**Zeitschrift:** Bulletin des Schweizerischen Elektrotechnischen Vereins, des Verbandes Schweizerischer Elektrizitätsunternehmen = Bulletin de l'Association suisse des électriciens, de l'Association des entreprises électriques suisses

**Herausgeber:** Schweizerischer Elektrotechnischer Verein ; Verband Schweizerischer Elektrizitätsunternehmen

**Band:** 65 (1974)

**Heft:** 16

**Artikel:** Electromagnetic Compatibility

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**DOI:** https://doi.org/10.5169/seals-915440

# Electromagnetic Compatibility [1])

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*Elektromagnetische Kompatibilität bezieht sich auf die Möglichkeit verschiedener Systeme (oft nicht nur elektronischer Art) richtig zu arbeiten, wenn elektrische Ströme, magnetische Felder, elektromagnetische Strahlung, von anderen Systemen verursacht, mit anwesend sind.*

*Im Spital hat man empfindliche Instrumente neben Hochfrequenzgeneratoren. Streuströme verschiedener Apparate können den Patienten auf dem Operationstisch gefährden.*

*Eine Kernexplosion in der Exosphäre unterbricht alle Radioverbindungen und kann elektronischen und elektrischen Apparaten grossen Schaden zufügen.*

*Bei den sehr grossen unterirdischen Antennen für tiefe Frequenzen ist Kompatibilität mit der Umwelt eine wichtige Frage.*

*Bei Frequenzplanung für Rundfunk und Kommunikation kommt Kompatibilität an erster Stelle.*

*Elektronische Rechner und ihre Verbindungen sind für Impulsstörungen empfindlich. Für Mensch und Tier sind Strahlungen verschiedener Art schädlich.*

*Das Internationale Spezielle Komitee für Radiostörungen (CISPR) befasst sich in erster Linie mit allen Apparaten, die den Empfang von Rundfunk und Fernsehen beeinträchtigen können.*

*La compatibilité électromagnétique se rapporte au fonctionnement efficace de systèmes différents (souvent, pas toujours électroniques), en présence de courants électriques, de champs magnétiques, ou d'un rayonnement électromagnétique d'autres appareils.*

*Dans un hôpital, on dispose d'instruments sensibles, mais aussi d'appareils de diathermie. Les courants de fuite d'appareils divers peuvent mettre en danger le patient sur la table d'opération.*

*Une explosion nucléaire dans l'exosphère interrompt toutes les radio-communications et peut causer des dégâts importants aux appareils électroniques et électriques.*

*Les grandes antennes enterrées pour basses fréquences posent des problèmes de compatibilité avec l'ambiance.*

*Pour la planification en radiodiffusion et télécommunications la compatibilité électromagnétique est une affaire importante.*

*Les ordinateurs électroniques sont sensibles aux perturbations impulsives. Les radiations de diverses natures sont dangereuses pour les personnes et les animaux.*

*Le Comité International Spécial des Perturbations Radioélectriques (CISPR) s'occupe avant tout des appareils qui peuvent dégrader la qualité de la réception des signaux de radiodiffusion et de télévision.*

## 0. Introduction

"Compatible" is according to the Oxford Dictionary "able to exist together with". "Electromagnetic compatibility" is the ability of a system to function properly together with an electric current, a magnetic field or a source of electromagnetic radiation. There are nuances in judgment when one is asked, whether or not a system functions adequately. The International Telecommunication Union has defined the term "harmful interference": Any emission, radiation or induction which either singly, or with others, endangers the functioning of a radionavigation service or of other safety services or seriously degrades, obstructs or repeatedly interrupts a radiocommunication service operating in accordance with the Radio Regulations. In the CCIR documentation we also find the terms "acceptable", "permissible" and "allowable" interference. They all define levels of interference which would not cause the total noise power to exceed another defined level which is one of the transmission standards of the circuit as a whole.

The term "electromagnetic compatibility" does not only refer to communication systems, as we shall see, but also in the general case we will have absolute incompatibility where the functioning of one system is impossible, when the other works, and acceptable compatibility, where the functioning of one system though less good than possible, when the other system is used, is still in agreement with certain standards.

