PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
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Digital Coaxial Cable Systems

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Digital coaxial cable systems

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To produce digital transmission systems, the same types of coaxial pairs as are already used for analogue systems are needed, namely, the small size pair (1.2/4.4 mm) and the standard size pair (2.6/9.5 mm).

For a long time the coexistence of analogue and digital systems in the same cable will be necessary: this constrains the latter systems to use common infrastructures. The most important constraint concerns the regenerative section which will have to be consistent with the amplifier section of analogue systems. As regards the quality of the coaxial pairs, it seems almost certain that the manufacturing quality achieved to meet the requirements of high capacity analogue systems would also be sufficient for digital systems having comparable capacity; nevertheless it seems sensible to investigate the electrical characteristics strictly relevant to digital transmission in order to be able to submit newly manufactured coaxial cables to tests concerning this new type of transmission; studies in this area have developed quickly and will perhaps be completed soon.

As regards new types of coaxial pairs to be used only for digital transmission, in the last few years a very small size pair (0.7/2.9 mm) has been produced, and has been called the 'microcoaxial pair'. It is devoted to medium capacity, but nevertheless trends do not seem to be favouring production of further types of coaxial pairs for digital transmission only.

The choice of information bit rates to be assigned to the different systems has been and still is one of the main problems; both the multiplexing hierarchy recommended for the terminal equipment, and the economic optimization of transmission by coaxial pairs have to be taken into account, as also does the need for maintaining a certain competitiveness with the analogue systems. At present, the 34 Mbit/s system on the microcoaxial pair and the 140 Mbit/s system on the small size pair (1.2/4.4 mm) seem to be the optimum ones. On the other hand, the optimum bit rate for the systems to be used on the 2.6/9.5 mm coaxial cable has not yet been defined: it is likely to be allocated between 500 Mbit/s and 1000 Mbit/s, probably nearer the latter.

Nowadays several types of digital coaxial systems are either in service or undergoing field trials, from 34 Mbit/s to a maximum of 400 Mbit/s. For such systems, international recommendations do not yet exist; however, it is certain that international standardization studies will be concentrated on a few systems, probably with priority given to the 34 and 140 Mbit/s systems.

The problems that still have to be faced concern (1) the definition of the quality-error rate, jitter and bit-sequence independence; (2) the potentialities of completely regenerative and hybrid solutions; (3) the line code and signal characteristics; (4) the alarm conditions and supervision criteria.

The success of the multiplexing digital techniques, testified by the progress achieved in international standards and by the increasing use in various countries, can, to a certain extent, be attributed to two factors: the prospect of setting up, albeit on a long term basis, a new network integrated in transmission and switching, and also in the various services themselves; and the economic advantages offered in comparison with the f.d.m. multiplexing systems, particularly for the non-telephonic signals.

As table 1 shows, the multiplexing hierarchy has been sufficiently defined; only level 5 of the European standards has not yet been specified. Studies have not been confined to the coding and multiplexing of the various information sources, but have also, of course, included problems of transmission both by radio links and by cable. Here the problem was the fact that a digital cable system basically costs more than a f.d.m. system of comparable telephonic capacity, on the same type of cable. Therefore, in economic terms (considering multiplexing equipment and the transmission system), there is a critical distance beyond which the f.d.m. technique is more economic.

Table 1. P.c.m. hierarchical bit rates in Mbit/s

level	Europe	North America	Japan
1	2.048	1.544	1.544
2	8.448	6.312	6.312
3	34.368	44.736	32.064
4	139.264	274.176	97.728
5	*ca.* 560 to *ca.* 840	—	400.352

The hierarchical levels indicated in table 1 have, to a large extent, been based on considerations regarding the use for digital techniques of existing transmission media in the local conditions of networks, and the possibility of producing new types of media especially designed for this purpose. However, this in itself is not enough to explain the adoption of different standards. Different implementation schedules of digital systems in the various countries have played a major rôle.

In practice, there is a tendency to foresee transmission line systems with bit rates which correspond to those of the hierarchical multiplexing levels. However, line multiplexing facilities greatly reduce the constraints imposed by transmission media and, therefore a technically and economically optimal system, studied for each type of transmission medium not corresponding to the hierarchy would appear to be fully justified.

