Planning aspects of digital terrestrial television

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New bit–rate reduction techniques and the development of powerful modulation schemes offer the possibility of squeezing one or even more digital television programmes into an 8–MHz wide television channel. The article gives an overview of the availability of frequency bands, including the use of the so–called "taboo channels". The situations in Europe and the United States are compared. Protection ratios and minimum usable field–strength values, including margins for reliable operation of a digital service, are discussed.

Using the OFDM technique, a digital service can be operated as a single–frequency network. It is shown that in addition to frequency efficiency, the SFN offers further advantages compared to other approaches.

1. Introduction

Developments in recent years have led to remarkable bit–rate reductions in source coding. This is true not only for audio but also for the video frequency range. Through the use of redundancy reduction, the bit–rate of television pictures can be reduced to very low values and it now seems possible to squeeze one or even several digital video signals into a single television channel if appropriate modulation techniques, such as OFDM, are used. A service based on this modulation technique can operate in a very hostile environment characterized by severe multipath propagation conditions. Since the signal can cope with multipath and echoes, one or several programmes can be operated in a single–frequency network (SFN), leading to high spectrum efficiency.

2. Availability of frequency bands

In most European countries, the frequency bands allocated to television are in intensive use and the allocation of additional spectrum to broadcasters, in particular below 1 GHz is rather unlikely. It is therefore necessary to consider ways of accommodating the new digital service within the bands already used for television.

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2.1. Use of "taboo channels"

One of the solutions proposed recently involves the use of the so–called "taboo channels". This expression describes various channels which are not normally used when selecting frequencies for use at the same transmitting site. These channels are:

– the co–channel *N*;

– the lower and upper adjacent channels *N*–1, *N*+1;

– the oscillator channels *N*+5, *N*–5;

– the image channel *N*+9.

The co–channel *N* can be excluded from further consideration because the protection ratios required for both services (analogue and digital) would be too high. Therefore every channel in use at a transmitter site has five taboo channels. In practice, three or four programmes are often operated from a common site, leading to a total of 15 to 20 taboo channels. If these taboo channels can be used for digital services, with appropriate transmitter powers, and achieve the same coverage contour as is achieved by the transmitter on channel *N*, then full area coverage could be expected for these digital services.

2.2. Situation in Europe

Television planning in Europe is based on the Stockholm Plan 1961. The lattice used at the Stockholm Planning Conference is represented in *Fig. 1*. The co–channel transmitters are at the corners of a rhombus. A special feature of this lattice is the frequency separation, equivalent to three channels, between adjacent transmitter sites in one direction through the lattice. This permits the simple grouping of three programmes using channels *N*, *N*+3, *N*+6.

The rhombus can be divided into two equilateral triangles with side length d_c; this length is known as the co–channel distance. In central Europe, d_c is approximately 200 km. The centre of gravity of the triangle is the point having the greatest distance to the corners (see *Fig. 2*), so it is generally allocated to the adjacent channel even though the protection ratio for the image channel may be considerably higher in some cases (depending on the television standard used).

If the co–channel distance is 200 km, the distance to the centre of gravity will be 115 km. *Fig. 3* shows a typical example of co–channel and adjacent–channel use in Germany. Channel 59 is taken as being the co–channel, and it is seen that six of the adjacent–channel distances are slightly larger than the theoretical distance of 115 km and 11 are considerably smaller.

In most European countries the 1961 Stockholm Plan has undergone many changes. Several thousand fill–in transmitters have been taken into service, as is the case in Germany, for example (*Fig. 3, top*). The use of these fill–in transmitters leads to rurther restrictions and in some countries even the taboo channels are partly used due to the shortage of frequency spectrum.

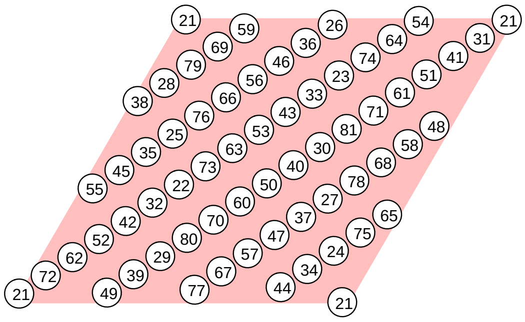


Figure 1
Theoretical allocation of channels in Bands IV and V
(Stockholm Plan, 1961).

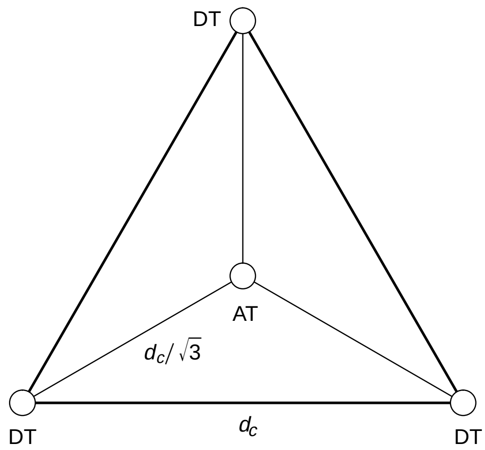


Figure 2
Equilateral co–channel traingle with three digital transmitters (DT) and one analogue transmitter (AT) at the centre of gravity.