In many cases the system that has to function properly is an electronic system, e.g. a receiver of radio, television or communication signals, or an amplifier of a medical apparatus. The interference can reach the receiver via the antenna, or via the supply wires, or by direct pick-up of the chassis. We may thus have either conducted or radiated interference. In the case of a ferrite or frame aerial the magnetic field is the most important parameter.

The system that is interfered with, however, does not need to be an electronic system. It may be a living system, human or animal. The human body needs protection against radiation in the Megahertz or microwave region. Electric currents can harm us. Magnetic fields affected the growth rate of young chicken.

In most cases the interfering effect is not intended, but a byproduct of the use of an electric or electromagnetic system for another purpose. Already for about forty years representatives of the broadcasting organisations, the telecommunications services and industry meet each other in the International Special Committee on Radio Interference. They try to reach a compromise between the wish of industry to manufacture modern electric and electronic equipment at a reasonable price, and the desire of the broadcasting authorities to give undisturbed reception to listeners and viewers with the field strength on which their planning is based.

In case living systems are affected agreement on maximal leakage currents, or maximum permissible radiation levels is necessary.

Finally intentional interference may occur even in peacetime. Then the task of the EMC expert is to design his own equipment so that it will work well despite the intended disturbance. There are several ways in which he can try to reach his goal, e.g. by spread spectrum techniques or by redundancy. During recent years attention has been drawn to the effect of the Electro Magnetic Pulse, caused by a nuclear explosion in the exosphere. Such a pulse may disturb and even do irreparable damage to electronic or electric systems, and the possibility "to exist together with" is a matter of life and death for defense organizations.

In electronic systems one has to weigh the immunity for undesired signals against the sensitivity for desired signals. In computers it may be desirable to work with low power microcircuits, yet when the equipment has to work in a high level interference ambiance, we will use higher levels in the computer.

[1]) This paper was first given as an invited paper at Eurocon 1974, The European Conference on Electrotechnics, Amsterdam, April 1974.

The simplest solution may not be the best one. For some-time it was thought that an increase in the power of the national transmitter was the easiest method to reduce the interference from a foreign transmitter. However, this may well only lead to an escalation, and now international agreement on a sound basis of computer calculated service areas is the preferred mode of action.

After this general survey we will discuss some subjects in more detail:

1. Electromagnetic compatibility and the hospital
2. The nuclear Electro Magnetic Pulse
3. Effects of very low frequency fields
4. Planning frequency allocations for a broadcast transmitter network
5. General planning of communication systems
6. EMC in computer systems
7. Work in the domain of CISPR

### 1. Electromagnetic compatibility and the hospital

In a hospital we have sensitive instruments such as cardiac pacemakers, the electrocardiograph, the electromyograph and the electroencephalograph. There are also digital devices susceptible to transient or impulse type interference in data processing computers, physiological signal analysis and read-out apparatus. On the other side we have diathermy apparatus, high frequency heat-sealing equipment, electrosurgical units, appliances using switches like refrigerators and lifts, microwave ovens, paging systems, and domestic appliances such as vacuum cleaners, fluorescent tubes, toasters, radio and television receivers. Some precaution must be taken by suppressing the interference at the source, or putting the worst offenders in a Faraday cage. The latter measure is also taken to create radiofrequency free areas for sensitive instruments [1].

Some pacemakers [2] were found vulnerable to field intensities as low as 0,3 mV/m. However this seems to be an extreme case (or a misprint) and in a number of other experiments [3], effects start at 3 V/m and some units function normally in fields of 40 to 100 V/m. The effect depends on the modulation, especially in case of pulse modulation.

The pacemaker is also susceptible to low frequency magnetic fields of approximately 1 Gauss, with one unit susceptible to 47 milligauss. The wearer of a pacemaker should stay away a few meters from microwave ovens, and the active electromagnetic fields of weapons detectors may cause trouble.

Exposure to continuous wave signals may cause damage, but whereas the USSR allows only 10 μW/cm², in the USA a limit of 10 mW/cm² is considered safe (for durations of 6 min). Young chicken [4] collapsed at 25 mW/cm² (16 GHz) and egg production was already influenced by 400 μW/cm². The electromagnetic radiation seems to act as a tranquillizing agent for animals. Experiments showed that plants died after several days of continuous radiation at 10 GHz of about 1 mW/cm².

