RECOMMENDATION ITU-R S.730*

Compensation of the effects of switching discontinuities for voice band data and of doppler frequency-shifts in the fixed-satellite service

(Question 7/4)

(1992)

The ITU Radiocommunication Assembly,

considering

a) that circular non-geostationary satellite systems are subject to Doppler frequency-shifts influencing the radio-frequency stability and to differential Doppler frequency-shifts resulting in baseband frequencies "stretch" or "shrinkage", for analogue interconnections and in frame slips for digital interconnections, respectively;

b) that the orbital perturbations of the geostationary satellites may result in a cyclical variation of the transmission path time delay of less than 3 ms;

c) that the difference between an audio frequency applied to one end of the circuit and the frequency received at the other end should not exceed 2 Hz according to ITU-T Recommendation G.225;

d) that the maximum allowed frame slip performance of the digital interconnections depends on the network systems connected;

e) that the hand-over operation of circular non-geostationary satellite systems will cause switching discontinuities due to the different propagation paths via the two satellites,

recommends

1 that differential Doppler shift correction is necessary for analogue telephony transmission via a non-geostationary satellite in the fixed-satellite service if the product(s) of the baseband (MHz) times the number of the revolutions per day of the satellite relative to the Earth exceeds 0.666;

2 that compensation for switching discontinuities is necessary for time differences greater than 20 ms for analogue telephony transmission and that therefore suitable variable time-delay devices should be implemented for such a compensation;

3 that elastic buffer stores should be applied for the differential Doppler-shift correction of digital satellite links on either the receive or transmit side, respectively, where the buffer dimension depends on the orbit parameters, the data rate and the maximum allowed frame slips;

4 that for the digital interconnection of national synchronous networks the buffer store should be dimensioned by considerations which allow for the complete removal of the transmission delay variations;

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* Radiocommunication Study Group 4 made editorial amendments to this Recommendation in 2001 in accordance with Resolution ITU-R 44 (RA-2000).

5 that the following Notes should be regarded as part of this Recommendation.

NOTE 1 – The transmission of data and telefax in an analogue telephone channel compensated according to § 1 and thus fulfilling the ITU-T Recommendation G.225 requires no further provisions for the compensation of the differential Doppler shift.

NOTE 2 – Data transmission requiring wider bandwidth than a single telephone channel needs correction of the differential Doppler shift at a smaller value of *s* as in the case of § 1.

NOTE 3 – The transmission of analogue television signals in practical systems in the fixed-satellite service is not adversely effected by differential Doppler shift or switching discontinuities due to the propagation path difference and therefore does not require corrections.

NOTE 4 – For the transmission of data the occurrence of switching discontinuities may be subject to the system's error correction technique.

NOTE 5 – For the compensation of the differential Doppler shifts as mentioned in § 1, variable time-delay devices as for § 2 may be used. A common device used for both tasks may be applied.

NOTE 6 – *recommends* 1 applies for non-geostationary circular satellite orbits only. Other kinds of non-geostationary orbits such as highly inclined elliptical orbits (e.g. MOLNIYA or TUNDRA) need further study to provide for the future use of these systems.

NOTE 7 – Switching discontinuities of 20 ms as considered in § 2 are expected to be non-critical for present telefax group 3 systems, and cause no unacceptable degradations. However, future Recommendations of the ITU-T on the quality of service of telefax transmission may include dedicated information on maximum possible transmission interruptions which may then require further study.

NOTE 8 – The analysis on which the *recommends* are based, is contained in Annexes 1 and 2.

ANNEX 1

The effects of Doppler frequency-shifts and switching discontinuities in the fixed-satellite service

1 Doppler frequency-shifts (applicable to non-geostationary satellites)

The magnitude of the total Doppler frequency-shift between the terminals of a system in the fixed-satellite service depends upon the wavelengths used and the relative velocities of the satellite with respect to the earth stations. The major component of the effect of the Doppler shift, i.e. the shift of the carrier or a reference-frequency of the transmission, can be removed in the receiver; however, it may be necessary also to compensate for the differential shift across the radio-frequency spectrum of the signal that produces a frequency "stretch" or "shrinkage" of the baseband signal. Depending upon the relative locations of the earth stations and the orbit, the Doppler shifts between transmitting earth station and satellite and also between satellite and receiving earth station can either add or subtract. If 5 000 km is taken as a probable minimum orbital height for a communication satellite, then the "stretch" or "shrinkage" of the baseband signal will not exceed two parts in 10^5. In most practical cases, the orbital height will be greater and the Doppler shift would be considerably less than this, and in the particular case of the geostationary satellite, there would be no significant Doppler shift.