2.3. Situation in the USA

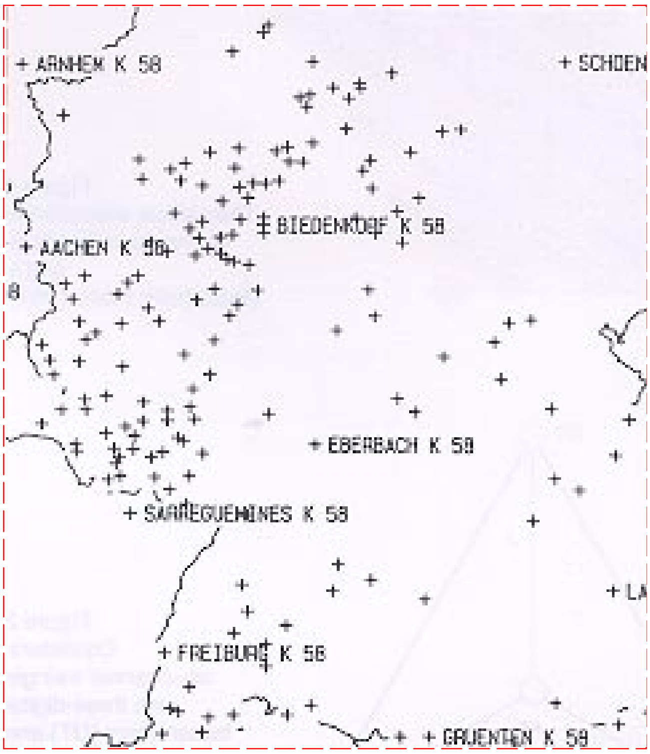
Fig. 4 shows a typical channel distribution (co–channel 45) in the United States of America. Planning is not based on a regular lattice and 19 adjacent–channel distances are greater than 200 km and only one is less than 100 km. Statistics for all UHF channels (14 to 69) show that in more than 1300 cases the adjacent–channel distance is greater than 200 km, this being greater than the co–channel distance in Europe. In some cases, however, the use of taboo channels would not lead to sufficient coverage.

2.4. The “clear channel” solution

In some European countries, the upper part of the UHF spectrum (790–862 MHz) is not used for television services. The availability of this sub–band may offer an opportunity for the opening of a digital terrestrial television (DTV) service. However this approach is unlikely to be applicable as a general solution for Europe, since in some countries the sub–band is already used for television Owing to the requirements of international coordination, the sub–band has to be shared by several neighbours. This would allow only two or three channels per country. On a local or sub–regional basis, up to nine channels may be possible.

3. Quality standards

A new digital television system should offer good flexibility in order to facilitate its introduction on a Europe–wide scale. Bearing in mind that the requirements in terms of quality and number of programmes differ greatly in the different countries, a hierarchical system may offer advantages over a single standard. At present, at least two levels of reception are being considered:



Main stations and fill–in transmitters in channel 58 in part of Germany.

0 50 100 150 200 250 km

●upper adjacent channel (60)
●co–channel (59)
●lower adjacent channel (58)

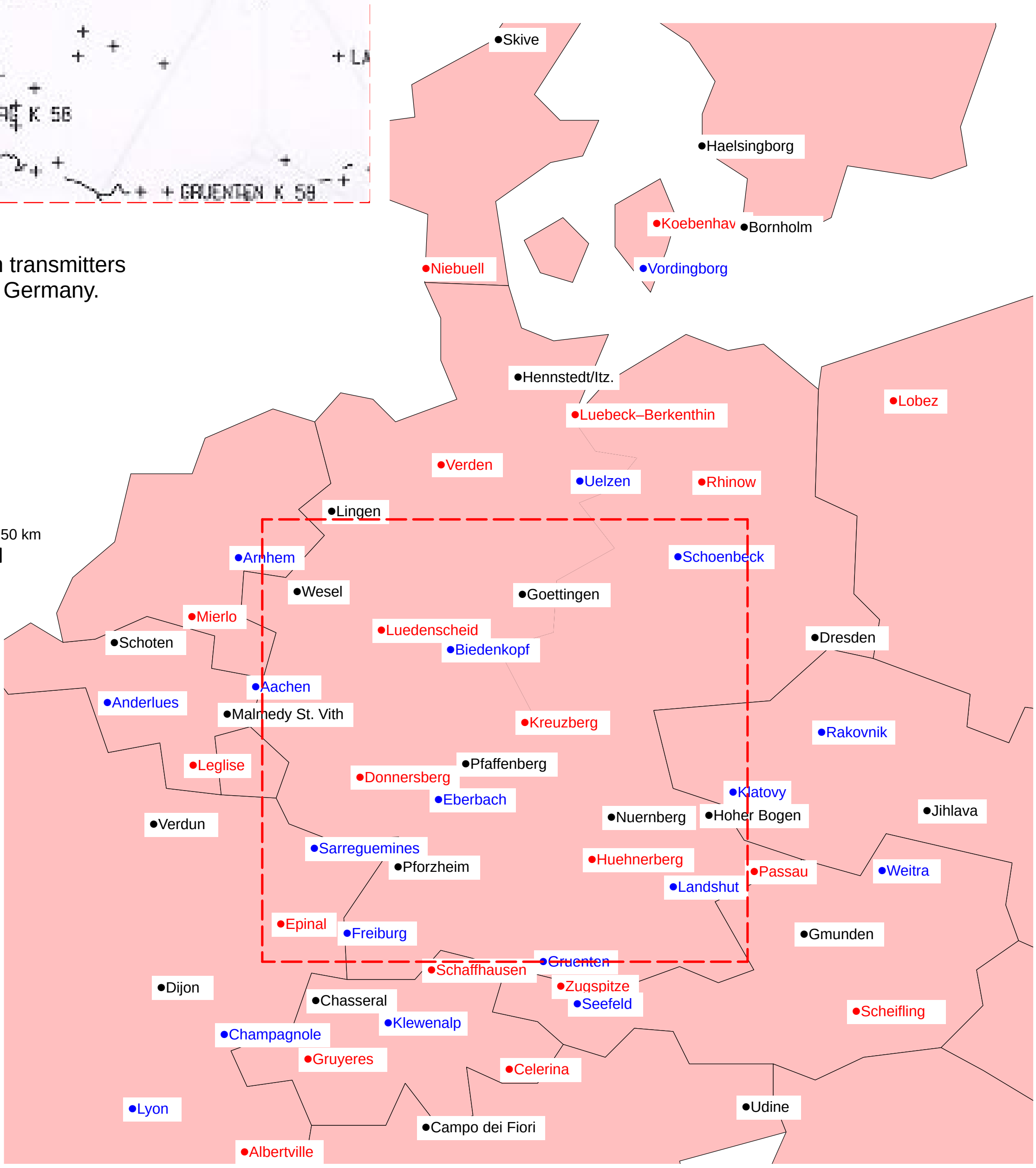


Figure 3
Adjacent channels to channel 59 in Germany and neighbouring countries.