We are familiar with the stories of accidental electrocution in operating rooms. Leakage currents of the order of milliamperes can shock a person in his everyday normal state of activity, and this is one of the limitations in using capacitors for radio interference suppression. CISPR has a special working group on safety for this reason, and its chairman is a member of ACOS, the IEC committee on safety of equipment. A patient on an operating room table, anesthesized and in many cases lying on a metal sheet electrode with a conducting jelly enabling the use of an electrosurgical scalpel, is in a highly vulnerable state, where currents of the order of microamperes can cause a severe jolt, and in some cases irreversible fibrillation and death. Sets in hospitals have been found with leakage currents in the order of 50 μA. With care a level of 1 μA can be reached. Periodic checking of such equipment is necessary [1].

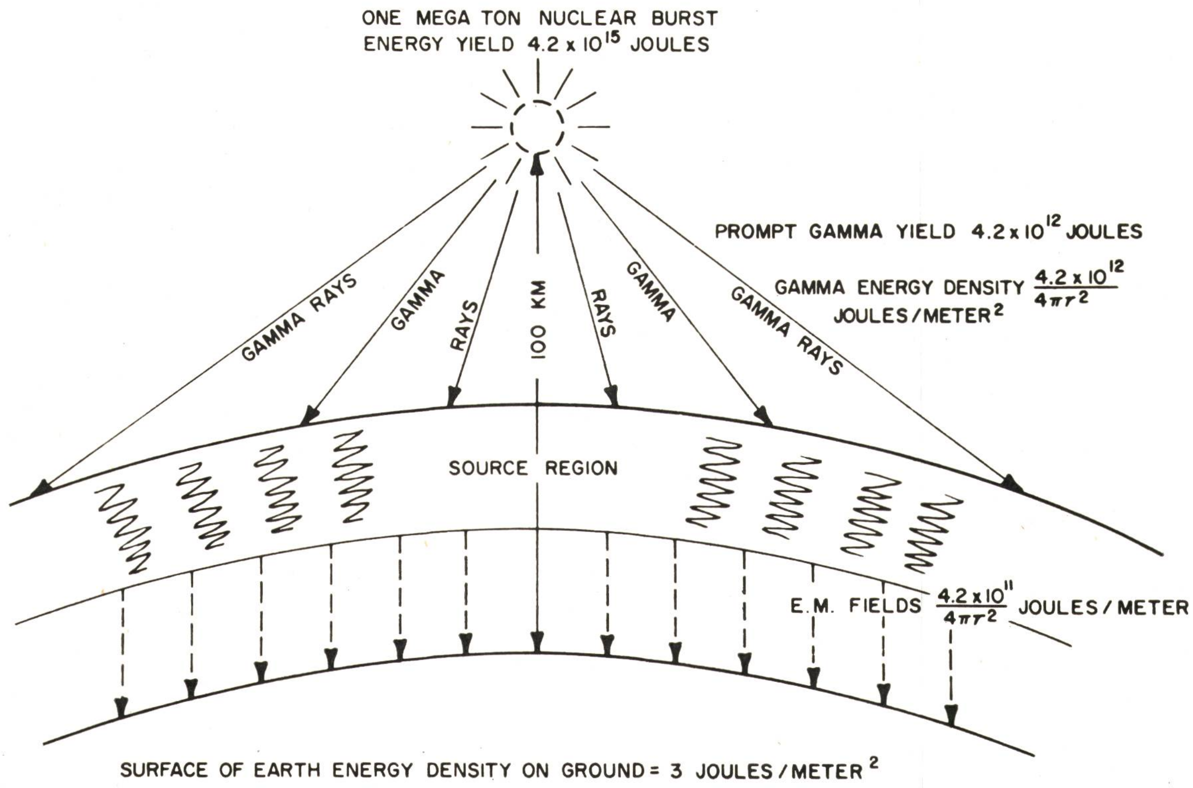


**Fig. 1 Diagram showing the effect of a nuclear explosion in the exosphere**

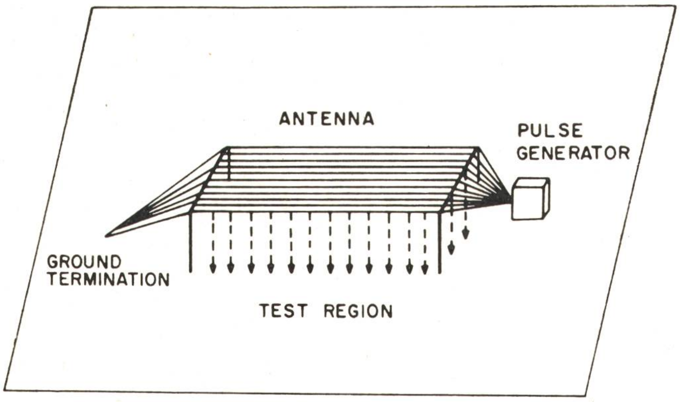

Fig. 2 Transportable similator of EMP

### 2. The Nuclear Electromagnetic Pulse

A nuclear explosion is accompanied by two principal electromagnetic effects: black out and electromagnetic pulse (EMP). Black out refers to the disruption of radar and radio transmissions, as a result of alterations of the electrical properties of the atmosphere, possibly created by the ionizing radiation from the exploding device [5]. Serious concern about EMP effects has recently centered on the high altitude (exosphere) nuclear burst. At burst heights above 50 km there is not sufficient atmosphere around the weapon to create large currents. Instead the gamma rays travel unimpeded until they strike the atmosphere, where they produce Compton electrons. Fig. 1. The region of high current, called the interaction region, is pancake shaped and centered between 20 and 40 km altitude. Its lateral extent may be limited only by the earth's curvature. In a realistic encounter the number of high altitude defensive and offensive bursts is likely to be many dozen spread out over a few minutes or hours. Lightning protection techniques are fairly well established and can be used as a reference point for development of EMP technology. Voltages considerably in excess of 160 KV can appear across the antenna coupling network in an EMP. A transportable simulator with as supporting members hollow fiber glass poles machined and joined together like a 27 m fishing pole has been built. Fig. 2 shows a smaller transportable simulator with threat level capacity at 50 m distance. A logical approach to EMP protection is the use of damage resistant components, an example of which is the use of vacuum tubes in place of transistors at receiver front ends. Shielding of military operating centres, computer buildings, automatic telephone exchanges may be necessary.

