THE BELL SYSTEM TECHNICAL JOURNAL
Vol. 62, No. 10, December 1983
Printed in U.S.A.

Synchronization of Noncolocated TV Signals in a Satellite Time-Compression Multiplexing System

By K. Y. ENG* and B. G. HASKELL*

(Manuscript received June 15, 1983)

We describe here a simple method to synchronize three TV signals originated from noncolocated up-link stations in a satellite Time-Compression Multiplexing (TCM) system. In this system, information in three fields of each TV picture is compressed into a single field time so that the compressed signals from the three sources can be time multiplexed for transmission. The up-link synchronization ensures that the Radio Frequency (RF) bursts from different sources will arrive at the satellite without collision. Our method employs a dynamic master/slave arrangement whereby the first station signing on assumes the role of a master. The other stations subsequently can synchronize their transmissions to the master's by simply monitoring the received RF bursts from the satellite, measuring their respective delays to the spacecraft, and then phase locking their local color subcarrier clocks to the master's transmitted bursts. When the master station stops transmitting, an automatic procedure is provided for the second station to take over as the new master. The worst-case jitter performance is well below 100 ns, and the initial acquisition time can be kept less than one-half second. These are more than adequate for the present TV application, although further improvements are possible if necessary.

I. INTRODUCTION

Time-Compression Multiplexing (TCM) is a method of multiplexing various signals by time compressing their (analog) waveforms into segments in such a way that the compressed segments from different

---

* Bell Laboratories.

sources can be sent on the same channel in separate time intervals (time-division multiplexing).[1,2] Previous published works[3–5] have discussed various properties and ways to implement TCM in the transmission of multiple high-quality TV signals through a single satellite transponder of 36-MHz bandwidth. More recently, this idea has further been refined to the transmission with practical hardware of three broadcast-quality TVs in a transponder[6] (i.e., the received peak-to-peak video to weighted rms noise ratio $\geqslant$56 dB.) As with other TCM systems, one requirement in the latter proposal is that the input three TV signals be synchronized, at least to the extent that their vertical-blanking intervals overlap. If the signals are colocated in the same up-link earth station, it merely implies that frame synchronizers be used. However, if they are to be transmitted from separate earth stations, then the up-links have to be synchronized. Of course, the up-link synchronization is needed to ensure that signal bursts from different sources would arrive at the satellite without collision. We show and discuss in this paper how this can be accomplished with simple and easy-to-implement hardware arrangements.

Synchronization techniques in communications satellite systems have been studied extensively in past years,[7–9] mostly in connection with digital Time Division Multiple Access (TDMA) applications. They could all be used in the present problem of synchronizing three TV up-links. However, these previous techniques were designed for performance far exceeding the present requirement and hence tend to be more complicated than what is needed. More importantly, they were meant for digital signals and are not suitable for analog TV where the color subcarrier and various sync pulses must bear strict phase and frequency relationships and thus cannot be advanced or retarded with respect to one another arbitrarily. We will show in the next section how a TV up-link station can synchronize its transmission by simply monitoring the Radio Frequency (RF) bursts sent by other station(s) already on the air. Such an approach enables synchronization between the three stations without a centrally controlled master station or clock, without the knowledge of one another's exact location, without the demodulation of one another's baseband video, and without the use of a separate control channel. The only assumption imposed is that the three up-link stations be within the down-link coverage of the satellite. This is true for satellites similar to Telstar III. The hardware implementation is quite simple (Section III) and can be realized by conventional equipments and digital circuits. Our timing analysis (Section IV) shows that its performance can cover all requirements under a variety of worst-case conditions, and simple procedures for failure recovery are discussed in Section V. Finally, we will make brief comparisons with other methods by showing a number of practical advantages in using the present technique and also discuss possible extensions to further improve its performance.

II. SYSTEM DESCRIPTION

We outline in this section the basic concept and operation of the present method. Detailed parameters and performance evaluation are left for subsequent discussions. The system configuration is illustrated in Fig. 1, where three up-link earth stations are to transmit their color TV signals to a satellite. The TV pictures are assumed to be National Television System Committee (NTSC) and are to be time compressed with processing prior to transmission so that TCM can be employed. More specifically, three fields of each TV are to be time compressed into one field period, F, (≈1/60s) in a manner previously described in Ref. 6. The resulting waveform of a time-compressed TV contains successive triplets of a field with picture information followed by two blank field periods. The RF transmission of each earth station will