The maximum value of the Doppler shift, resulting from transmission to, or from, a space station on a satellite in a circular orbit, can be estimated from the relationship:

$$\Delta F \approx \pm 1.54 \times 10^{-6} \times F \times s \tag{1}$$

where:

ΔF: Doppler frequency-shift

F: operating frequency

s: number of revolutions per day (24 hours) of the satellite with respect to a fixed point on the Earth.

This relationship may also be used for calculating the maximum differential Doppler frequency-shift over a frequency band. A few values of s for various circular equatorial orbit altitudes are provided below (Table 1) to facilitate the calculations for individual cases.

TABLE 1

Revolutions per day relative to the Earth, *s*	**Altitude for circular equatorial orbits (km)**	**Period (h)**
0	35 600	24
1	20 240	12
2	13 940	8
3	10 390	6
4	8 080	4.8
5	6 420	4
6	5 170	3.4
7	4 190	3

In a frequency-division multiple-access (FDMA) system, each participating station uses a portion of the frequency band of the satellite repeater. Since the transmissions from each station are independent in time, there is no adverse effect from any relative time-shift. There will, however, be a Doppler frequency-shift in the transmission from each station which varies with time.

For satellites employed to relay signals simultaneously from a number of earth stations, special consideration of Doppler shift may be necessary.

Table 2 shows the maximum possible Doppler frequency-shifts at the satellite at 6 GHz. The figures are based on equatorial orbits and assume that the satellite moves in the same direction as the surface of the Earth.

Because of various perturbing forces, the position of a geostationary satellite varies. If the satellite position is maintained within ±0.1° of longitude and latitude, the maximum relative velocity of a satellite with respect to an earth station is less than approximately 3.8 m/s, and the maximum Doppler frequency-shift will not exceed 76 Hz at 6 GHz.

To prevent interference between adjacent radio-frequency channels caused by Doppler frequency-shifts, guardbands can be used. Depending on the location of the stations, the signal transmitted by one station may be shifted upward, while that from a station on an adjacent channel may be shifted downward. Alternatively, the frequency-shifts may be corrected by available techniques.

For example, allowing a guardband equal to the maximum possible Doppler frequency-shift shown in Table 2 for a ten-channel system, the total guardbands would then be 18 times the figures shown (at 6 GHz).

TABLE 2

Maximum Doppler frequency-shift

Period (h)	6	8	12	24
Approximative altitude (km)	11 000	14 000	20 000	36 000
Minimum elevation of antenna: 5° Maximum Doppler frequency-shift at 6 GHz (kHz)	27.7	18.5	9.3	0.0

In the time-division multiple-access (TDMA) system, all earth stations transmit on the same nominal carrier frequency. This requires that the transmitter carrier be on only during that interval of the frame assigned to the station. During transmission, the carrier would probably be modulated by phase-shift keying or frequency-shift keying. Because of the Doppler frequency-shift, transmissions will arrive at the satellite and be repeated at frequencies which vary above and below the nominal carrier frequency. To accommodate this shift, the earth-station receivers must be capable of adjusting to the sudden changes in carrier-frequency which will occur. This may impose the requirement for increased interburst guard time and for more time within the burst to be allowed for carrier recovery and burst synchronization for satellites in a non-geostationary orbit.

1.1 Telephony

When frequency-division multiplex telephony is used, it is necessary to limit the bandwidth or the apparent geocentric angular velocity of the satellite to prevent unacceptable differential Doppler frequency-shifts (unless corrections are applied to compensate for the Doppler effects).

According to ITU-T Recommendation G.225, the difference between an audio-frequency applied to one end of the circuit and the frequency received at the other end should not exceed 2 Hz. The question of error in reconstituted frequency is still under study in Telecommunication Standardization Study Group XV.

It may be noted that an error of 2 Hz is not exceeded in a single satellite link, if the product(s) of the baseband (MHz) times the number of revolutions per day of the satellite relative to the Earth does not exceed 0.666; however, additional error is likely to be introduced by the multiplex equipment.