### 3. Very low frequency effects

Very low frequency radiation propagates as an evanescent wave over the ocean. It can be used for communication with submarines [5]. The April 1974 issue of the IEEE Transactions on Communications is devoted to this subject. Here we mention only that EMC engineers were asked whether the enormous antennas with north–south and east–west legs of about 25 km length, energized with 300 A of current in the 45 to 75 Hz region, buried 2 m deep, would be compatible with the environment. The current was steadily increased to the final value, and no significant change in the flora and fauna of the plot was found. The Electromagnetic Radiation Management Advisory Council commended the effort because the attempt to understand all environmental aspects of a program before the system goes into operation was a correct decision that established significant precedent. In the meantime a checkerboard like grid of cables ranging from 60 to 120 kms square has been proposed, and its environmental safety is still a matter of controversy.

### 4. Planning frequency allocations for a broadcast transmitter network

In October 1974 another conference will be held on the frequency allocation for broadcast transmitter networks at low and medium frequencies (long and medium waves). Planning should cover the areas of Europe, Africa and Asia. According to CCIR [6] the mutual interference to be expected between two adjacent-frequency channels of a sound broadcasting transmitting network in bands 5 (LF) and 6 (MF) operating, e.g. with double-sideband amplitude modulation is the governing factor in the design of such a network and the attainable quality of the transmitted signals.

The most essential parameters of the transmitter and receiver are:

the channel spacing $\Delta F$,
the bandwidths of the transmitter $B_N$ and of the receiver $B_R$,
the rate-of-attenuation slope of the band-limiting filters at the transmitter $\alpha_N$ and the receiver $\alpha_R$,
out of band radiation of the transmitter,
the modulation factor $m$,
the spectral energy distribution of the modulating signal,
pre-emphasis and de-emphasis at respectively the transmitter and the receiver,
the dynamic compression.