- standard television quality (SDTV);
- high–definition television quality (HDTV).

The high bit–rates of 30 Mbit/s needed at present for HDTV signals would require a highly–sophisticated modulation scheme. This will have a strong influence on the carrier–to–interference (C/I) values.

The protection ratios and minimum usable field–strengths may therefore differ widely between the different standards. The higher values necessary for HDTV may only partially be compensated by the different receiving environment (e.g. roof–top antenna). Reception at ground level with a low–gain antenna, coupled with building penetration loss, requires the addition of a considerable margin, especially in the case of portable reception.

Depending on the quality standard, the different bit–rates will lead to different bandwidths. Instead of one HDTV programme, up to four SDTV programmes could be accommodated in a single 8–MHz television channel. If HDTV services cannot be included in the start–up package of digital television, the possibility of HDTV transmission at a later stage should nonetheless be envisaged since after analogue services have been phased out it can be expected that more frequency spectrum will become available.

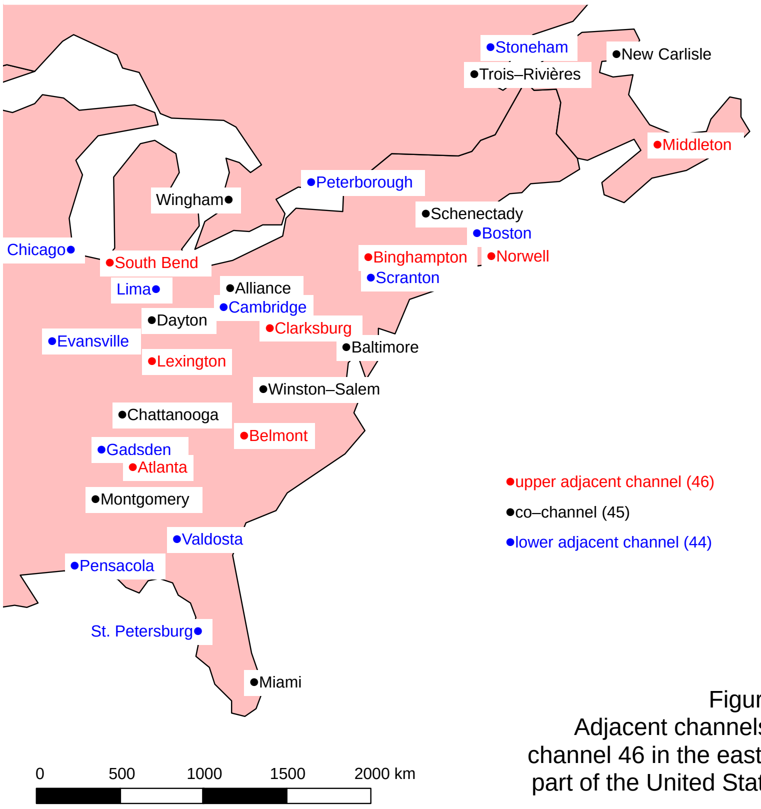


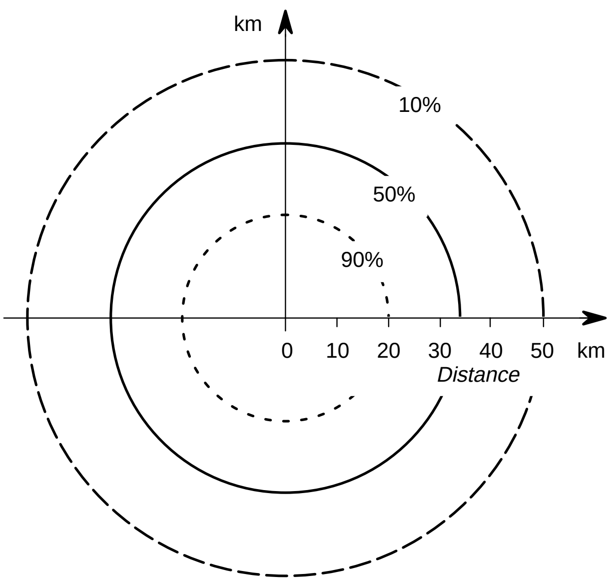
Figure 4
Adjacent channels to channel 46 in the eastern part of the United States.

4. Planning parameters

4.1. Coverage and propagation

Before deriving the planning parameters in terms of minimum usable field–strength and protection ratios for a digital television system, some consideration should be given to coverage aspects for analogue networks.