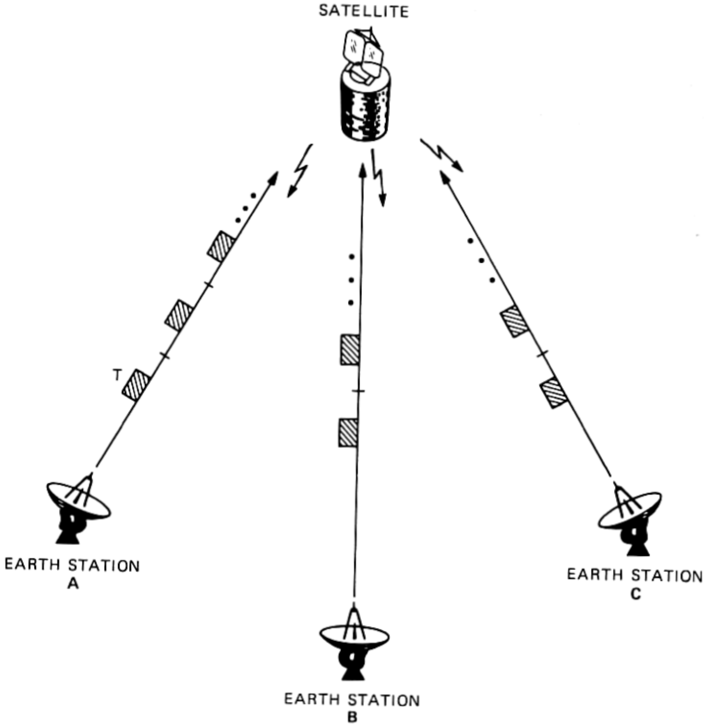

Fig. 1—A three TV/transponder TCM system.

then consist of bursts, each having approximately one field duration, with two blank field periods as separation between successive bursts (Fig. 2). The synchronization problem at hand is to align these bursts from the three stations so that they arrive at the satellite without overlap. All three stations are assumed to be within the down-link coverage of the satellite.

One could design the system, at least in principle, such that the entire portion of the vertical-blanking interval (≈1.4 ms) within each TV burst is used for guard time. This would be sufficient to account for the diurnal drift of the satellite itself (maximum round-trip delay variation of about 500 μs according to Ref. 7). With the exact locations of the stations known, simple open-loop synchronization is then possible. The drawback of such an approach is twofold. First, the deletion of the entire vertical blanking is undesirable in TV transmission because a variety of test signals and nonvideo information are frequently inserted in this time period. Second, the exact known location requirement renders the scheme inflexible for the inclusion of transportable transmit earth stations.

We feel that the deletion of only a portion of a scan line (during vertical blanking, say 15 μs) for interburst guard time is reasonable and would not limit or interfere with picture performance. In addition, we do not assume that locations of the stations are known to one another. Instead, each station is assumed to know only its own approximate location, say to within ±100 km. Note that the latter assumption is not imposing at all since every station needs some location information of its own for antenna pointing purposes anyway.

To illustrate the operation of the present system, the three up-link

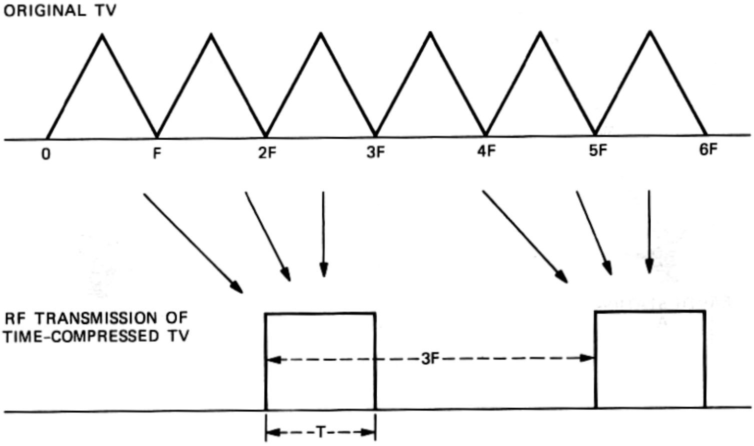

Fig. 2—Time-compression processing of a TV signal (F = Field period, T = F minus a small guard time).

earth stations are labelled A, B, and C. Station A is assumed to be the first to transmit. It can do so at will because no other transmission is taking place, and its transmission is simply synchronized to its own NTSC TV clock.

We now consider the start-up of B after A has been on the air. Station B first monitors the arrivals of the RF bursts from A and records their arrival times. Note that B does not have to demodulate A's signal; it only needs to detect the RF pulses received. (Indeed, A's baseband signal need not be video, as long as its RF timing is otherwise compatible.) The RF pulses from A occur in one out of three fields, the period is perturbed mainly by the time-varying propagation delay between A and B due to the spacecraft motion. Using these arrival times, B can extrapolate for the immediate future arrivals of A's pulses, and with the knowledge of its own approximate location (±100 km), B can compute its propagation delay to the satellite with an accuracy better than ±1.2 ms (including satellite drift). This estimated delay enables the translation of the arrival times of A's bursts from the time reference at B to that at the satellite. Using all this information, B can then position the transmission of a narrow pulse so that it arrives at the satellite in a time window adjacent to a burst from A, but not interfering with it. This narrow pulse is then received back by B, and we have an actual delay measurement, done inband, between B and the satellite. Once the actual delay is obtained, B can derive a windowing signal (frequency = one-third of the TV field rate) that denotes the proper transmission times in order to maintain collision-free synchronization with A.