All these factors are taken into account in the mathematical model. Two channels with the carrier frequencies $f_s$ and $f_r$ are assumed whose frequency difference is equal to the channel spacing $\Delta F$. The transmitter power density spectrum $F_s$ is calculated taking into account multiplicative subfunctions (attenuation, spectral energy distribution, pre-emphasis) and additive subfunctions (out-of-band radiation). In a similar way the overall response of the receiver, including weighting of the noise power with the aid of the psophometric filter, is represented by the function $F_R$, depending on the relative frequency $(\Delta F - f)$. In the case of double-sideband modulation, $F_s$ and $F_R$ are symmetrical to the respective carrier frequencies. Fig. 3 shows the fundamental shape of the functions $F_s$ and $F_R$ as well as the shape of the most important sub-functions.

The weighted interference power caused in the receiver by the adjacent channel transmitter is given by the convolution integral:

$$\Delta P_s = \int_{f_1}^{f_2} F_s(|f|) \cdot F_R(|\Delta F - f|)\, df$$

When performing the integration for $\Delta F = 0$ (receiver exactly tuned to the transmitter frequency), one obtains the wanted receiver power $\Delta P_N$. The relative RF protection ratio $A$ is defined as the ratio of interference power in the adjacent channel to wanted power in dB.

$$A = 10 \log \frac{\Delta P_s}{\Delta P_N} \qquad \text{dB}$$

One can if so desired separate the effect of the carrier (beat note) from that of the sidebands. The calculation was compared with measurements according to the objective method, and the correspondence was excellent, as expected because the objective method measures in precisely the same way as the calculation is performed.

The ineluctable limit for efficient use of the frequency spectrum is reached, when interference, not noise is the limiting factor. This statement considered controversial when *Norton* first came with the idea, was accepted by CCIR after an international commission of which Norton and Rice (USA), Eden (Germany), some other scientists and this author had studied its consequences. Now Commission I of the CCIR has the optimum use of the frequency spectrum as its main task.

In the LF and MF bands, propagation conditions are substantially different in the day-time and during the period of darkness. The ground wave is present at all times and provides a highly reliable service with acceptable quality up to a distance that decreases rapidly with increasing carrier frequency. The skywave is sufficiently strong only at times of reduced ionospheric attenuation, that is to say, from about two hours after sunset until two hours before sunrise. Contrary to the ground wave which provides a stable signal with hardly noticeable fluctuations, the sky wave signal is subject to considerable field-strength fluctuations.

In order to obtain optimum coverage it is appropriate that each group of three transmitters sharing the same channel forms an equilateral triangle of sidelength D. Rigorous application of this principle leads to completely regular triangular lattices (Fig. 4) [7; 8].

From the propagation properties one can derive that it is possible to achieve full coverage with about ten programs when reception is effected by the ground wave during daytime and by the skywave during periods of darkness. When reception is effected by the ground wave under night-time conditions partial coverage (about 20 % of the total area) with one program only is possible. In order to obtain optimum coverage during the hours of darkness with the 121 channels at present available in Europe in the MF band the average distance between transmitters has to be about 450 km. This is equivalent to only one frequency assignment per 175 000 km². When in order to increase the number of transmitters in a plan, the average distance between transmitters is reduced, there will inevitably result a reduction in coverage. With cochannel distances of less than 3000 km (which corresponds roughly to average distances less than 270 km, that is to say, one frequency assignment per 60000 km²) the skywave coverage will be eliminated completely.

With receiver characteristics representative of the many millions of receivers actually in use, the optimum channel spacing has been calculated at 8 kHz. With this channel spacing better reproduction quality can be achieved than with current receivers. Optimum values of the distance between transmitters sharing the same channel may be estimated: they are about