The propagation of radio waves is considered as a statistical process in which a field–strength value within the coverage contour is predicted for certain time and location probabilities. Although the minimum usable field–strength is dependent on the performance of the receiver, and is therefore in-



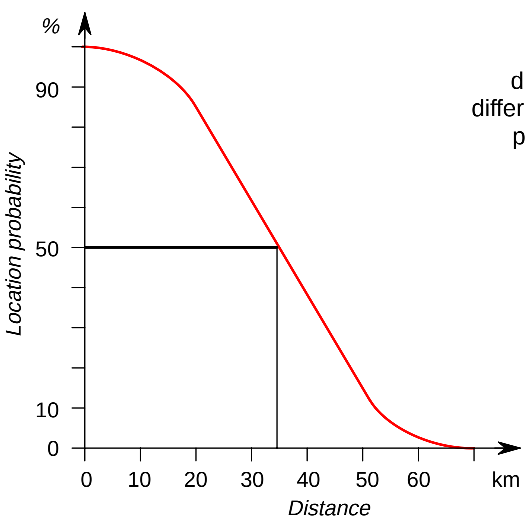
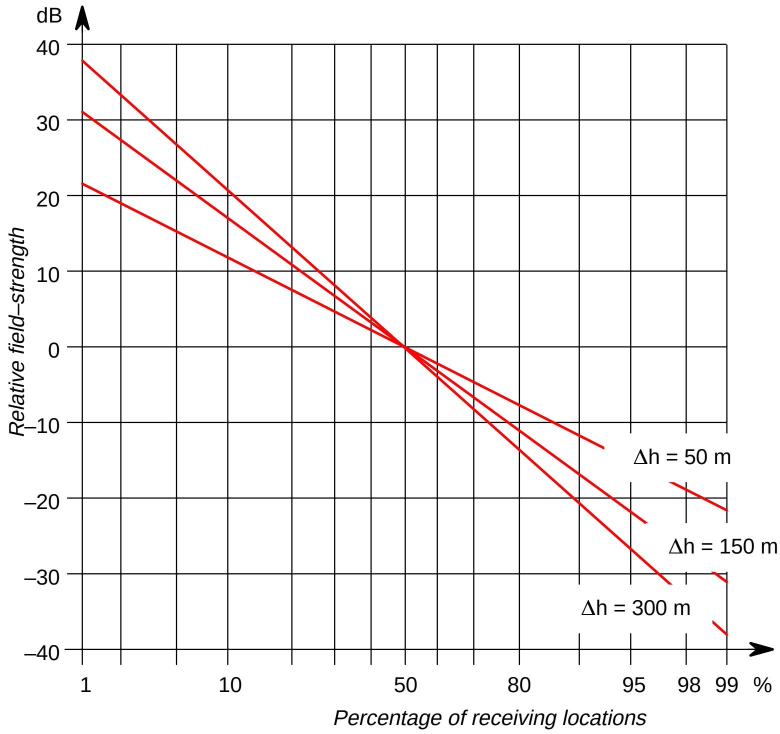


Figure 5
Coverage distances for different location probabilities.



Δh: difference between the heights exceeded by 10% and 90% respectively of the terrain height measured at regular intervals in the range 10 to 50 km from the transmitter.

Figure 6
Variation of field–strength for different percentages of receiving locations.

dependent of time and location, reference is nonetheless made to certain time and location percentages when measurements are taken, or during laboratory tests, for the purposes of practical planning. In the case where there is a single wanted transmission (i.e. there is no interference), 50% of locations and 50% or time are taken as the reference conditions. On the basis of the minimum usable field–strength this statistical field–strength value determines the coverage contour. For analogue services, it is associated with a given picture or sound quality. Inside the coverage contour the service quality is better; outside the contour the quality is poorer and the transition is smooth. Inside the contour the number of locations which are not served decreases rapidly (see *Fig. 5*), when moving towards the transmitter site. Nevertheless, even outside the coverage contour locations can be found which are still served with the agreed quality.

In general the coverage contour is interference–limited rather than noise–limited. The interference–limited contour passes through receiving locations where the field–strength of the wanted signal and the usable field–strength are equal, the latter being the product of the interfering field–strength and the protection ratio. For the determination of the interfering field–strength the published propagation curves for 1% of time[1] and 50% of locations are taken into account. Thus, inside the coverage contour the required quality is achieved for at least 99% of the time and at 50% of locations. Although the agreed quality is not attained at the remaining 50% of locations, reception may still be posible because of the smooth transition from good to poor quality.

Digital systems show a different behaviour. Above a certain value of carrier–to–interference ratio (C/I) the quality is always excellent and below this threshold value the system will generally fail, preventing reception completely. This characteristic may be improved to some extent by introducing several thresholds, each associated with a lower quality standard. The graceful degradation of analogue systems cannot be achieved, however. Due to the abrupt failure characteristic the definition of coverage area for digital systems is different and more difficult, compared to analogue systems. Use of the CCIR propagation curve for 50% of locations, in the same way as for analogue systems, may lead to complete system failure at many locations. This is not acceptable, so appropriate precautions must be taken.

4.2. Correction factors

The propagation curves given in CCIR Recommendation 370 will lead to intolerable system failure rates if they are applied directly to digital systems. In the case of a digital terrestrial television system, at least 90% of locations have to be covered. If a mobile system is considered the requirement may be even greater, perhaps approaching 99% of locations.

This problem could be resolved either by determining the appropriate propagation curve for the relevant location probability (e.g. 90%), or by adding a correction factor. The latter solution seems more appropriate since this would allow the existing propagation curves to be used also for digital services. *Fig. 6* is taken from CCIR Recommendation 370. It shows that the field–strength has to be increased by 12 dB in order to achieve a location probability of 90%; otherwise the coverage area will be reduced as shown in *Fig. 5*. This correction factor has to added to the wanted field–strength, or to the minimum usable field–strength, in order to apply the propagation curves of CCIR Recommendation 370. Since the influence of different time percentages on the wanted signal is quite limited inside the coverage area, a margin for higher time percentages may be disregarded.

1. Sometimes a higher percentage of time (e.g. 5%) is chosen.

The corresponding correction factor (margin) needed for the protection ratio is:

$$12\sqrt{2} = 17 \quad \text{dB}$$

This is true assuming that there is no correlation between the wanted and unwanted signals and that the standard deviations of the two signals are equal (see CCIR Recommendation 945). DAB field trials have shown that wide–band signals have a lower standard deviation than narrow–band signals such as VHF/FM. It can therefore be assumed that the margin can be reduced by a few decibels.