There are three types of coaxial pairs which it is thought will be widely used in the 1980 and in the successive years:

(*a*) the pair 0.7/2.9 mm, known as 'microcoaxial';
(*b*) the pair 1.2/4.4 mm, known as 'small coaxial';
(*c*) the pair 2.6/9.5 mm, known as 'normal coaxial'.

The main features of these three types of coaxial pairs have been standardized by the C.C.I.T.T., which has issued the relevant recommendations. It should, however, be pointed out that while the first type of coaxial pair, recently produced, has been designed essentially, if not exclusively, for digital transmission, the other two, which have been used for many years, were originally intended for analogue transmissions, and it is to this use that the present C.C.I.T.T. recommendations refer.

The 'microcoaxial' pair (0.7/2.9 mm) is to be used for medium capacity systems over short and medium distances: the electrical characteristics of the pair must therefore be checked in a relatively narrow frequency band.

In accordance with this consideration, the C.C.I.T.T. recommendations establish that checks may be made up to a frequency of 20 MHz. In this case, the only checks necessary are:

impedance, attenuation, crosstalk and random impedance irregularities (echo pulse measurements). In the view of the limited frequency band, it is unnecessary to check also equidistant and systematic irregularities. On the other hand, the coaxial pairs 1.2/4.4 mm and 2.6/9.5 mm will be mainly used for long distances and high capacity systems. The electrical characteristics of these pairs will have to be checked in broad frequency bands which are at present expected to reach, for the same characteristics, 200 MHz for the 1.2/4.4 mm pair and at least 800 MHz for the 2.6/9.5 mm pair.

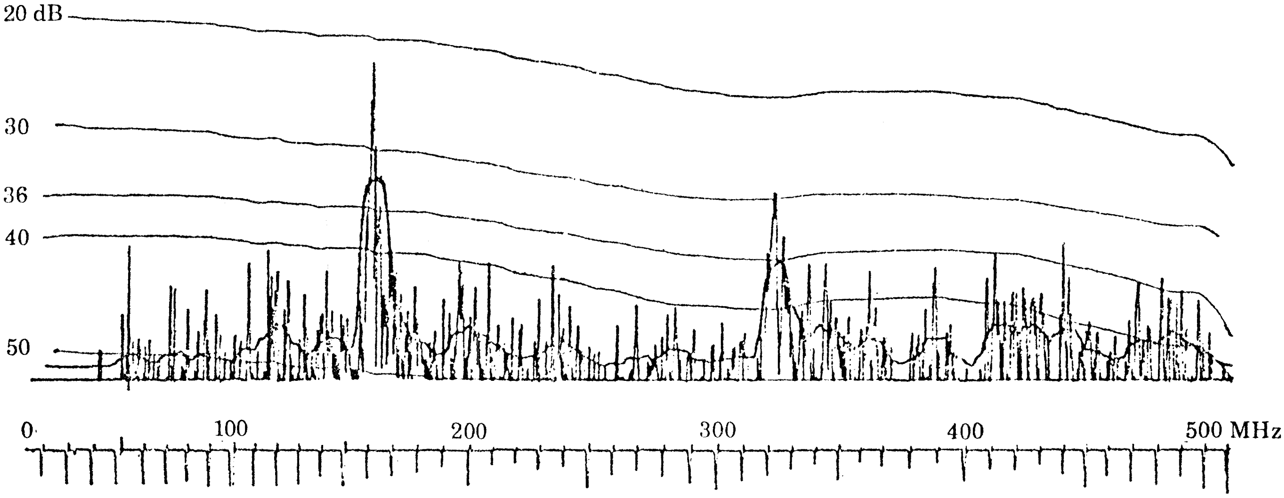

FIGURE 1. Return loss (spiked curve) and reflected power (smooth curve) in the 2.6/9.5 mm coaxial pair in an 8 coaxial pair cable.

The C.C.I.T.T. recommendations concerning these two types of coaxial pairs refer, as mentioned previously, to analogue use at 12 MHz and 60 MHz respectively, and do not cover the frequencies mentioned above. However, it is hoped that new recommendations will shortly be issued covering the frequencies in question and particularly: impedance, attenuation, crosstalk, random impedance irregularities and equidistant and systematic impedance irregularities. This last type of irregularities, which is checked by measurements of return-loss at single frequencies of the range considered, and of average reflected power in suitable frequency ranges (e.g. 10 MHz), is in this case particularly important, as the cable manufacturing techniques existing today lead to return loss peaks at certain frequencies in the transmission band.