The derivation of this window signal at B would mean the end of the problem if the system were for digital transmission. However, for TV applications, the picture information cannot be arbitrarily advanced or delayed without regard to the phase and frequency relationships between its color subcarrier and its sync pulses. Therefore, we propose frame (or field) synchronizing the TV picture at B to a local color subcarrier clock that is in turn phase locked to the aforementioned window signal in order to achieve proper transmission timing. This will be explained further when we discuss the hardware implementation.

Note that throughout the above procedure of synchronizing B to A, the up-link delay from A to the satellite remains unknown to B. This is possible because the timing error of B's narrow pulse (as will be shown later) is small compared with the start-up guard time allotted, i.e., a field period. Subsequent synchronization is maintained by B monitoring and updating the delay information and making adjustments accordingly. In this way, A is the master by virtue of being the first comer in the system, and B is locked onto A as a slave.

When station C wants to join in for its transmission, it has to go through the same procedure as B did, except it would lock onto B instead of A. If A drops out of transmission, B would detect that and take over as the master, using its own free-running clock, and C would stay locked to B. When A wants to resume its transmission later, it would have to join in as a slave to C. Therefore, the system assumes a dynamic master/slave arrangement where the first comer assumes the role of the master. Although this arrangement, as described, can only function properly if the three stations join the system sequentially, the time required by a station to establish itself as a slave can be designed to be well within a second, and thus for all practical purposes the initialization can be achieved almost instantaneously. We will show in the next section how all of these operations can be implemented with simple hardware.

III. HARDWARE IMPLEMENTATION

We describe in this section the hardware implementation of the present method. The following discussion will be divided into two major parts. The first part outlines the generation of a window signal that marks the proper transmission time for the time-compressed TV bursts at the local earth station. This window signal is denoted by $r(t)$. The second part explains how $r(t)$ can be used to synchronize the incoming TV picture such that its time-compressed bursts automatically align with the transmission windows.

The window signal, $r(t)$, is a pulse train with pulse width, T, equal to a TV field period minus the guard time and with a repetition rate $= 1/3F$. It is generated by the window processor depicted in Fig. 3. We assume that an external clock of eight-times B's color subcarrier frequency is made available to the window processor. This (≈28-MHz)

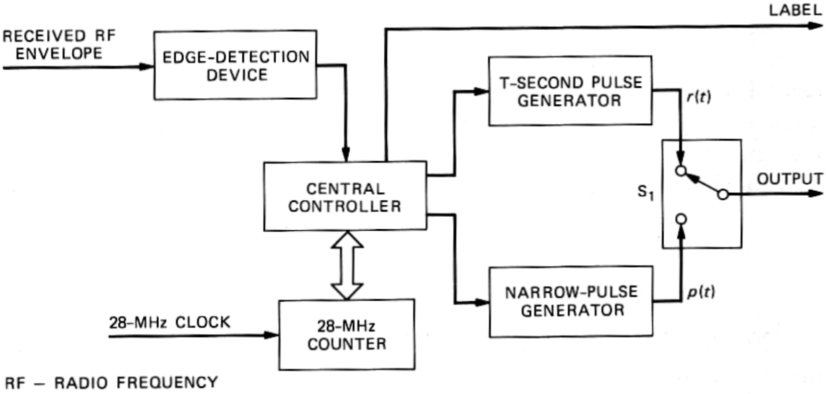

Fig. 3—Window processor for TDM/TCM synchronization.

clock is probably necessary for the time-compression operation itself, and its use here does not impose any additional burden on the system. The other input to the window processor is the received RF envelope from the satellite broadcast. In the trivial case of the first station (A) to go into the system, the window processor does very little because the transmission is free running. Let us consider the operation when the second station (B) wishes to start transmission. The received RF envelope (at B) is simply edge detected, and the arrival times of the bursts from A are recorded using the 28-MHz counter shown in Fig. 3. (Some accommodation for noise may be required, e.g., first detect envelope pulse of duration $\approx$T, then detect edges.) This information is supplied to the central controller, which could be a microprocessor and/or hardwired logic designed to carry out the windowing procedure outlined in the previous section. After acquiring the initial arrival times of the bursts from A, the central controller makes a crude estimate of the future arrival times. Furthermore, based on its location, it can compute an approximate delay to the satellite. Putting all these together, the controller produces a narrow pulse (pulse width $\ll$T) via the narrow pulse generator and sends it via the switch S_1 (in the lower position) to the transmitter. This narrow pulse will arrive at the satellite well within a predetermined time slot without collision with A's transmission. The return of this narrow pulse from the satellite completes a round-trip delay measurement that is then used to refine the arrival-time estimates. After a few cycles of this operation, the proper transmission time windows, $r(t)$, can be established by generating a sequence of pulses from the T-second pulse generator with S_1 switched to the upper position. Note that the pulse width and repetition rate of these T-second pulses are both computed using B's 28-MHz clock. A representative $r(t)$ is shown in Fig. 4a. The label output distinguishes the master from the slaves, and will be discussed later.