The derived correction factors are valid for a single wanted or unwanted signal. In a single–frequency network, the internal network gain can also be taken into account.

4.3. Minimum usable field–strength

The minimum usable field–strength determines the coverage area in the absence of interference from other transmitters. A basic carrier–to–noise ratio (C/N) of 14 dB is assumed for standard–quality television, and 26 dB for HDTV quality. A vision bandwidth of 8 MHz and a noise figure of 6 dB will lead to a receiver noise power of –130 dBW. This value is degraded by the effective antenna aperture which is assumed to be:

$$20 \text{ dBm}^2$$

in the upper part of the UHF band. Taking account of the C/N ratio leads to the minimal power flux density, which then has to be corrected for the receiving antenna gain and the feeder loss (*Table 1*).

This field–strength has to be provided at at least 90% of locations. Since the wanted signal does not vary much with time, the values of field–strength for 50% of time, as used for analogue transmissions, may be sufficient. Therefore a margin of 12 dB, as derived in *Section 4.2.* has to be added to the minimum usable field–strength value derived in *Table 1*, in order to use the field–strength propagation curves of CCIR Recommendation 370 (*Fig. 6*).

Therefore for a single wanted signal an overall value of 54 dBμV/m is required for the minimum usable field–strength (standard–quality television)

Bandwidth	8	MHz
Receiver noise figure	6 865	dB K
Receiver noise power	–130	dBW
Effective antenna aperture	20	dBm^2
C/N ratio	14 (26)	dB
Minimal power flux density	–96 (–84)	dBW/m^2
Antenna gain	11	dB
Feeder loss	3	dB
Reference minimum usable field–strength (see *Note 1*)	42 (54)	dBVμ/m

Note 1: dBW/m^2 + 145.8 dB $\equiv$ dBμV/m.

Note 2: Values in brackets are for HDTV quality.

Table 1
Derivation of the minimum usable field–strength (freq = 800 MHz)

in order to apply the CCIR propagation curves. It will be shown that this value can be reduced in the case of a single–frequency network, since several transmitters will contribute to the wanted signal.

4.4. Protection ratios

Protection ratios are one of the most important parameters in frequency planning. In existing television networks the coverage area of a transmitter is determined mainly by interference from other transmitters, rather than by the minimum usable field–strength of the television signal. In *Fig. 7*, both contours are depicted for the German television transmitters on channel 58. In general, the minimum usable field–strength contour is over–optimistic, since in most cases the coverage area is interference–limited. In this section, some consideration will be given to the expected protection ratios.

It is most likely that digital television will be introduced in the existing television bands, if no other band can be made available. Therefore the following co–channel protection ratios are important:

– DTV to TV (DTV/TV);

– TV to DTV (TV/DTV);

– DTV to DTV (DTV/DTV).

Table 2
Protection ratios for digital terrestrial television (DTV).

Co–channel protection ratios (dB)			
DTV/TV	37		Tropospheric
DTV/TV	45		Steady
TV/DTV (*Note 1*)	14	(26)	Referred to vision signal
DTV/DTV (*Note 1*)	14	(26)	
Adjacent–channel protection ratios (dB)			
DTV/DTV	–30 to –40		
TV/DTV	–30 to –40		
DTV/TV (*N*+1)	0 to 20		
DTV/TV (*N*–1)	–10 to 0		

Note 1: When applying the propagation curves of CCIR Recommendation 370, a margin must be taken into account.

Note 2: Values in brackets are for HDTV quality.

Interference from the DTV channel into the analogue channel can be treated in a quite simple way, whereas the inverse situation will depend largely on the residual level of the vision and sound carriers.

If analogue television suffers interference from digital television, a protection ratio of 37 dB may be assumed in the case of tropospheric interference. It should be noted that this value is higher than those generally adopted for analogue television planning.

The co–channel interference from an analogue television transmitter may be reduced by not transmitting information in the OFDM spectrum which falls at the spectral positions of the analogue vision and sound carriers. If two slots are left unused, one at the position of each of these carriers, the protection ratio necessary to protect the digital television signal may be assumed to be lower, since the peak power of the vision modulation signal is roughly 16 dB lower than that of the vision carrier.

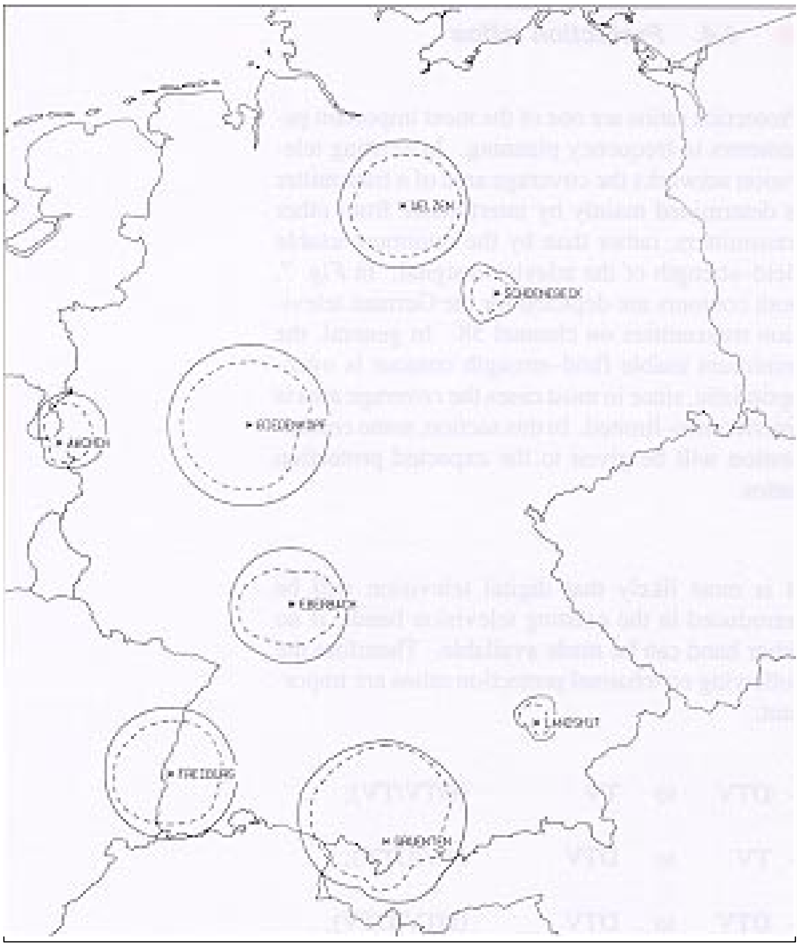
If the vision signal is treated as a noise–like signal, then for SDTV a protection ratio of 14 dB (referred to the vision signal) may be assumed. If reference is made to the vision carrier, a protection ratio 16 dB lower (i.e. –2 dB) can be assumed when the digital television signal suffers interference from an anlogue television signal. In the case of HDTV quality, protection ratios of 26 and 10 dB respectively may be needed. However, the introduction of spectral slots would lead to some loss of data capacity.