Figure 1 shows the return loss and the reflected power (in 10 MHz bands) measured in the 2.6/9.5 mm coaxial pair in an 8 coaxial pair cable produced in Italy. The worst values given in this figure (22 dB for return loss and 33 dB for the reflected power), although rather low, should not prevent one from using the cable correctly for digital transmissions. Although the question is still being studied, it would appear that the figures of approximately 20 dB for the return loss and 30 dB for the reflected power can generally be considered acceptable, at least for the type of digital systems we have in mind today. Nevertheless, many countries are presently taking measurements on the types 1.2/4.4 mm and 2.6/9.5 mm coaxial pairs in the frequency range indicated previously, in order to establish whether the manufacturing and laying conditions used until now for analogue use can be considered adequate for digital use. The results of these measurements tend to indicate that the present characteristics of cables do not present any serious difficulties for digital systems with a voice channels capacity equivalent to that of the analogue systems.

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The choice of the information bit rates to be assigned to the different systems, which influences the corresponding voice channels capacity, is one of the main problems. This choice is governed by a large number of sometimes conflicting factors which must be considered together in order to arrive at the best possible solution. The most important of these factors are:

(1) The electrical characteristics of the coaxial pair, particularly attenuation, which remains the dominant design factor for digital coaxial systems.

(2) Outside constraints. The main constraint for a first generation of systems to be used in the 1980s on 1.2/4.4 mm and 2.6/9.5 mm pairs lies in the fact that analogue and digital systems must be able to coexist in the same cable, using common infrastructures. This involves in particular the use, for the digital systems, of repeater-spacings compatible with those of analogue systems. Moreover, to ensure the compatibility mentioned above, certain precautions must be taken with regard to power feeding characteristics, and an attempt must be made to see that the power feeding span is of equal length for all systems in the same cable. Other constraints, in the case of coexistence of digital and analogue systems in the same cable, may arise when common containers are used, from the necessity to ensure thermic compatibility with the analogue amplifiers which use regulators with thermic-sensitive elements. Another constraint may be provided by legislation prohibiting a certain value of current from being exceeded for the remote power feeding.

(3) Quality features to the digital system. These have not as yet been agreed upon or defined at an international level. However, it is known that the most important parameters to be considered are design error rate, jitter, alarm conditions and supervision criteria, and bit sequence independence. As regards the value to be attributed to the design error rate, there seems to be general agreement that this value should be established on the basis of the length of the link, bearing in mind the requirements of telephony only, and not those of other services which may be stricter. For the medium and high capacity coaxial systems (from bit rates of the order of 34 Mbit/s) the design error-rate most likely to be accepted is 10^{-10}/km. As regards jitter, the various administrations are conducting studies and trials in an attempt to find better methods of measurement (type of check signal and value to be considered: root mean square value or peak value or peak-to-peak value) and to find also the acceptable limits. The first results of these trials indicate that a root mean square value of 0.01 unitary interval for regenerators can be considered acceptable. As regards alarm conditions and supervision criteria, besides the problem of error rate values to be attributed to the major alarm threshold (which cuts out the system) and the minor alarm threshold (which provides a local indication), there is the problem of localizing faulty repeaters. This involves an important decision because of the economic implications: this can be done with the system functioning or only when it is not operating. As regards the bit sequence independence, now considered necessary by many administrations, it is a question of designing a digital system that we might describe as 'transparent', that is, capable of receiving an input digital signal with no particular frame structure constraints. This is in order to enable all present and future services to use the line system and naturally means that the system must be autonomous as regards the characteristics of the input signal frame.

(4) Technical feasibility. This is a very important point as it is obvious that a system will be used only if the necessary components are available on the market at reasonable prices and are reliable.

(5) Sufficient economic compatibility with analogue systems of comparable capacity, in the field of use. This is a factor to be borne in mind, although it must be remembered that economic

considerations must not be made on the basis of transmission systems only, but must take into account all the components of the network.

We have thus indicated the various factors which influence the choice of a digital transmission system and in particular the bit rate. When designing a system, the choice of a correct line code is of fundamental importance, as this enables one to comply with many of the requirements mentioned above.