Before describing the rest of the hardware implementation, we show in Fig. 4 the conceptual sequence of operations needed to complete the synchronization. The transmission window is established by $r(t)$ in Fig. 4a. We use this to align (or phase lock) a composite TV sync signal, $s(t)$, such that every third, vertical sync pulse in $s(t)$ straddles the beginning of a transmission window (Fig. 4b). The sync signal, $s(t)$, is then used to synchronize an incoming video, resulting in $x_s(t)$, as shown in Fig. 4c. Finally, the video, $x_s(t)$, can be time compressed to obtain $x_c(t)$ (Fig. 4d), which is in synchronism with the transmission windows. The complete hardware to do all these is shown in Fig. 5.

Referring now to Fig. 5, the TV signal, $x(t)$, is passed through a frame synchronizer (and/or time base corrector) whose reference sync signal, $s(t)$, is derived from the TCM synchronizer. The frame synchronizer aligns $x(t)$ to $x_s(t)$ (Fig. 4c). The subsequent time compres-

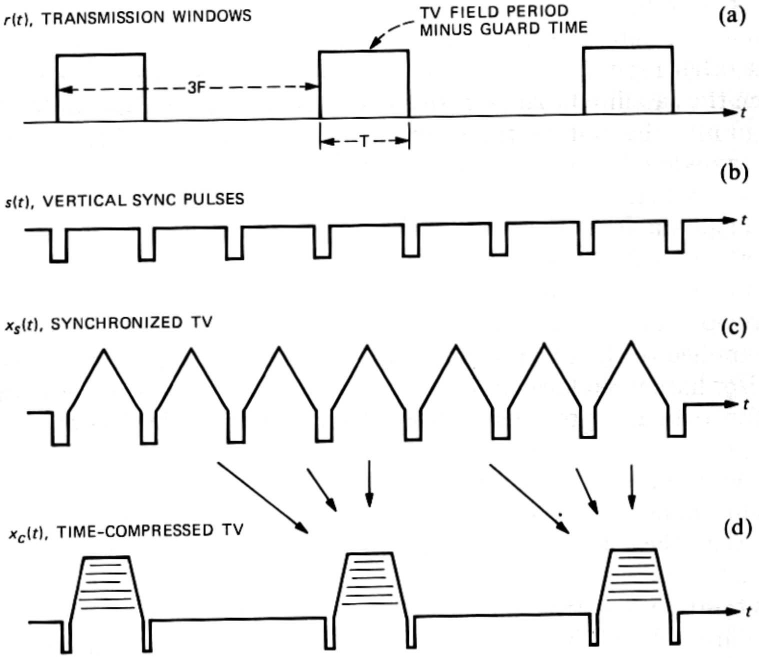

Fig. 4—Illustration of synchronization procedure. Horizontal sync, color burst, etc., are now shown.

sion on $x_s(t)$ is done in the time-compression processor previously described in Ref. 6. In this example, we assume that the time-compression processor requires three clock inputs in addition to the incoming video: a four-times color subcarrier clock (≈14 MHz), an eight-times color subcarrier clock (≈28 MHz), and the transmission window signal, $r(t)$. The time-compressed video, $x_c(t)$, is ready for immediate transmission through the FM modulator and the rest of the system. The *pin* modulator shown after the FM modulator is included to ensure the proper transmission timing as well as to enable the transmission of the narrow pulses at start-up.

As for the TCM synchronizer, its output is $s(t)$, as mentioned previously, and its input is the received RF envelope from the satellite broadcast. From the detected RF pulses, the window processor (Fig. 3) generates either $r(t)$ or the narrow pulses, depending on its state. When it is in the delay measurement mode, i.e., narrow pulses are being generated, the rest of the TCM synchronizer is free running. After $r(t)$ is generated, an internal 3.58-MHz color subcarrier is phase locked onto $r(t)$ via a TV sync generator and appropriate dividers as shown in Fig 3. This simple scheme ensures that the composite sync, $s(t)$, is synchronized with the transmission windows, $r(t)$. The label