Doppler effects will also shift the pilot frequencies used in FDM telephony for satellites with such angular velocities. Possible methods which could be used for correction of these shifts are:

– a suitable variable time-delay device;

– the carrier-frequencies used in the frequency-division multiplex equipment could be automatically controlled to compensate for the effects of Doppler shift and so reduce the overall frequency errors to acceptably small values.

The first of these methods has the advantage of effectively cancelling the errors resulting from the movement of the satellite, in a manner similar to that in which they are introduced (i.e. by change in transmission delay during the pass). This method would, therefore, also eliminate all the effects of Doppler shift on the baseband signals and by suitable arrangements, would avoid switching discontinuities when transferring the information flow from one satellite to the next in the orbital pattern. Control of the variable delay could be performed, either by using predicted orbit information or on a servo basis employing a pilot signal transmitted from the earth station to the satellite and back to the same earth station (loop method). The loop method has the following advantages:

– it would ensure that only the correct frequencies were received at the satellite. This facility could be of particular importance for certain systems, for example, those using closely-spaced channels or blocks of channels with single-sideband modulation in the Earth-to-satellite direction;

– Doppler frequency "stretch" might to some extent be obviated, e.g. by splitting the receiving bandwidth into appropriately separated portions and providing independent compensations for the blocks of circuits arriving from each of the other earth stations.

Alternatively, compensation for the variable delays could be applied only at the receiving end and controlled by pilot signals originating at the distant stations. In this case, the Doppler frequency "stretch" or "contraction" of the baseband would need to be accommodated by adaptations of the frequency-division multiplex equipment at each earth station. Administrations are requested to submit to the ITU-T their recommendations, or findings concerning such adaptations involving control of the earth station frequency-division multiplex equipment, either on a loop basis, as is described under the first method above, or on a route-by-route basis.

Doppler-shift correction may be necessary in any system in the fixed-satellite service using single-sideband amplitude modulation.

1.2 Telegraphy and data transmissions

If telephone channels comply with the requirement of ITU-T Recommendation G.225 this implies that, for telegraph and data channels derived from such telephone channels, the effect of Doppler frequency-shift may be ignored or has been adequately compensated for (see § 1.1).

1.3 Phototelegraphy

If phototelegraphy channels are derived from telephone channels complying with the requirement of ITU-T Recommendation G.225, the effect of Doppler frequency-shift may be ignored as being adequately compensated for.

1.4 Wideband data

It should be noted that Doppler correction would need to be provided for carrier-derived phototelegraphy or data channels requiring wider bandwidths than a single telephone channel (e.g. group or supergroup bandwidths).

1.5 Television

The change in field frequency introduced by Doppler frequency-shift is very small. In normal monochrome television practice, the accuracy of the field frequency at the programme source is likely to be the limiting factor as far as disturbance to domestic receivers is concerned and Doppler shift will not be of concern.

It may ultimately be desirable to correct for the effects of Doppler shift on colour television signals, but the initial tests made with the satellites have demonstrated that standard colour receivers and, in particular, those using crystal controlled sub-carrier oscillators, will operate satisfactorily, with the order of Doppler frequency-shift likely to be encountered in a practical system in the fixed-satellite service.

2 Switching discontinuities (applicable to non-geostationary satellites)

Satellites which rise and set can be used by any two or more earth stations only while mutually visible. These stations must then switch or “hand-over” to another mutually visible satellite, to maintain communication with some orbit systems, or with excessively separated earth stations; relatively long interruptions may occur when mutual visibility of the first satellite is lost before another satellite has been acquired. Such interruptions can be avoided by the use of controlled, equally separated satellites of sufficient number in orbits having a recurrent earth-track. Such satellite orbit systems are often referred to as systems of phased satellites. The phased circular equatorial orbit system is the simplest and best-known such system.

Even though such systems can prevent hand-over interruptions, there will generally be slight discontinuities of overlap of communication between two stations at the instant of hand-over, depending on whether the propagation path via the new satellite is shorter or longer than that via the former satellite. The calculation of these propagation path lengths or delay times, and their difference, is dependent upon simple geometric relationships.