If the DTV signal suffers interference from another DTV signal, a protection ratio of 14 (26) dB may give satisfactory reception under stable conditions.

In the light of the above considerations, the protection ratios shown in *Table 2* can be assumed.

The adjacent–channel interference introduced into the digital channel depends mainly on the guard band in use, and hence on the selectivity of the receiver and the linearity of the transmitter. Values between –30 and –40 dB may be assumed. In the opposite direction, the values will depend on the performance of the analogue television receiver and the linearity of the transmitter. In the case of the upper adjacent–channel, values up to +20 dB have been measured. However, with the relative power levels considered this would mean that operation from the same transmitter site would not create any problems. An equivalent coverage can not be assumed, however. The use of adjacent frequency blocks or channels in overlapping coverage areas may create problems if the field–strength values vary to a large extent.

Figure 7
Coverage contours of channel 58 transmitters in Germany.
min. usable field–strength ——
interference limited – – –



4.5. Polarization discrimination

Transmissions from main television stations are generally horizontally polarized. If different polarizations are used, a polarization discrimination of 16 dB will be obtained (CCIR Recommendation 419). It can be expected that this value would be exceeded at 50% of locations. For higher percentages of locations a lower value must be assumed, for example 10 dB at 90% of locations. It may therefore be appropriate to assume the use of different polarizations for the analogue and digital services. Since planning of the analogue television service is based on 50% location probability, a value of 16 dB, as recommended, is taken into account. For digital television a lower value, of the order of 10 dB seems to be justified since the service must be planned for a higher location probability.

5. Full area coverage with a single–frequency network

In a single–frequency network (SFN) all the transmitters operate at exactly the same frequency.

The advantages of the SFN approach are:

– high frequency efficiency;

– low–power operation (internal network gain);

– high location probability;

– easy gap–filling (frequency re–use).

The disadvantages are:

– network splitting is not possible;

– the SFN cannot use taboo channels;

– synchronization is necessary;

– feed control is required.

Consider a receiver near the fringe of the coverage area of one transmitter. In general this receiver will pick up signals from several transmitters broadcasting the same programme. Although these signals are synchronized at the transmitters, they will reach the receiver with different delays. They cannot be distinguished from multipath signals, provided that the modulation is exactly the same. A modulation system is suitable for SFN operation if it can operate in conditions where a large excess delay is prevalent. If an SFN is based on existing transmitter separation distances, topographical obstacles will not produce larger excess delay than the signals of the various transmitters in the network. Signals from more–distant transmitters will exceed the maximum delay allowed for the OFDM signal. They will contribute only partly to the wanted field–strength and the greater the distance the greater will be the tendency for these signals to cause interference. However the network–generated self–interference of an SFN can be kept sufficiently low by careful choice of the system parameters and transmitter powers.

If there are still some gaps in the coverage area of a network, they can be filled by additional low–power stations having the same frequency. In the case of terrain shielding, the same technique can be used as in conventional network planning, i.e. those regions can be covered by fill–in transmitters. If the necessary degree of isolation between the receiving and transmitting antennas can be achieved, the fill–in transmitter may work as a simple rebroadcast transmitter except that the transmitted frequency is the same as that received at the input, rather than having to transpose to a different frequency. If large buildings in urban areas provide the isolation, the “active reflector” technique may be of interest in such areas also. In principle the rebroadcast transmitter consists only of an amplifier the maximum gain of which is limited by the degree of isolation achieved between the antennas.

If there are differences in the programme or data content of the same service block, the advantages of the SFN concept are lost because of the resulting