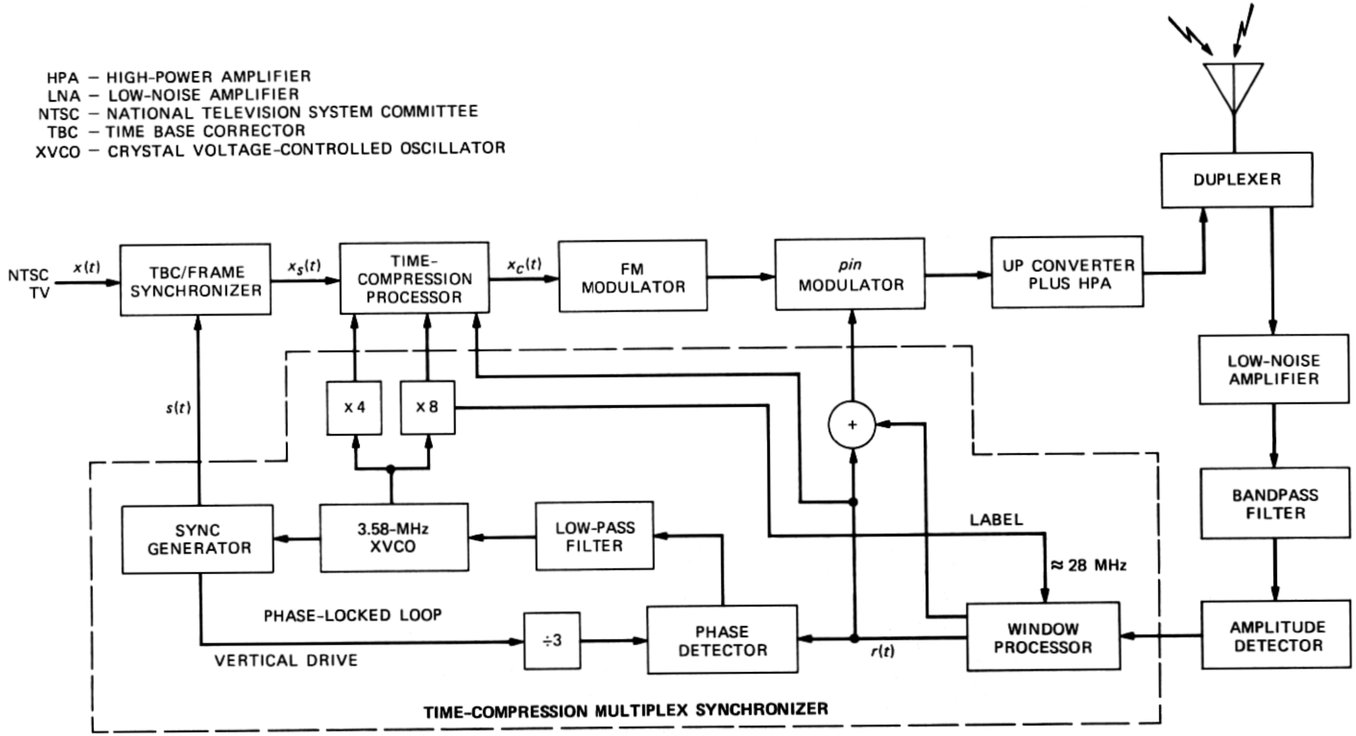

Fig. 5—Block diagram for earth station using present method for synchronization.

output of the window processor causes short RF pulses to be generated in the guard time in order to distinguish master from slaves. More discussion of labels will follow.

IV. TIMING ANALYSIS

Two important timing parameters reflecting the performance of the synchronization method are considered here: the initial acquisition time and the subsequent timing jitter in steady state. In our case of TV broadcasting, transmission is usually planned ahead of time and thus an initial acquisition time of, say, a few seconds should be adequate. However, faster acquisition is probably desirable in the case of failure recovery, as will be discussed later.

The guard time needed between bursts from different users is obviously determined by the timing jitter of the synchronization method and is a rather critical parameter. In the present system, each RF burst has the duration of a TV field time minus guard time, and the TCM synchronizer at the transmit earth station has to detect these bursts individually in order to start, as well as to maintain, lock-up. Therefore, we must ensure that some detectable gap always exists between successive bursts. Since we have the freedom to choose how to segment the original TV into three-field groups before compression, we may as well do it in a way that creates a small gap, and therefore we propose that the segmentation be done during a line of the vertical-blanking interval, which contains no information. Furthermore, we deliberately delete from transmission a portion of that line, thus generating a gap between bursts that could amount to, say, 15 μs. This deletion during vertical blanking does not affect the video quality because it is done where there is no information. The resulting benefits of this are twofold: we have created the necessary time gap between bursts from different stations; and we have a sizable guard time of 15 μs to accommodate the timing jitter (and to include labels to be described in Section V).

The major causes and their effects on the steady-state timing jitter in our system are summarized in Table I. We now discuss briefly the

Table I—Summary of timing jitter performance

Parameter	Jitter (ns)
Delay measurement uncertainty	±22
Up-link delay drift	±11
Down-link delay drift	±1
Clock resolution	±17
Field-rate jitter	±0
Total	±51

meaning of each entry in the table, while the detailed derivation is left to the appendix:

1. Delay measurement uncertainty—Delay measurement is made either via the narrow pulses or by the monitoring of the up-link's own returned TV bursts. In either case, a local 28-MHz clock is used to record the time elapsed, and the clock resolution is limited to half a cycle. It is implicit that fixed delays through the satellite and earth station hardware can be calibrated out from the raw measurement. Since this measurement is done in the communication band, propagation effects are automatically minimized.