In the case of multi-hop connections, the switching discontinuities in the different hops will not often be coincident in time, so that the number of discontinuities per 24 hours will be approximately $n \times m$, where n is the number of hops and m the mean number of switching discontinuities per 24 hours per hop. With systems employing phased satellites, the time differences for some pairs of earth stations would not exceed 10 ms; whilst for other pairs of earth stations, the time differences would be up to 20 ms or even more. In unphased satellite systems, the time differences would have durations between 0 and 30 ms or more. It should be noted that these discontinuities are predictable and that counter-measures are possible. The use of variable delay devices could reduce these switching discontinuities to negligible proportions.

NOTE – An earth station using any satellite, non-geostationary or geostationary, may have its circuits interrupted for predictable periods when the satellite in use has approximately the same orientation from an earth station as the Sun or another satellite at the same frequency, or when the satellite uses a solar power supply without batteries and is eclipsed by the Earth. To avoid interruptions of these types, alternate routing via surface circuits or via a different satellite may be used during periods of outage.

2.1 Telephony

Time differences, of up to perhaps 20 ms during transfer from one satellite to another, should not cause difficulty with telephone conversations. However, a discontinuity in transmission of this duration can cause errors in existing telephone MF signalling systems such as the Intercontinental ITU-T No. 5 and TASI. Signalling techniques, (such as ITU-T No. 6), that employ high-speed pulsing rates, may be much more susceptible to errors from this source.

2.2 Telegraphy and data transmissions

The effects of present interest are those due solely to differences in transmission time between one satellite path and another, and these are of two types:

– lengthening or shortening of telegraph elements when the transmission time differences are relatively large, i.e., exceeding a significant part of an element;

– phase discontinuities of voice-frequency tone, sometimes giving rise to telegraph distortion, whenever the transmission time differences exceed a fraction of the time occupied by one cycle of the highest baseband frequency utilized by a telegraph channel of a broadband system carrying voice-frequency telegraphy.

According to preliminary information from one source (see Appendix 1), it appears that, in an unprotected 50 Bd start-stop telegraph channel the average number of character errors caused by discontinuities of up to about 7.5 ms may not exceed about 0.25 per discontinuity. The average number of character errors increases probably to about 1.0 for discontinuities of duration about 10 to 12 ms, whilst it may approach 2 or more for discontinuities of duration up to 20 ms or 30 ms.

Time duration of the discontinuities likely to be encountered in non-geostationary satellite systems would cause character errors in synchronous telegraph systems and in time-division multiplex telegraph systems. Time discontinuities can falsify selection signals such as used in telex, causing incorrect routing and, particularly on automatic systems, the possibility of incorrect charging might arise.

Automatic error-correcting (e.g. ARQ) equipment is used on some telegraph circuits, for example when the traffic is extended over HF radio links. It may be noted that ARQ would not only protect against errors arising from switching discontinuities, but also against errors arising from other causes. Justification for any special treatment of circuits routed through systems in the fixed-satellite service should take into account the relative frequency of error producing disturbances in the satellite links and in their terrestrial extensions as well as in international circuits using other means. If, after account has been taken of the various sources of error in telegraph channels, it seems necessary to take special measures to deal with errors caused by satellite switching discontinuities, then it appears that consideration might be given to the possibility of using some device such as a buffer store. This might commence to store the telegraph signals on receipt of a "satellite change" signal, and would retransmit at a slightly higher rate after the satellite switching operation.

Another method of reducing the number of errors due to satellite switching would be to use a suitable variable delay device.

Switching discontinuities of up to perhaps 20 ms would affect data transmission by causing:

– errors to occur in one or more blocks;

– loss of block phase.

Provided the switching from one satellite to another is fairly infrequent, the errors of the first type would not be serious, and would in fact be similar to the effects of occasional switching or noise disturbances to be expected on normal line circuits. The loss of block phase results directly from the time discontinuity and has no equivalent in line systems.

Block phase would thus need to be re-established on data circuits each time a switch from one satellite to another occurs, unless means are adopted to compensate for the delay discontinuity. However, if the switch-overs are not unduly frequent, and re-phasing of the data transmission system is arranged to take place automatically, the loss of circuit time due to this cause would not be a serious disadvantage.