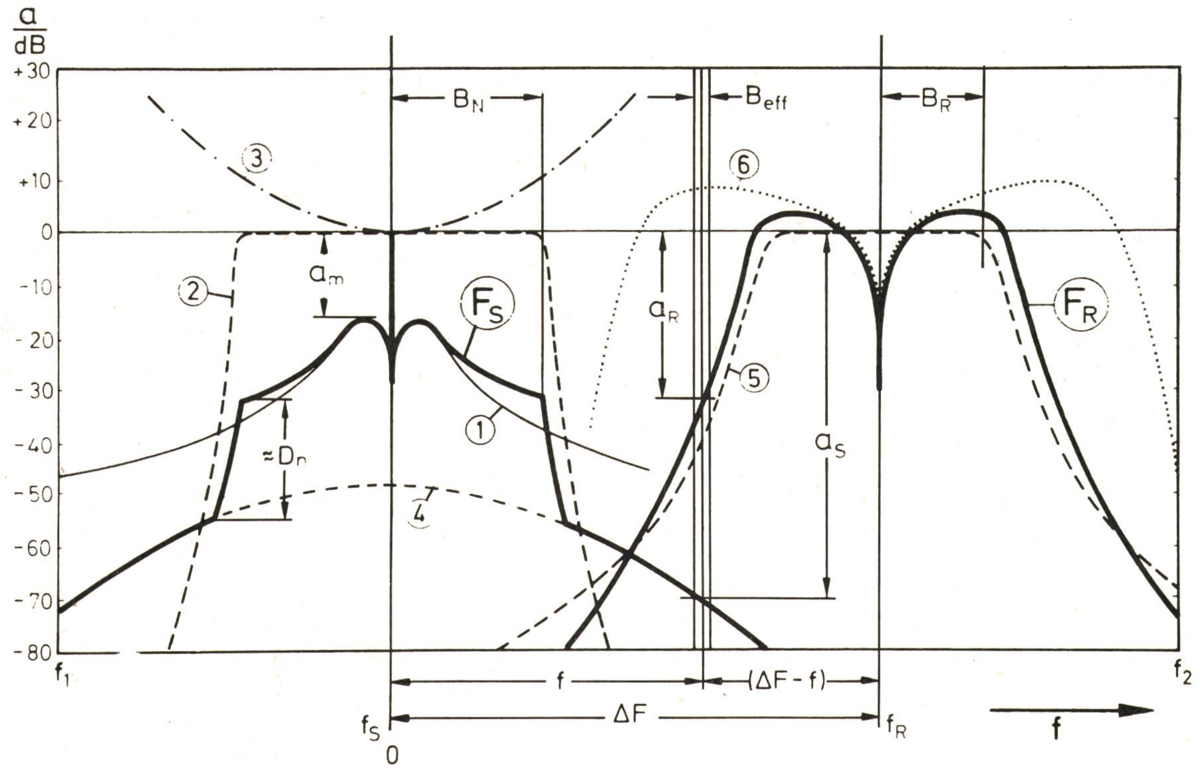


**Fig. 3 Basic relations between receiver and adjacent channel transmitter**

$B_N$ = 3 dB bandwidth transmitter,
$B_R$ = 3 dB bandwidth receiver
$B_{eff}$ incremental bandwidth for calculation purposes
$f_s$ carrier frequency transmitter
$f_R$ receiver tuning frequency
$\Delta F$ carrier spacing
$F_s$ transmitter power density spectrum
$D_n$ attenuation intermodulation products
$a_m$ relative level of max. power density in the sideband
$F_R$ overall characteristic receiver, including weighing by means of psophometric curve

$a_s$ level transmitter spectrum at frequency $f$
$a_R$ weighted receiver attenuation at frequency $f$

*1* spectral energy distribution in the sideband (before pre-emphasis)
*2* filter attenuation characteristic for band limitation at the transmitter
*3* pre-emphasis at the transmitter
*4* out of band radiation transmitter
*5* filter attenuation characteristic receiver
*6* psophometer weighting curve