2. Up-link delay drift—This refers to the up-link delay variation from station A to the satellite, which is not known to station B. It is time varying because of the spacecraft motion. This cannot be eliminated because we assume station B does not know A's location or have any ranging information on the propagation from A to B.

3. Down-link delay drift—This refers to the down-link delay variation between the satellite and station B. It is also time varying because of the spacecraft motion, but it is trackable via the delay measurement at B. A simple linear prediction should almost eliminate this.

4. Clock resolution—This is the limitation in the TCM synchronizer to time itself for the exact instant to start transmission due to the finite clock resolution (half a cycle in the 28-MHz clock).

5. Field-rate jitter—B and C are trying to lock to the inherent jitter in the RF bursts from A. However, if A's TV source conforms to the NTSC standard, this is so small that it can be dropped for all practical purposes. Otherwise, this item must be included in the table.

As we saw in Table I, the steady-state jitter is so small compared to the 15 μs guard time that under normal circumstances the system can be regarded as jitter free.

We now make a worst-case estimate of the initial acquisition time. It is convenient to make the simplifying assumptions that the system is jitter free and the satellite is truly stationary. The resulting error due to these assumptions is only in the order of less than 100 ns, while the acquisition time, as will be shown below, is in the order of a second. Again we will treat the case of station B trying a cold start after station A has already been on the air.

After turn-on at station B, the window processor needs to monitor a few received bursts from A before it can position its narrow pulses for delay measurements. Since the bursts from A are arriving every 50 ms, the monitoring takes $\approx$150 ms. After this 150-ms listening period, the narrow pulses are sent for delay measurements, and in order to allow for two delay measurements, we need a maximum of $\approx$500 ms. Therefore, after $\approx$650 ms have elapsed since turn-on, the synchronizer has completed the delay measurements and can compute the near-past, current, and near-future arrival times of A's bursts at the satellite. At this point, transmission can commence in the next available time slot, which in the worst case involves a delay of three field periods (≈50 ms). Putting everything together, we have a worst-case total of ≈700 ms between initial turn-on and the first TV transmission. Such an acquisition time certainly meets our objective of keeping it below a second. In fact, a potential saving of ≈250 ms exists if we do a single narrow pulse delay measurement instead of two. Therefore, we conclude that our acquisition time is less than one-half second with a single delay measurement and less than one second with delay verification.

V. FAILURE RECOVERY

In any prudent system design the possibility of failure of certain components must be taken into account. Here, we desire that the failure of one channel does not disrupt the transmissions of the remaining channels. In order to facilitate this, we provide for a labeling mechanism, in which the window processor causes short RF pulses to be transmitted immediately following the video RF burst, i.e., at the beginning of the guard time. These pulses are then used to distinguish the master from the slaves, as well as to detect anomalies.

For example, station A (being the master) could transmit three pulses. Station B, the next in command, would send two pulses, and station C, one pulse. Additional pulses could identify the up-link station or, alternatively, this information could be embedded in the baseband video.

The window processor keeps track of time and labeling of all received RF bursts, and is ready to accommodate to any change in operating conditions. For example, if A finishes its transmission and goes off the air, B becomes the new master transmitting three pulses, and C becomes second in command transmitting two pulses.

It is never possible to predict all failure modes. The best we can do is accommodate the most likely ones. For example, a brief up-link failure will not be detected at any earth station (including, possibly, the faulty one) for about 240 ms, and during that time it is possible for transmission to resume. Moreover, corrective action by the faulty earth station will not be known to the remaining ones for another 240 ms. Thus, in the case of an up-link failure at master station A, station B should not try to take over as master immediately. Otherwise, there would be the possibility of two masters existing at the same time. In any event, as soon as station A determines that its up-link is unreliable, it should resign as master. This could be done by not transmitting any pulses following its video RF burst. The other stations would recognize this condition and assume their proper responsibilities, after which station A would begin transmitting a single pulse designating itself as last station aboard.

In the case of a down-link failure, continued operation is not possible unless the faulty station is master. If it were not already the master, it could take over this role by sending, say, four pulses following the video RF burst. The other stations would then recognize this condition and assume their proper responsibilities.

In the case of an earth station power glitch, transmission would have to cease immediately and the start-up procedure would be reinvoked, since the window processor would, in all probability, lose its timing information. Such a restart could be speeded up considerably if nonvolatile memory were provided, however.

VI. COMPARISONS AND DISCUSSIONS

As mentioned previously, a number of synchronization methods are applicable to solve the present problem. The most obvious one is probably that of a centrally controlled station broadcasting a master sync to all three up-link stations. Within this broad class of techniques, a large variety of alternatives are possible. As an example, one fixed station may be assigned as the master and the other stations must lock their transmissions to the master; a master sync marker may be broadcast to all stations by a centrally controlled station, and the marker could contain sufficient information to TV field and color subcarrier synchronizations, as well as ranging data for extremely fast open loop acquisition. In fact, only one such master is needed for the whole satellite system. Its main advantages are that fast acquisition is possible, and the various up-link stations do not have to monitor one another's transmissions, although the hardware implementation at each up-link station is certainly not simpler than our method. The key concern, though, is the reliability of the master station—its maintenance and hardware complexity. A single up-link failure at the master station would immobilize the whole system. In contrast, our method would tolerate quite a combination of different failures because an automatic takeover procedure exists for the master assignment. Any single up-link or down-link failure at a station can interrupt service only at that station and has no bearing on the rest of the system.