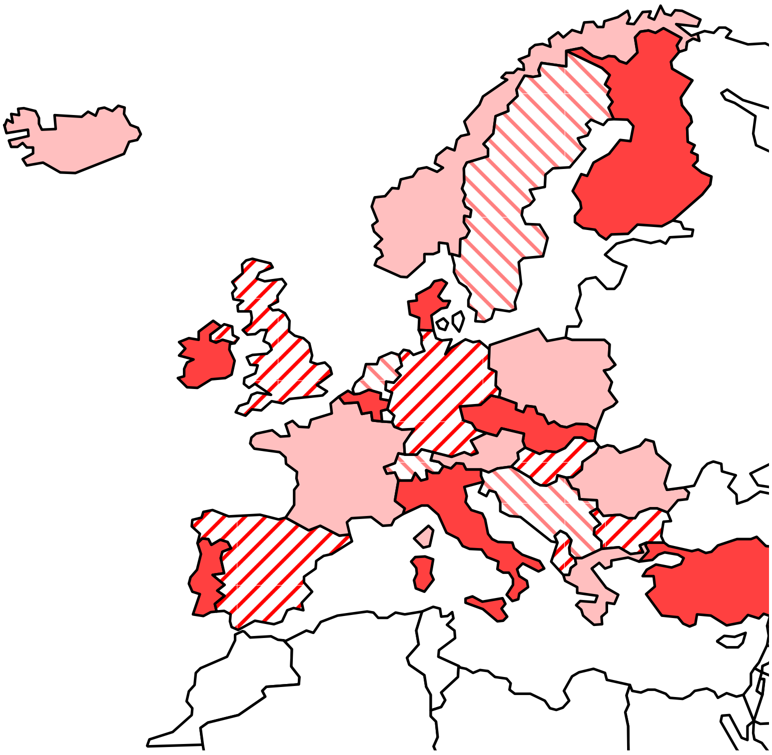


Figure 8
Possible distribution of four frequency blocks in western Europe.

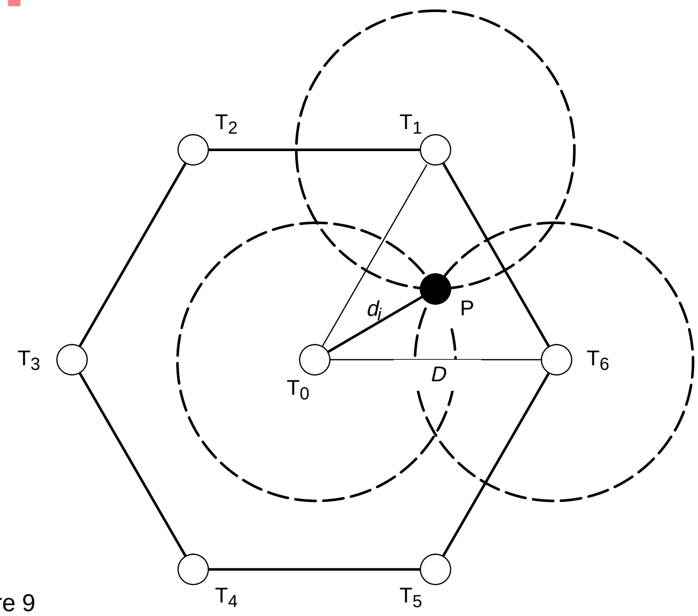


Figure 9
First hexagon of regular lattice.

interference. In these circumstances the appropriate protection ratios must be observed (*Table 2*).

In a single–frequency network different frequency blocks or channels must be allocated to adjacent countries or areas where the programme or data content will usually be different. In *Fig. 8* it is shown that four blocks or channels might be sufficient to cover most areas in Europe, Problems might arise in certain areas (e.g. Luxembourg, around Lake Constance) where the distances between the same frequency blocks are rather low or no topographical shielding can be assumed. In these areas five or even more blocks may be necessary, depending on the size of the country or area and the frequency block re–use distance. Similar problems must be expected when dividing a country into different regions.

In general it can be concluded that the number of frequency blocks or channels will increase as the division of countries into regions or local areas with their own SFNs increases. In the extreme case an SFN would consist of a single transmitter (and perhaps some relays) requiring nearly as many channels, over a large area, as a conventional network.

6. *Internal network gain in a single–frequency network*

The possibility of creating SFNs is one of the great benefits of the OFDM system. Due to its multipath capability there exists, within delay time limits, a mutual addition of the signals of all transmitters belonging to the network. This effect is called the "network gain" of the SFN. It comprises two components, an additive element and a statistical element.

The additive part is simply the result of the fact that there is more than one useful signal; hence the signal strengths have to be added up. The statistical component is due to the locational variation distributions of the fields. Since the overall standard deviation of the sum signal is smaller than that of the individual signals, the margin which is needed to achieve 90% or 99% coverage probability can be reduced.

This can be demonstrated as follows for the case of three transmitters. *Fig. 9* shows the first hexagon of a regular lattice where the basic transmitter distance is assumed to be 60 km. The least–favourable receiving location within the equilateral triangle $T_0 - T_1 - T_6$ is at its centre of gravity (point *P*). At this location the mean value of the field–strength of one transmitter (situated at one corner of the equilateral triangle) with an e.r.p. of 250 W and an antenna height of 150 m is equal to 42 dB. Its probability distribution is represented by the solid line in *Fig. 10*, where the complement of the coverage probability[2] is plotted. The simple sum of all three field–strengths (power sum method, PSM) yields the dashed line, some 5 dB higher, having the same standard deviation as the single signal. This gives the additive component.

The statistical sum of the three signals is represented by the dash–dotted curve. In the upper probability domain in particular, it shows significantly higher field–strength values, e.g. for 1% the statistical component amounts to 11 dB, giving a total network gain of 16 dB. Therefore, assuming a minimum usable field–strength of 42 dB the coverage probability for a single transmitter is 50% but for the three transmitters together, as a result of the network gain, a coverage probability of about 95% is obtained.

In general an SFN consists of more than three transmitters. *Fig. 11* reproduces the results for an infinite hexagonal transmitter lattice having the same parameters as the previous example. The graph shows four curves corresponding to cases where only the strongest transmitter is considered, the three strongest, the six strongest and all the transmitters. The difference between the three–transmitter and all–transmitter cases is about 2 dB, showing that the major part of the network gain is provided by the few strongest signals.

