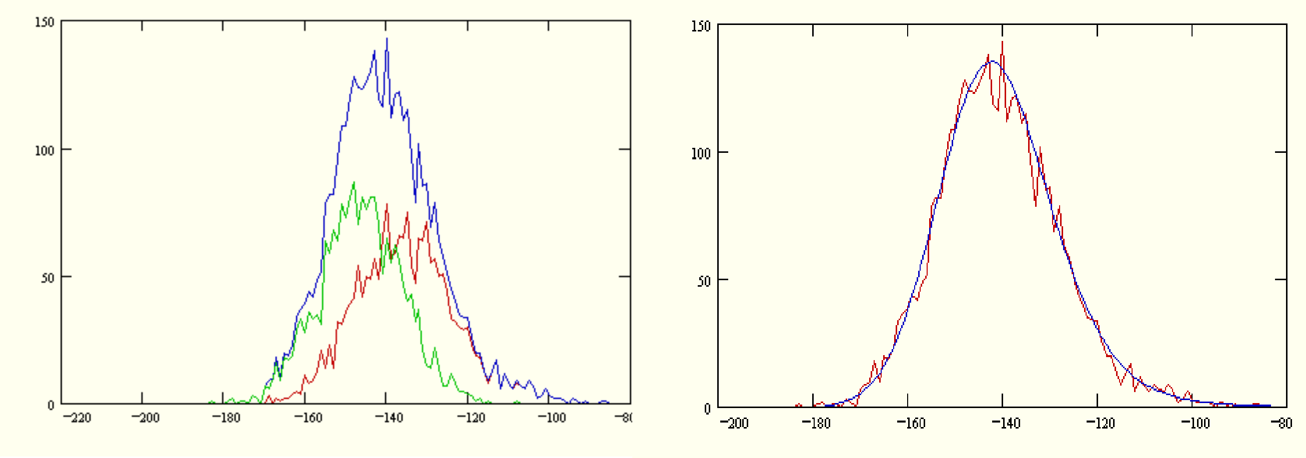

Fig 16: Transmitted levels histograms.

On the left chart, you can see, in red a received level histogram from the 2000 nearest transmitters set, in green the levels received from the 2000 next transmitters and in blue the global histogram.

On the right chart, in red the previous histogram obtained by simulation and in blue the theoretical value. You can see the perfect identity, on simple generic scenarios, of the two results. As expected, some distant transmitters are received with a rather high level while nearer transmitter levels are much lower.

The efficiency of the scenarios based evaluation method is shown by the two examples presented below.

3.1 Influence of propagation deterministic model errors :

If we have to study a radio-relay network, the right way is to suppose that frequency allocations will be chosen with a determinist propagation model. This model peak-to-peak error has to be taken in account. As signal to interference is a ratio, the needed link margin is twice this value. A 5-dB peak-to-peak propagation forecasting error is very low. In this case, a total margin of 10 dB has to be added. The effect of this margin is identical to a 10-dB rise in the jamming signal level (fig17).

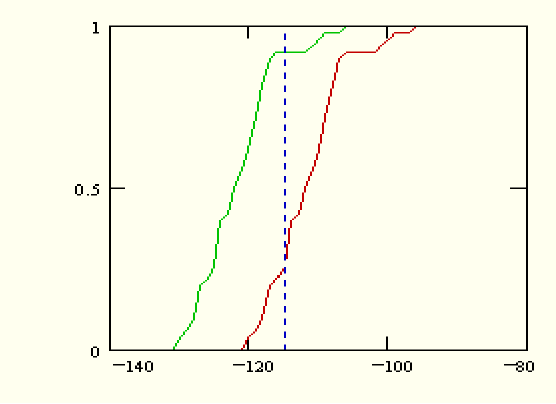

Fig 17: Free channel probability versus threshold level.

The green curve is the channel availability on 50 frequency channels. The red curve is that curve 10 dB translated. The blue line is a specific level supposed to be the maximal jamming level accepted by a given channel.

In that specific case, the channel availability, i.e. the probability of finding a channel free, effectively better than 90% is estimated at only 20%.

3.2 Influence of channel spacing :

Since frequencies are allocated to specific uses, the definition of the right channel spacing has been done carefully. However, it is easy to show that channel spacing isn't a sensitive parameter for spectrum congestion.

Let us have a look at the received levels. The channels number is 50 and the channel spacing is adapted to the signal bandwidth (fig 18).

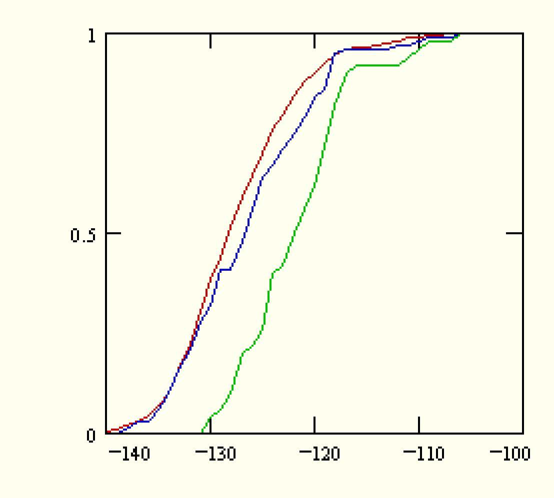

Fig 18: Free channel probabilities.

The green curve is the probability of receiving a signal lower than a given level. If we use in the same total bandwidth 100 central frequencies instead of the 50 possible ones, the curve becomes the blue line, and for 500 frequencies the red one. In figure 19, you can see the received spectrum. The green curve is now higher than the two others are. In that case, between the 50 allocated channels, some frequencies are not used efficiently.