It is possible to use a separate channel to perform interstation ranging as proposed in Ref. 9. The bandwidth requirement for this ranging channel is critically determined by the rise time of the ranging pulses, which, in turn, affects the resulting synchronization accuracy. Therefore, the addition of this ranging channel could be an imposing requirement in the system.

Improvements in the jitter performance and the acquisition time in our system are both possible. The up-link drift could be removed if the up-link delay information from each station were inserted into one of the vertical-blanking pulses, and the stations could then demodulate for these data. Higher clock frequencies could be used in the delay measurement, thereby decreasing its uncertainty. This would also increase the time resolution of system and thus enable the synchronizer to time the transmissions more accurately. As for the acquisition time, if an accurate site location plus its up-link delay were provided by the first (or the master) station in one of its vertical-blanking pulses, then the other stations could compute their respective delays to the spacecraft without performing the narrow pulse measurements, resulting in a significant reduction in the acquisition time.

VII. CONCLUSIONS

We have described a method of synchronizing up-link earth stations in a TCM system where the stations take turns transmitting TV information in bursts, each lasting for a field duration. The technique is simple and requires only that the stations receive their own as well as others' transmissions. It has a dynamic master/slave arrangement whereby the first station signing on assumes the role of a master. The other stations subsequently can synchronize their transmissions to the master's by simply monitoring the received RF bursts from the satellite, measuring their respective delays to the spacecraft, and then phase locking their local color subcarrier clocks to the master's transmitted bursts. When the master station stops transmitting, an automatic procedure exists for the second station to take over as the new master. As a result, any single up-link or down-link failure can only affect the station involved, and there is no need to have centralized control. Most of the hardware in the synchronizer can be implemented digitally. The worst-case jitter performance in the system is well below 100 ns, while the initial acquisition time can be kept to less than one-half second. These are more than adequate for the TV application, and we conclude that the proposed method offers a practical means to synchronize the three up-links in our TCM system.

REFERENCES

1. J. E. Flood and D. I. Urquhart-Pullen, "Time-Compression-Multiplex Transmission," Proc. IEE, *111*, No. 4 (April 1964), pp. 647–68.
2. D. H. Morgen and E. N. Protonotarios, "Time Compression Multiplexing for Loop Transmission of Speech Signals," IEEE Trans. Comm., *COM-22*, No. 12 (December 1972), pp. 1932–9.
3. K. Y. Eng and O.-C. Yue, "Spectral Properties and Band-Limiting Effects of Time-Compressed TV Signals in a Time-Compression Multiplexing System," B.S.T.J., *60*, No. 9 (November 1981), pp. 2167–85.
4. K. Y. Eng and O.-C. Yue, "Time Compression Multiplexing of Multiple Television

Signals in Satellite Channels Using Chirp Transform Processors," IEEE Trans. Commun., *COM-29*, No. 12 (December 1981), pp. 1932–40.
5. K. Y. Eng and B. G. Haskell, "TV Bandwidth Compression Techniques Using Time Companded Differentials and Their Applications to Satellite Transmission," B.S.T.J., *61*, No. 10, Part 1 (December 1982), pp. 2917–27.
6. K. Y. Eng, B. G. Haskell, and R. L. Schmidt, "Time-Compression Multiplexing (TCM) of Three Broadcast-Quality TV Signals on a Satellite Transponder," B.S.T.J., this issue.
7. P. P. Nuspl et al., "Synchronization Methods for TDMA," Proc. IEEE, *65*, No. 3 (March 1977), pp. 434–44.
8. J. J. Spilker, Jr., *Digital Communications by Satellite*, Englewood Cliffs, NJ: Prentice-Hall, 1977.
9. A. Acampora, "Synchronizing Transmissions From Two Earth Stations to Satellite," U.S. Patent 4,320,503, applied for August, 1979, issued March 1982.
10. D. D. Slavinskas, private communication.

APPENDIX

Parameters for Timing Jitter

We show briefly here the derivations for the various contributions to the steady-state timing jitter (Table I). The following estimates are, by and large, worst-case and very conservative.

A.1 Delay measurement uncertainty

The slave stations have to measure their respective delays to the satellite in order to start, as well as to keep, synchronized with the master. This is done in the beginning via the narrow pulses, and then it is updated continuously via the monitoring of its own returned bursts. The delay is, of course, measured from edge to edge in the transmitted and received RF bursts. Given a 36-MHz RF channel bandwidth, the fastest RF pulse rise time is in the order of 30 ns. If we have to measure delay from one edge to another, an accuracy of ±5 ns seems reasonable. In addition, the clock used for the measurement is resolution limited due to its finite frequency ($\approx$28 MHz, or eight-times color subcarrier frequency). The uncertainty due to this clock is about ±17 ns, yielding a total uncertainty of ±22 ns.