Let it suffice to recall the various points that must be considered when choosing the code:

(*a*) Absence of a direct current component so as to make possible the use of d.c. remote power feeding and the connections by means of transformers.

(*b*) Possibility of guaranteeing a limited number of consecutive symbols of the same level, so as to facilitate the feeding of the rhythm to the regenerators without requiring any restriction of the input binary signal.

(*c*) Minor importance of the low and high frequency components in the signal energy spectrum, with the energy concentrated around the central part of the spectrum. This will make it possible to adapt the repeater spacing on the basis of the attenuation of the coaxial pair at a frequency half that of the symbol rate.

(*d*) The components of the energy spectrum should not be too subject to the influence of the statistical properties of the input binary signal, so the system will operate correctly whatever the input signal.

(*e*) Reduction, if necessary, of the line symbol rate with respect to the input bit rate. This is in many cases a particularly attractive possibility achieved by using a multilevel code, because it permits the reduction, for an assigned bit rate, of the range of the frequency band on the line.

Within this framework, in some applications the alphabetic codes called MS 4/3 and 4B/3T which reduce the line symbol rate to three quarters of the input bit rate have been used. The advantages which can be obtained using multi-level codes have to be compared with the better quality characteristics necessary for the transmission media and with the greater circuitry of the regenerative devices: all these elements can determine an excessive increase in cost. So, taking into account these considerations, the use of codes with many levels (for example seven or more) appears restricted to the 'hybrid' systems which are different from the 'regenerative' systems because many analogue repeaters are placed between two regenerators along the cable. In some particular circumstances of use these hybrid systems should allow a non-negligible economic saving.

Table 2 shows the main characteristics of the digital coaxial systems presently developed in Europe. The present developments only concern systems studied to be applied on micro-coaxial pairs and 1.2/4.4 size coaxial pairs. As regards the first type of pair, the optimization could be the system at 34.368 Mbit/s rate which corresponds to the third hierarchical level indicated in table 1; for the second one the optimization could be achieved for a distance of few hundreds of kilometres, using a system at 139.264 Mbit/s, provided that the various compatibility conditions with the 12 MHz analogue systems (repeater spacing, repeater size, power feeding characteristics and span, and fault-location span) are pre-determined. To obtain this result it seems necessary to use alphabetic line codes to reduce the line symbol rate to three quarters of the input bit rate. As alternative solution a hybrid repetition is proposed with a long chain of *ad hoc* designed 35 MHz amplifiers: the line code is the level class IV partial response code by which the symbol rate is reduced to about 70 Mbaud/s and the line signal band-width to about 35 MHz. The large number (40) of intermediate analogue repeaters allow the placing of digital repeaters in the main station only; thus the need of remote fault location is restricted to analogue repeaters. This system has been developed in Italy; an experimental link is in operation from October 1974, with good results. Naturally the systems at 140 Mbit/s, regenerative or hybrid type, can also be adapted in order to be applied on 2.6/9.5 mm coaxial pairs with a repeater spacing of 4.5 km. This solution is not the best one and can be justified only in particular situations. So, for example, in Italy the old coaxial cables currently equipped with 12 MHz valve analogue systems, which are not suitable to be applied to 60 MHz systems for their inherent and laying characteristics, could be equipped with 140 Mbit/s systems. The 140 Mbit/s network which could spring out of that is shown in figure 2.

Table 2. Digital coaxial cable systems in Europe

bit rate/(Mbit/s)	8.448	54.368	51.747	120.000	139.264	139.264
tube size/mm	0.7/2.9	0.7/2.9	1.2/4.4	1.2/4.4	1.2/4.4	1.2/4.4
type of repetition	regenerative	regenerative	regenerative	regenerative	hybrid	regenerative
maximum digital repeater spacing/km	4.1	2.05	2.032	2.1	80	2.10
maximum analogue repeater spacing/km	no	no	no	no	2.05	no
line code	HBD3	MS43	HDB3	4B3T	class IV p.r. (7 levels)	MS43 or 4B3T
line symbol rate	8.448	25.776	51.747	90	69.632	104.448
power feeding current/mA	50	100	200	50	100	†
power feeding voltage/V	± 400	± 400	± 600	± 250	± 400	
power feeding span/km	80	80	100	30	80	100
design error rate	2.5×10^{-10} per km	10^{-10} per km	—	2×10^{-7} for 2500 km	10^{-10} per km	10^{-10} per km
types of allocation	short and medium haul trunks	short and medium haul trunks	short and medium haul trunks	intercity trunks	intercity trunks	intercity trunks
degree of implementation	in service	experimental link	in service	experimental link	experimental link	under development

† Different characteristics are envisaged by different countries.