2. complement = 1 – coverage probability

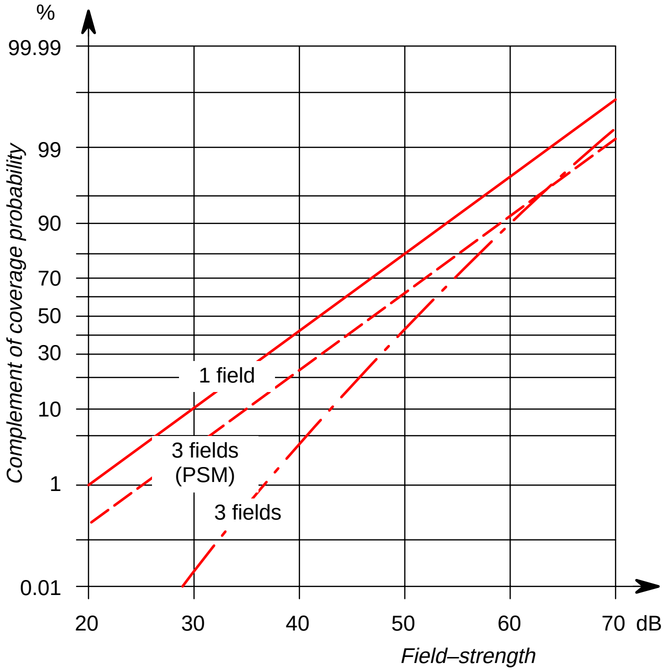


Figure 10
Overall sum distribution of three log–normal fields.

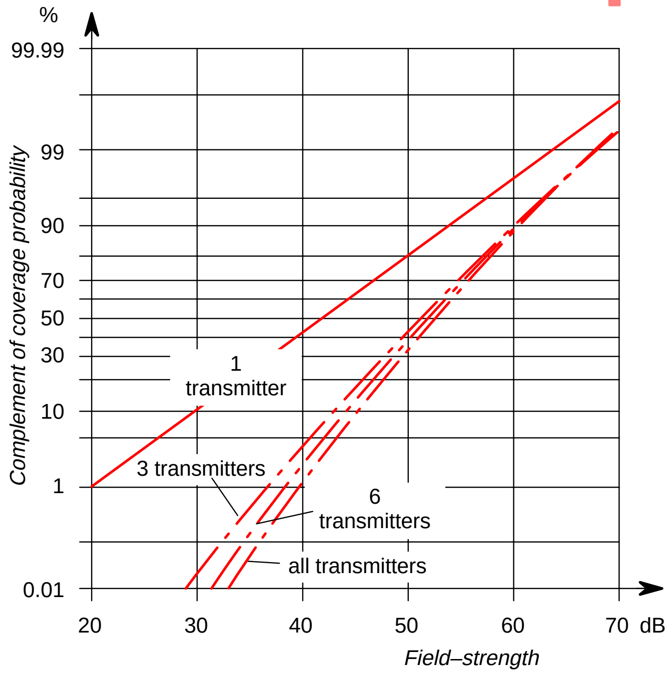


Figure 11
Network gain of 1, 3, 6 and all transmitters in a single–frequency network.

Since the individual contributions of the transmitters vary with the receiving location, the network gain is also location–dependent. Hence there is no fixed overall network gain for the SFN. It is high at the location *P* (*Fig. 9*) where the support from a single transmitter is low and it decreases as soon as the field–strength of one of the transmitters begins to dominate. However, as this network gain reduction occurs the necessary coverage probability is already assured by the single, dominant transmitter.

A second and more serious restriction is encountered at the fringe of the coverage area. For particular locations one or even two of the supporting transmitters may be missing; hence the network gain would tend towards zero. This may be compensated by a fill–in transmitter.

Receiving antenna directivity, in the case of fixed reception, and the local topography may lead to further restrictions. A detailed calculation taking account of the real situation (including the topography) may then be more appropriate as a means of determining the network gain.

7. Conclusions

The frequency bands allocated to television are already extensively used in most European countries. Therefore the additional use of the taboo channels at the same transmitting sites becomes of increased interest, even for the analogue service. Several countries have already started to use some of these channels for analogue television. The coverage area of analogue taboo channels is normally very much reduced, compared with the co–channel transmitter. In a regular linear network (e.g. the Stockholm Plan), this is also true for digital transmission.

A comparison with the situations in the USA and central Europe shows that there are substantial differences in the use of the adjacent–channels. The distances between co–channel and adjacent–

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channel transmitters in the USA are generally twice as great as they are in central Europe. Thus, in the USA, the integration of a digital television service carried in the taboo channels, and having coverage nearly equivalent to that of the analogue services, may be possible in the majority of cases.

It is known that digital systems can operate reliably with low values of C/I, of the order of 10 to 20 dB. However this is restricted to stable propagation conditions. If coverage has to be assured for a high percentage of locations (e.g. 90%), a considerable margin has to be added to the C/I value in order to apply the CCIR propagation curves.

This margin can be reduced if the internal network gain of an SFN can be taken into account, since several transmitters normally contribute to the wanted field–strength. This network gain is lost when using the analogue television taboo channels, since SFN operation – one of the main advantages of the OFDM technique – is not applicable in such channels.

HDTV signals require considerably higher protection than lower standards of quality (e.g. SDTV). Therefore, under equal receiving conditions (e.g. roof–top antenna), different coverage areas must be assumed. The greater bandwidth requirements of HDTV signals compared with SDTV is a further drawback. Bearing in mind the spectrum shortage, both elements make the short–term introduction of HDTV in terrestrial networks rather unlikely.

New FAX and MODEM numbers for EBU Headquarters, Geneva

On 1 December 1993, the EBU's general fax number in Geneva will change.

Old number: (+41 22) 798 58 97

New number: (+41 22) 717 24 81

The fax numbers of individual departments and operational services within the EBU Permanent Services in Geneva will also change on 1 December 1993. Regular correspondents using these numbers will be notified of the new numbers in due course. In the meantime, fax messages may be sent to the above number, with a clear indication of the name of the addressee.

The modem call numbers for certain operational services will also change on 1 December. Authorized users will be informed of the new numbers.

In case of difficulty, assistance may be obtained from the EBU Telecommunications Centre
tel: (+41 22) 717 23 02.