2.3 Phototelegraphy

The effect of these discontinuities would be an immediate displacement (either in an advance or a retard direction) of any succeeding elements of the picture, relative to the position before switching. For equipment conforming to ITU-T standards and using a drum speed of 60 r.p.m., a delay discontinuity of 20 ms would produce a displacement of about 2% of the picture width, e.g. 0.5 cm displacement in a picture 25 cm wide. This displacement would be a serious defect in most pictures or in typescript, meteorological charts, etc. With higher scanning rates, the displacement would increase in proportion. The amount of such displacement that could be accepted as tolerable is, of course, a matter to be decided in consultation with the ITU-T. It seems likely, however, that switching discontinuities of the order of 20 ms would produce unacceptable distortion in the majority of cases, and would, therefore, need to be avoided, either by suitable delay-compensation techniques or by arranging that the picture transmissions do not occur during switching times.

2.4 Television

Switching from one non-geostationary satellite to the next is very similar to, and will generally produce the same effects as, switching between "non-synchronous" programme sources, and can result in temporary disturbance to the receiver field time-base. The actual time over which the disturbance exists will vary in practice depending upon the relative phase relationship at the moment of switching, but will normally lie between 0.5 s and 2 s.

The change in transmission delay on switching may introduce a small discontinuity in the sound signal which, although noticeable, should not be disturbing.

As switching in a system in the fixed-satellite service will be infrequent, the effect on both vision and sound signals would not prove too serious.

3 Summary

The significance of Doppler frequency-shift and switching discontinuities in systems in the fixed-satellite service varies with the type of service or signal transmitted, and with the characteristics of the satellite orbit. In general, geostationary satellites are not expected to introduce significant Doppler frequency-shifts or switching discontinuities. Non-geostationary satellite systems will introduce greater Doppler frequency-shift and switching discontinuities.

The major component of the Doppler frequency-shift can be removed in the radio-frequency receiver, but there will remain a "stretch" or "shrinkage" of the baseband spectrum due to differential frequency shift. The effect on monochrome television will be insignificant and the effect on colour television will probably be tolerable. In telephony, with the general use of broadband single-sideband frequency-division multiplexing techniques, the changes in baseband spectrum (differential Doppler) will require compensation in the form of transmission delay equalization of the entire baseband or of automatic control of the carrier frequencies used in the multiplex equipment. It is felt that such compensation is feasible. Telegraph, data and phototelegraphy channels, derived from channels adequately corrected for telephony, should not require any further consideration of Doppler effects.

It appears that, unless special steps are taken, time discontinuities due to satellite switching may lead to error rates on telegraph channels which, for certain pairs of earth stations with particular orbital configurations, could exceed the desirable limit suggested in ITU-T Recommendation R.54 of 2 errors per 100 000 telegraph characters. Some discussion of this matter, and of possible means of mitigating the effects on telegraph transmission, is given in Appendix 1.

The attention of the ITU-T and Telecommunication Standardization SG 9 is drawn to the problems which may arise in systems in the fixed-satellite service due to Doppler frequency-shifts and switching discontinuities; the ITU-T with regard to telephony, telegraphy and data transmission and Telecommunication Standardization SG 9 for television transmission, including the related sound channel.

APPENDIX 1

TO ANNEX 1

1 ITU-T Recommendations

ITU-T Recommendation R.57 calls for a maximum isochronous distortion over a single telegraph link not exceeding 10%.

ITU-T Recommendation R.54 suggests, in the *considerings*, an error-rate not exceeding 2 per 100 000 telegraph characters due to distortion as a desirable overall transmission objective.

2 Telegraph error-rates in 50 Bd start-stop telegraph systems

In a preliminary series of experiments, the relationship between the duration of switching discontinuities and telegraph error-rate in 50 Bd start-stop telegraph systems has been explored. The error-rate is dependent, to a small extent, on the nature of the transmitted text. It appears that the error-rate may not vary greatly when the duration of the switching discontinuity is varied between 0 and about 7.5 ms; the average number of errors is then about 0.25 per switching operation. For durations exceeding about 7.5 ms, the error-rate increases; this may be explained by the evident fact that, in these circumstances, the lengthening or shortening of the telegraph elements approaches or exceeds 50% of the duration of the elements. The preliminary experiments suggest that the average number of character errors per discontinuity may be about 1 for discontinuities of duration of about 10 to 12 ms, whilst it may approach 2 or more for discontinuities of duration up to and exceeding 20 ms. These results, as stated above, apply to telegraph signals at a speed of 50 Bd; the duration of each element is 20 ms and it is not unreasonable to find that, for discontinuities of a duration up to about 30 ms, there may not be more than two telegraph character errors.