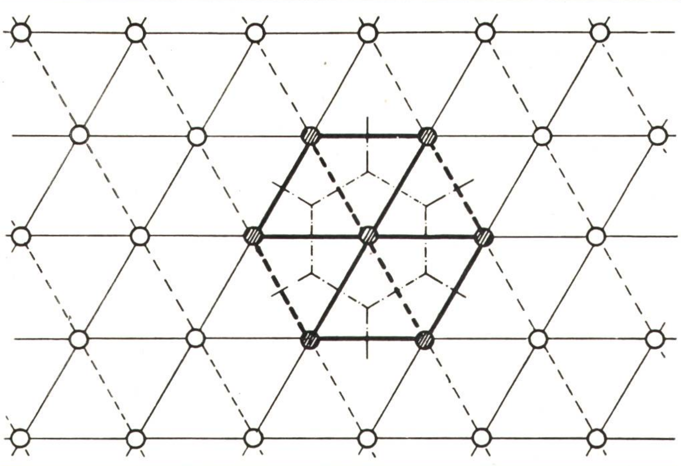

**Fig. 4 Ideal triangular lattice for co-channel transmitters on a plane earth**

500 km by day and roughly 5000 km during darkness. There are, however, very few broadcasting authorities, who accept the idea of transmitting only in daytime and closing down at night. Therefore shorter distances will be used at the forthcoming conference, resulting in a more or less severe reduction in coverage. A compromise idea is to reserve the upper part of the spectrum for sky-wave coverage, but even this may be politically difficult.

We have already seen that the six cochannel transmitters form a regular hexagon around a given station. If we now choose a transmitter of a different frequency inside one of the triangles and look again for the six equidistant stations at this new frequency, we can easily convince ourselves that apart from the original station only two of the six are inside the hexagon. This leads to the conclusion that we can choose one set of available frequencies inside a rhombus, and then repeat them at equal distances. An example of a regularly distributed set of frequency allocations is given in Fig. 5. The distance between a given transmitter and the transmitter in the adjacent channel is about $D \cdot 3^{-\frac{1}{2}}$.

If $D$ is the cochannel distance, $C$ is the number of channels available, $S$ is the total area for which frequency assignments are required, $N$ is the number of frequency assignments desired, then

$$D^2 = 2\,CSN^{-1} \cdot 3^{-\frac{1}{2}}$$

Now the continents have to be subdivided into triangular surfaces of average sidelength $D$, and a suitable channel distribution has to be applied in every rhombus. Frequency channels are now assigned to actual transmitters by distorting as slightly as possible the geometrically regular channel distribution scheme. This does not take into account the density differences over the whole area, but it gives a good starting point. It remains necessary to compute all relevant field strengths taking into account differences in transmitter power.

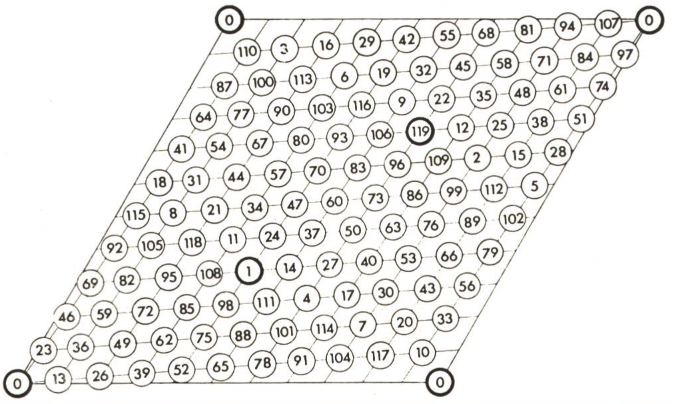

**Fig. 5 Frequency allocation pattern for 120 channels**

## 5. Generalized frequency planning

The same type of frequency planning as discussed above was already used at the FM and TV frequency allocation conference in Stockholm 1962. In this and the former case all channels use the same modulation. More difficult problems arise at the boundary of the frequency domain where the adjacent channel may have a different type of modulation.

In a general situation cochannels and adjacent channels may have different types of modulation. In the book "Spectrum engineering; the key to progress" one can find the mutual interference for 27 different types of modulation in cochannel situations. A number of different cases have been calculated by the Electromagnetic Compatibility Analysis Centre in the United States, also for adjacent channel interference [9].

The compatibility between satellite receivers and transmitters and radio link receivers and transmitters that have the same frequency allocation, is a special problem to which a number of CCIR Reports are devoted. Frequency dispersal techniques avoid too great a power concentration in a small frequency interval.

Another difficult case is presented by the radio astronomical observatories. Their sensitive receivers are sometimes disturbed by harmonics of transmitters that are considered permissible by administrations for all other purposes.

The necessity of spectrum management is obvious when we see that 320000 private land mobile radio communication systems were authorized in the USA alone. The a priori environmental data base of the american Electromagnetic Compatibility Center has more than 1600000 frequency assignments registered.