A.2 Up-link delay drift

In the absence of any knowledge of the master's (or A's) location, a slave station (or B) cannot predict the up-link delay from the master to the satellite. Furthermore, this up-link delay is time varying due to the motion of the spacecraft. The net result is that B's prediction of the near-future burst arrivals from A can never be exact, even though the down-link delay between B and the satellite can be predicted exactly. To illustrate this point, let us consider a burst transmitted from A to B at $t = 0$. The up-link delay (from A to the satellite) is u_0; the down-link delay (from the satellite to B) is d_0; and the delay through the satellite is conveniently chosen to be zero. The arrival time of this burst at B is simply

$$T_0 = u_0 + d_0.$$

Now, at a later instant $t = t_1$, A transmits another burst to B. The corresponding up-link and down-link delays are u_1 and d_1, respectively. Again $u_0 \neq u_1$ and $d_0 \neq d_1$ because of the spacecraft motion. The arrival time at B is then

$$T_1 = u_1 + d_1 + t_1.$$

In order to predict T_1 at B at the time T_0, B has to compute

$$T_1 - T_0 = (u_1 - u_0) + (d_1 - d_0) + t_1,$$

where t_1 is known to B because A is transmitting at a fixed rate; $(d_1 - d_0)$ can be extrapolated based on B's delay measurements; but the quantity $(u_1 - u_0)$ cannot be estimated without knowing A's location. In this example, $(u_1 - u_0)$ is simply the up-link delay variation for A due to the spacecraft displacement in the time interval t_1. As such, an easy upper can be written as

$$|u_1 - u_0| \leqslant cvt_1,$$

where c is the velocity of light; v is the radial velocity of the spacecraft toward or away from an earth station; and t_1, the time interval, is understood to be small compared to a day. If we replace v by the highest radial velocity of the spacecraft, and t_1 by the round-trip satellite propagation delay (≈300 ms), we have a worst-case estimate on the up-link delay drift. According to an example given in page 149 of Ref. 8 and comparisons to data from more recent communications satellites,[10] a convenient upper bound on the spacecraft radial velocity in geostationary orbit is 10 m/s. Using this, the worst-case up-link delay drift is ±10 ns.

A.3 Down-link delay drift

With the spacecraft radial velocity limited to 10 m/s and continuous updates on the delay measurement, we feel that the down-link delay drift can easily be computed with an accuracy an order of magnitude lower than the up-link delay drift, or about ±1 ns.

A.4 Clock resolution

Using a 28-MHz clock, the resolution is about half a cycle or ±17 ns.

A.5 Field-rate jitter

This refers to the jitter in the rate at which the master station is transmitting its RF bursts. The burst transmission is of course governed by the TV field rate, and only one burst is sent in every three fields. The NTSC standard specifies that the color subcarrier frequency (3,579,545 Hz) must be stable within ±10 Hz and cannot vary more than 0.1 Hz/s. For a worst-case situation, we assume that the color subcarrier is at the lowest value, i.e., 3,579,535 Hz. It then drifts at the maximum rate of 0.1 Hz/s. Thus, at the end of a second, the new frequency is 3579535.1 Hz. The difference in TV field period derived from these two frequencies is only 7.8×10^{-15} s. The net result is that the TV field rate is jitter free over a short period of time, say a few seconds. Moreover, this implies that a much less stable color subcarrier frequency is still quite compatible with our synchronization system.

AUTHORS

Kai Y. Eng, B.S.E.E. (summa cum laude), 1974, Newark College of Engineering; M.S. (Electrical Engineering), 1976, Dr. Engr. Sc. (Electrical Engineering), 1979, Columbia University; RCA Astro-Electronics, 1974–1979; Bell Laboratories, 1979—. Mr. Eng has worked on various areas of microwave transmission, spacecraft antenna analysis, and communications satellites. He is presently a member of the Radio Research Laboratory, studying TV transmission through satellites. Member, IEEE, Sigma Xi, Tau Beta Pi, Eta Kappa Nu, Phi Eta Sigma.

Barry G. Haskell, B.S. (Electrical Engineering), 1964, M.S., 1965, and Ph.D., 1968, University of California, Berkeley; University of California, 1965–1968; Bell Laboratories, 1968—; Rutgers University, 1977–1979. Mr. Haskell was a Research Assistant at the University of California Electronics Research Laboratory and a part-time faculty member of the Department of Electrical Engineering at Rutgers University. At Bell Laboratories, he is presently Head of the Radio Communications Research Department, where his research interests include television picture coding and transmission of digital and analog information via microwave radio. Member, IEEE, Phi Beta Kappa, Sigma Xi.