Table 3 shows the main characteristics of digital coaxial systems presently developed outside Europe. None of the solutions envisaged may represent the best relating to the network areas typically covered by 60 MHz analogue coaxial systems. Anyway the above-mentioned solutions have been envisaged and developed because of special local situations. So in the United States the typical long distances involved between high-rank centres make it unlikely for digital coaxial systems to be comparable economically with existing analogue coaxial carriers. Waveguide facilities only have been planned for digital transmission on long-haul trunks, nevertheless digital lines at 274.176 Mbit/s on 2.6/9.5 mm coaxial pairs find convenient application in metropolitan areas and short-haul trunks. In the case of Canadian choice the absence of competitive long-haul high-capacity f.d.m. coaxial carriers, the importance given to digital data and video transmission and finally the intent of rapidly introducing digital systems may have influenced the Canadian decision, even if some advantages in choosing higher bit rates were recognized.

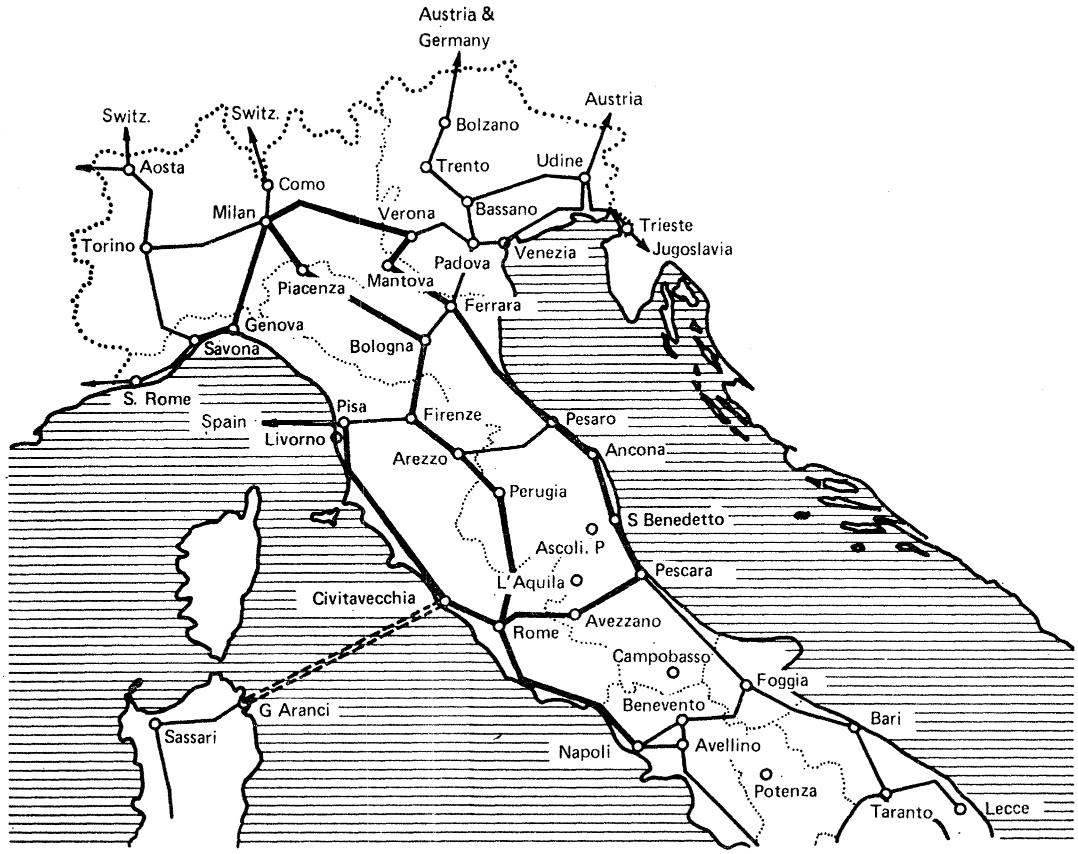

FIGURE 2. ——, Cables with two 12 MHz valve analogue systems; ━━, possible solution with one 12 MHz analogue system and one 140 Mbit/s digital system.