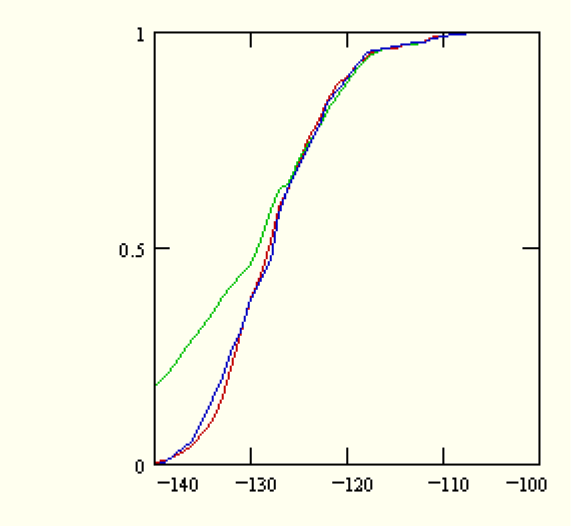

Fig 19: Free frequency probabilities.

This shows that choosing the transmitting frequency randomly is more efficient than to define the occupied channel precisely. However, this method uses more computer time and was not possible 50 years ago.

4 The current spectrum management method:

The frequency management method is the key point. A new system will be fielded only if it is possible to introduce a suitable frequency band in the spectrum. The previous user systems will be effectively protected only if this frequency band does not create new interference.

Traditionally, frequency allocation has been done in a multi-level process:

- At the international level, the allocation of a frequency band to a new service needs several times a three-year delay (due to the WRC periodicity of three years).
- On a national basis, if a coordination with another country is necessary, the time taken is usually more than six months.
- Inside each country, some administrative bodies such as the armed forces can allocate frequencies by local authority delegation. In this way, the time taken can be shorter.

Recently, since the cellular telecommunication systems development, a second allocation level has been under the control of “operators” or even of the systems themselves:

- In systems like the European GSM, operators are free to select their base station frequencies inside a defined set.
- In the French RITA, radiotelephones select their operating frequency by RCL (“ Recherche de fréquence libre “ or free channel selection). A similar process, named DFS, is used by hiperlans.

- Defence anti-jamming transmitters use frequency hopping (FH).
- Some systems are mixing all signals in a common frequency band (UMTS).

The incredibly large development of mobile phones is due to this second spectrum management level, which is often forgotten as it is under the operator's control
Compared with regulation authorities, operators have a huge advantage. They are able to make the balance between their various customer's requests, link quality and availability. They are able to adjust the interference level to the maximum acceptable level, with a view to maximising the traffic, and consequently their income.
Doing that, they proved that it is possible to widely increase the frequency spectrum transmission capacity, by accepting a large reduction of jamming margins and some reduction in system quality.

5 The frequency management evolution :

To cope with the ever increasing frequency band request, several changes have yet been decided:

- At the legal level, frequency allocations are attributed in an ever more precarious and revocable way. Fixed user royalties are introduced to incite users to free their insufficiently occupied frequency bands.
- At the technical level, the system's contribution to the frequency management processes optimise the spectrum use.

In the long term, the frequency spectrum management evolution should go in two different ways:

- A better adaptation of present method to modern digital systems.
- An increasingly efficient management inside the systems, or between systems sharing the same frequency band.

5.1 An overall frequency management :

That management level is and always will be mandatory. It has to be better oriented towards digital systems. This pre-supposes the followings evolutions:

- **Definition of new digital services:** Technically, current ITU services were defined when systems were analogue. With digital technology, they have lost a large part o their pertinence. It would be useful to define new services clusters classified according to their channel capacity, modulation type, environment (fixed, mobile, aeronautical or spatial), and the type of transmission (permanent, sporadic, etc).

- **Adoption of new interference criteria:** Instead of analogue radio sets, the digital system receivers are able to cope with the presence of a few high level pulses. Similarly, Modern Radar using steering antennas are much less sensitive to spatially or temporally limited jamming, their power being able to be dynamically allocated according to the needs.

- **A better system description:** It will be impossible to describe fully the systems behaviour for electromagnetic compatibility studies. However, a precise analysis of their spatial or temporal transmitted power fluctuation could allow the definition of new solutions able to allow them to share a common frequency band.

- **Lastly, new propagation studies,** oriented by electromagnetic compatibility studies and systems design are still needed.

However, an improved centralised management will stay unable to satisfy by itself the huge needs of future electromagnetic systems, as long as sporadic transmissions remain an important part of the user's request.

5.2 System's frequency management :

Only the system itself is able to take into account all specific parameters linked to his precise structure. Close to the user requirements, this type of management adapts to need fluctuations. Those points are the main reasons of the tremendous extent of mobile phone systems.

In a system such as the European GSM, operators continuously adapt to the optimal interference-capacity compromise. Moreover, a frequency hopping process randomises inter-cell jamming. Obviously, that process would have been rejected if the two cells have been the property of two independent allocators.

Systems designed for internal powerful frequency allocation partially applicable to the optimisation of intersystem interference level.

6 Conclusion :

The promotion of new frequency management techniques supposes, between the various players, a common technical analysis of the frequency allocation challenge. If they fully agree on the best technical solutions, they will become able to reach winner-winner type agreements.

To reach that objective, it seems necessary to adopt a pragmatic method, starting from simple concepts and clearly defined hypothesis, initially excluding any direct application to a specific system.

On that basis, it will be later possible to imagine a way of sharing frequencies between generic systems, brassboard of future intersystem agreements.

To manage the spectrum in an alternative way seems a utopic objective. However, the evolution process is still running. The need for a new spectrum management is taken into account by telecommunication systems and telephone operators. It will be accepted by all spectrum users in a forcible future.

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