## 6. Electromagnetic compatibility in computer systems

The computer functions as an interference generator and has to fulfill the requirements for radiofrequency industrial, scientific and medical apparatus. With good design this gives no problems. The computer is also susceptible to interference. Furthermore the computer may be linked by a communication system to another centre, and the line may give errors. A good special line may be guaranteed to an error percentage of $10^{-5}$ or $10^{-6}$. For computers one demands error rates of $10^{-12}$ to $10^{-13}$. Usually an error detection system is used that asks for retransmission if an error is detected. In the Arpa system large computers from all over USA are connected by communication links to each other and even to Cambridge (UK) and Trondhjem (Norway).

In factories a good method of getting the information correctly through an ambiance with a high interference level is to use an optical communication system.

Silicon rectifiers (thyristors) are a widespread cause of impulsive interference to numerical control systems. One method of reducing the susceptibility to interference is to use the right type of logic [10]. The immunity to external noise pulses is best for HTL (Zener diode transistor logic), but TTL (transistor transistor logic) and complementary MOS logic are also classified as very good for this purpose. Power line filtering is desirable as well as proper shielding.

### 7. The work of CISPR in the EMC area

The International Special Committee on Radio Interference [11; 12] (Comité International Spécial des Perturbations Radioélectriques), CISPR, is governed by a Plenary Assembly that nominates the chairman of CISPR. He is advised by a Steering Committee. There are three vice-chairman, one for Limits, one for Methods of measurement and measuring instruments, and one for safety. CISPR has six Subcommittees. Members of CISPR are all National Committees of IEC, the International Electrotechnical Commission, and several international organizations, such as the European Broadcasting Union (EBU), its counterpart in Eastern Europe OIRT; the Union Internationale des Chemins de Fer; the Comité International des Grand Réseau Electriques; UNIPEDE, the international union of producers of electric energy; the international transport union. The CCIR is represented at the meetings by an observer.

Subcommittee A treats measuring methods and measuring instruments, as well as statistical methods. (All measuring methods give results that vary because of differences in samples and also because of incompletely reproducible measuring methods.)

Subcommittee B treats radiofrequency (> 10 kHz) appliances for industrial, medical and scientific purposes, in which the generation of RF power is essential for adequate performance. It also treats such industrial apparatus as power thyristors.

Subcommittee C covers high voltage lines and high voltage equipment.

Subcommittee D treats combustion engines and their interference effect.

Subcommittee E's subjects are radio and television receivers, both as causes of interference and as susceptible (immune) to interference.

Subcommittee F has domestic applicances as its main interest. Clicks and buzzes from switching equipment, small motors, thyristors (e.g. for central heating systems, dimmers), fluorescent tubes fall in this domain.

The three permanent working groups cover terminology, safety aspects of interference suppression, and standardization of lists of complaints. They are only convened, when new developments make this necessary.

The CISPR limits are recommendations for maximum permissible interference from many individual sources. They are a guideline for governmental regulations.

It is expected that they will be the base for a standard interference legislation in the European Economic Community, in most cases followed literally, but sometimes amended. Statistical effects, internal and external immunity, coupling between sources and sensors (receivers), are all extensively studied, and these studies have their analogue in many other domains of electromagnetic compatibility. The internal immunity is the ability of a receiver to minimize the effect on its output of radio interference, which is applied to its aerial. This may occur in a receiver, that distinguishes between signals and impulsive noise, or in a computer that recognizes error syndromes. The external immunity is the ability of a receiver to reject interference which enters by other ways than the aerial, and the analogue we have in computers when they are made less sensitive to interference by high level logic.

### 8. Conclusion

We have shown that electromagnetic compatibility is an important subject with many ramifications. In the United States several universities give courses in this domain as well as possibilities for graduate studies. This should also become possible in Europe (at least one Danish university has this course already). In May 1975 the first International Symposium on Electromagnetic Compatibility organized in Western Europe will be held in Montreux. There it will be possible to go into much more detail and to follow the latest progress as shown by lecturers from many countries (Eastern and Western Europe, USA, Argentine, India, Japan are known to have offered contributions).

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