TABLE 3. DIGITAL COAXIAL CABLE SYSTEMS OUTSIDE EUROPE

country	U.S.A.	Canada	Japan	Japan
bit rate/(Mbit/s)	274.176	274.176	97.728	400.352
tube size/mm	2.6/9.5	2.6/9.5	1.2/4.4	2.6/9.5
type of repetition	regenerative	regenerative	regenerative	regenerative
maximum digital repeater spacing/km	1.74	1.9	1.6	1.6
maximum analogue repeater spacing/km	no	no	no	no
line code	binary	B3ZS	AMI + scrambler	AMI + scrambler
line symbol rate	274.176	274.176	97.728	400.352
power feeding				
current/mA	—	870	250	550
voltage/V	—	± 1500	± 350	± 650
power feeding span/km	—	208	24	100
design error rate	—	10^{-7} for 2500 km	10^{-8} for 200 km	10^{-8} for 2500 km
type of application	metropolitan areas	intercity trunks	intercity trunks	intercity trunks
degree of implementation	in service	in service	experimental link	experimental link

The following applications can be foreseen in Europe for further development of digital coaxial systems:

(*a*) use of the 1.2/4.4 mm coaxial pairs for transmission at 420 or 560 Mbit/s by hybrid or regenerative techniques with a 1 km repeater spacing (half of the spacing of 12 MHz f.d.m. or 140 Mbit/s systems);

(*b*) use of the 2.6/9.5 mm coaxial pairs for transmission at 560, 700 or 840 Mbit/s by hybrid or regenerative technique with a 1.6 km repeater spacing (the same as that used in 60 MHz f.d.m. system).

TABLE 4. POSSIBLE SOLUTION FOR A 700 Mbit/s DIGITAL TRANSMISSION SYSTEM ON 2.6/9.5 mm COAXIAL PAIRS

number of speech channels	9600
gross bit rate	706.304 Mbit/s
maximum repeater spacing	1650 m
power feeding	
voltage	± 1500 V
d.c. current	500 mA
power feeding span	80 km
type of repetition	regenerative
line code	MS 4/3
line symbol rate	529.728 Mbaud/s
design error rate	10^{-10}/km
out of service threshold	10^{-5}
type of fault control	in service
fault control span	80 km
dejitterization at each power feeding span	8 bit buffer

TABLE 5. 700 Mbit/s FRAME STRUCTURE (9600 SPEECH CHANNELS)

tributary bit-rate	139.264 Mbit/s
accuracy	$\pm 15/10^6$
number of tributaries	5
resulting bit rate	706.304 Mbit/s
accuracy	$\pm 10/10^6$
frame length	2970 bits
framing pattern and service bit length	15
stuffing control bits per tributary	5
frame redundancy	1/73.25
stuffing ratio	0.3965
maximum reframing time (99.87 % of cases)	33 ms

The aim of these two applications consists of achieving an economic competitivity with the 12 MHz and the 60 MHz f.d.m. systems, as well as in the long-haul trunks, typically in European networks. For these applications research and development is in progress in various European P.T.T. organizations and manufacturing firms. While the use of 560 Mbit/s can represent a useful solution for both types of coaxial pairs and is also particularly attractive because it seems to be feasible, from the technical point of view, on the basis of the present technology, the use of the higher bit rate more important if the digital transmission to be expanded to 2.6/9.5 mm coaxial pairs, up to 500–600 km, as necessary for some European countries.

In Italy, studies relating to a digital system on 2.6/9.5 mm coaxial pairs at a 706.304 Mbit/s bit rate are in progress. The characteristics envisaged for this system are shown in table 4.

In table 5 the frame structure which could be used for the input signal in this system is indicated: this format has been developed in full conformity with the lower level formats already recommended by C.E.P.T. and C.C.I.T.T. We intend to start with this system in about 1985. We already have under construction a new network using coaxial cables (8 or 16 normal coaxial pairs) laid along the motorways: in these cables two or more pairs are reserved for this new system.

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