3 Compensation by means of variable-delay correction devices

3.1 Compensation with moderate accuracy

It would be possible to greatly reduce character errors due to satellite switching if suitably controlled variable delay devices could be connected in tandem with satellite links, so that the overall signal delay could be kept constant. Compensation to an accuracy of the order of 200 µs would deal with character errors due to the lengthening or shortening of telegraph elements. The development of such broadband delay devices would have the additional advantage of substantially eliminating differential Doppler shift effects in the transmitted baseband; these would otherwise call for special control of supergroup and group translation oscillators to preserve the centring of voice-frequency telegraph signals in their appropriate filter bandwidths.

The effects of phase jumps at the instant of satellite switching would remain, and while the character error-rate would be less than that estimated to occur without compensation, a reliable estimate of the probable error-rate would require experimental investigation.

3.2 Compensation with high accuracy

To avoid character errors due to phase jumps at the instant of satellite switching, delay compensation to an accuracy corresponding to ±15° at the highest baseband frequency involved appears to be necessary. For telegraph channels carried in the highest frequency telephone channels of a 1 200-channel system with baseband frequencies up to 5 MHz, an accuracy of some 0.01 μs would be required. The probable limit of predicted satellite slant range, and therefore of transmission delay, is of the order of 50 μs. Consequently, direct compensation on a predicted basis in a single step to an accuracy sufficient to substantially remove telegraph errors is impracticable. Consideration might, however, be given to additional measures, for example, an electronically controlled variable-delay device, which has its delay changed until the baseband signals over the two satellite paths displayed complete correlation in time, the switch-over then taking place.

Another possibility to which attention might be drawn is the employment of a relatively slow "fade-over" instead of an abrupt switch-over. The major effects of sudden phase changes might thereby be avoided and only a small proportion of telegraph channels suffer from amplitude effects. FM voice-frequency telegraph systems can tolerate at least 15 dB reduction of signal level and printed error-rates of the order of 1 in 80 000 might be achieved, but this possibility requires theoretical and experimental investigation. The effect of such a "fade-over" on telephone, data and facsimile circuits would need to be assessed.

4 Summary of means of compensation

In considering possible methods of mitigating the effects of switching discontinuities on telegraph performance, it must be borne in mind that in any telegraph channel there may be a number of causes of error.

Telegraph errors due to satellite-switching discontinuities might be reduced in number by:

4.1 "buffer store" systems, which would commence to store on receipt of a "satellite change" signal transmitted over the system and re-transmitted at a slightly higher rate after completion of the change;

4.2 time discontinuity correction of moderate accuracy used in conjunction with any of the following measures:

4.2.1 placing of the telegraph channels in the lower part of the baseband spectrum;

4.2.2 inter-satellite switching, which takes place at the point where the telegraph signals are d.c.;

4.2.3 introducing slow "fade-over" devices to mitigate transients caused by rapid switching between satellites;

4.2.4 recoding of the telegraph information into special codes, such as those developed by Hamming, which give correction facilities without the necessity for retransmission;

4.3 precise compensation of transmission delays to minimize the delay discontinuity at change-over.

In addition, it would be possible to use ARQ or some equivalent system; this would be particularly useful in the event that the satellite link is extended by an HF radio link or another type of link liable to introduce a relatively large number of telegraph errors.

ANNEX 2

Influence of Doppler frequency-shifts on digital interface characteristics between satellite and terrestrial networks

1 Outline of problem

Digital transmission techniques are likely to spread throughout the networks of the fixed-satellite service in the next few years, since they lead to a much more efficient use of satellites than the present analogue systems. On the other hand, the introduction of digital satellite links is likely to create new problems of connection with terrestrial networks; since most of these are analogue systems, provision will have to be made for analogue-digital conversion. Since the switching operations at the International Transit Centre (TC) are carried out at channel level, it would seem advisable to install the analogue-digital conversion equipment there also. This clearly shows that it would be desirable in most cases to extend satellite digital links by using terrestrial digital links at least up to the international transit centres. This measure should also facilitate the integration of this link in the terrestrial network when this network is subsequently digitized.

In situations where it is desirable to retain analogue terrestrial links, transmultiplexers may be used at the earth station to perform the analogue-digital conversion process. It is considered that transmultiplexers will be economic and will provide performance superior to the alternative of analogue demultiplexing and demodulation followed by digital encoding and multiplexing.

1.1 Types of international digital links

Three types of digital transmission links appear to be candidates for probable use in the establishment of international digital communication networks:

– A digital transmission link based on single-channel-per-carrier PCM-PSK-FDMA transmission facilities. Typically this link would operate at a gross bit rate of 64 kbit/s, for telephony or data transmission. Rate 3/4 or rate 7/8 coding/decoding interfacing with the terrestrial network at a net bit rate of 48 kbit/s or 56 kbit/s could also be used if the error rate for data transmission were not good enough.

– A digital transmission link which basically utilizes multichannel PCM-TDM-PSK-FDMA transmission facilities: for example a primary or higher order multiplex employing PSK modulation. This type of transmission can handle a variety of signals; for example telephony with or without DSI (digital speech interpolation) or high speed data transmission.

– PCM-PSK-TDMA transmission links where the transmission rate within a burst might typically be about 60 to 120 Mbit/s although the information rate to any one destination would be less than this. For this type of transmission there will be a slight difference in rate between the transmitted and received signals due to satellite movement.

1.2 Types of networks

There are three types of network which require international connection. They are considered in historical order.

1.2.1 Analogue network

These form the majority of existing networks and comprise mainly analogue links, but digital links are being increasingly used in these networks. However, it is assumed that in this class of network the International Transit Switching Centre (TC) remains analogue.

1.2.2 Digital switching at TC, national networks non-synchronous

This is the likely next phase in the introduction of digital techniques in international communications. It is probable that at this stage the TC will be connected to the earth station by digital links.

1.2.3 Synchronous national networks interconnected by digital links

This will also include national networks using high stability clocks which are plesiochronously connected. This is foreseen to be the ultimate network configuration envisaged by the ITU-T.

It should be borne in mind that configurations comprising mixtures of these networks will have to coexist.

1.3 The interconnection of digital links timed by different clocks

When transmitting a digital stream from one digital link through a second digital link, the clocks controlling the stream of the first digital link and the second link may have timing differences which must be compensated so that information can pass into the second link.

Two methods can be used to achieve this compensation and to interconnect digital links having different clock rates. The first involves the application of frame slips (i.e., at intervals not to transmit a frame or to transmit one frame twice), and the second involves the use of justification.

If the frame slip technique is used, limits must be placed on the frequency of frame slip. In PCM telephony several slips per minute might be tolerated, whereas some types of data service might not tolerate more than one or two slips per day on a user to user connection.

Since the slip frequency is porportional to the clock frequency difference across the interface, the independent link clocks must be maintained to close tolerances in accuracy and stability, so that the links are nearly synchronous. A connection between two such nearly synchronous networks is termed a plesiochronous connection.

The second solution lies in offering on the second link a bit rate slightly higher than that of the digital stream. The difference is compensated by adding justification bits which must subsequently be dropped (de-justified) at the far end of the second link making it effectively transparent, and the mean output bit rate after de-justification is the same as the mean input bit rate before justification. Whilst no slips occur at the interface between the first link and the justified link, slips may still occur at the interface between the de-justified end of the second link and a third link if the clock rate of the third link differs from that of the first link.

The one-way time delay of the transmission path via a geostationary satellite may have a daily peak-to-peak cyclic variation in the order of 0.15 to perhaps 1.5 ms due to orbital perturbations. Longitudinal drift of the satellite about its nominal position can cause additional longer term cyclic variations of about the same order of magnitude. These variations result in a Doppler shift of the clock frequency of the satellite link which may be offset at earth stations, either on transmission or reception depending on the particular application involved, by means of elastic buffer stores. For conversion between two slightly different bit rates, the signals are stored at the reception rate and read at the transmission rate. If the transmission rate is greater than the reception rate, the store will tend to empty, and in the contrary case, to fill up. Since satellite movements are restricted, the two states will alternate and the mean in time will be zero. Conceivably, extreme bit rate variations can be absorbed without data loss or repetition by suitable dimensioning of the store capacity.

Ultimately an international digital satellite link will be required to interconnect two or more independent terrestrial digital networks.

If the satellite link timing is locked to the high stability clock of one of the networks (network A), no additional slips will result on connections between network A and the other networks providing the Doppler shift is compensated by elastic buffers at the interface, although additional slips will occur on connections between the other networks. If the satellite link timing is independent, additional slips will be suffered unless justification is used at the interface between the satellite link and the terrestrial networks. The use of such a justified link will not affect the net slip rate arising from the clock differences of the two networks.

It should be noted that the component of timing error due to satellite link propagation time variation will reappear after the point at which de-justification is carried out, and elastic buffering will still be necessary to compensate for this. It should also be borne in mind that the operation of multi-destination links and digital speech interpolation (DSI) will be restricted if justification is used.

2 Discussion of solutions

2.1 Analogue switched national networks

It is not considered desirable to provide the analogue to digital conversions at the earth stations because it will be necessary to include channel multiplexing equipment. Since further multiplexing will also be required at the International Transit Centre (TC) it would obviously be better if the TC to earth station link were also to be digital. However because the terrestrial network is mainly analogue and therefore digital switching at the TC is not used, the clock rate of the digital link is not critical. For point-to-point PSK systems, it should therefore be possible to control the digital transmission rate of the receive terrestrial part of the link from a clock derived at the earth station. This clock would originate from the clock at the transmit side of the remote TC coding equipment. In the case of TDMA systems the clock would be obtained from the frame reference clock generated by the reference station; the Doppler shift due to satellite movement is likely to be insignificant. However if slip is to be eliminated entirely, the clock variation due to Doppler shift will need to be absorbed by means of elastic buffers at the receive side of the link. With such a solution no loss of digital information will occur. The use in TDMA systems of DSI does not affect this solution.

2.2 Digital switching at the TC, national networks non-synchronous

In this situation there will generally be a small difference in rate between the clock controlling the switch at the TC and the digital signals coming into the TC. Thus, frame slips will have to be allowed. In this case there seems little point in avoiding frame slips again at the earth station interface. Assuming a clock in the TC accurate to 1 in 10^8 and a clock in the TDMA reference station accurate to 1 in 10^7, then one 125 µs PCM frame slip would occur no more frequently than every 19 min, if the satellite were in an ideal geostationary orbit; and every 12 min for a satellite having 3° orbit inclination and no elastic buffer to remove the transmission delay variations.

For these situations therefore, the direct digital interface equipment (DDIE) needs to perform only the alignment and frame slipping function and to carry out any necessary modification to the frame format (as stated in § 2.1). For satellites without orbit inclination control the DDIE may also need to include an elastic buffer to remove transmission delay variations.

2.3 Digital switching with synchronous national networks

It has been recommended by the ITU-T that the interworking between national synchronous networks be plesiochronous. With the national networks controlled to an accuracy of 1 in 10^{11} this would result in a minimum of 70 days between frame slips.

When the international connection is by means of a TDMA satellite system having reference clock accuracy substantially worse than 1 in 10^{11} then either the rate of frame slip must be substantially greater than 1 in 70 days or a DDIE with justification may be used. However this complication is avoided if the TDMA system itself is timed to an accuracy comparable with that of the national networks, i.e. 1 in 10^{11}. In such a case the DDIE will need to perform the alignment function, carry out any necessary modification to the format and remove the transmission delay variations caused by satellite movement by using elastic buffers at the transmit and receive sides of the link. This is therefore the preferred solution for the interconnection of national synchronous networks.

In a practical TDMA system only a relatively small number of earth stations need to perform as reference stations. It should therefore not be difficult to ensure the required TDMA timing accuracy by letting those countries with synchronous digital networks serve as reference stations. However, in the case of SS (satellite switched)/TDMA systems which are expected to be introduced into the international satellite networks in the near future, it may be difficult to operate the TDMA system on a plesiochronous basis if the satellite switch timing is not controlled from the ground. It may be necessary initially, when there are only very few countries with synchronous networks, to accept a lower TDMA system timing accuracy and allow slips more frequently, perhaps once per day. In spite of this it is preferable that an international satellite TDMA or SS-TDMA system should be designed to operate in a plesiochronous mode between the terrestrial digital networks which it interconnects.