THE EFFECT OF CHANGES IN ABSOLUTE PATH DELAY IN DIGITAL TRANSMISSION SYSTEMS

by

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One useful aspect of synchronous digital transmission is that we are not limited by noise in any given link when connecting in tandem a number of links. In the FDM world, the noise products are of critical importance in determining the number of tandem links permissible. A digital link operating without error for relatively long periods of time results in an operational performance that typically equates to the error burst distribution of the individual links. Over the years we have observed a large number of digital links and many of these are very long and made up of numerous tandem links. We noted, for example, that the error burst distribution on a 3600-baud, transatlantic data circuit between Frankfurt, Germany and the Washington, D.C. area was typically subjected to a short burst of errors approximately once every 20 minutes.

We also noted that the modulation rate up to the circuit maximum rate made no difference with regard to the number of error bursts. Changes in modulation rate from 600 to 3600 baud only changed the number of errored bits in any given burst.

Figure 1 shows a worldwide digital network now operating in a full synchronous environment. The individual links are operated from 2400 to 7200 BPS. The links are typically subdivided as shown and the channels are connected in tandem without buffering between each other. For example,

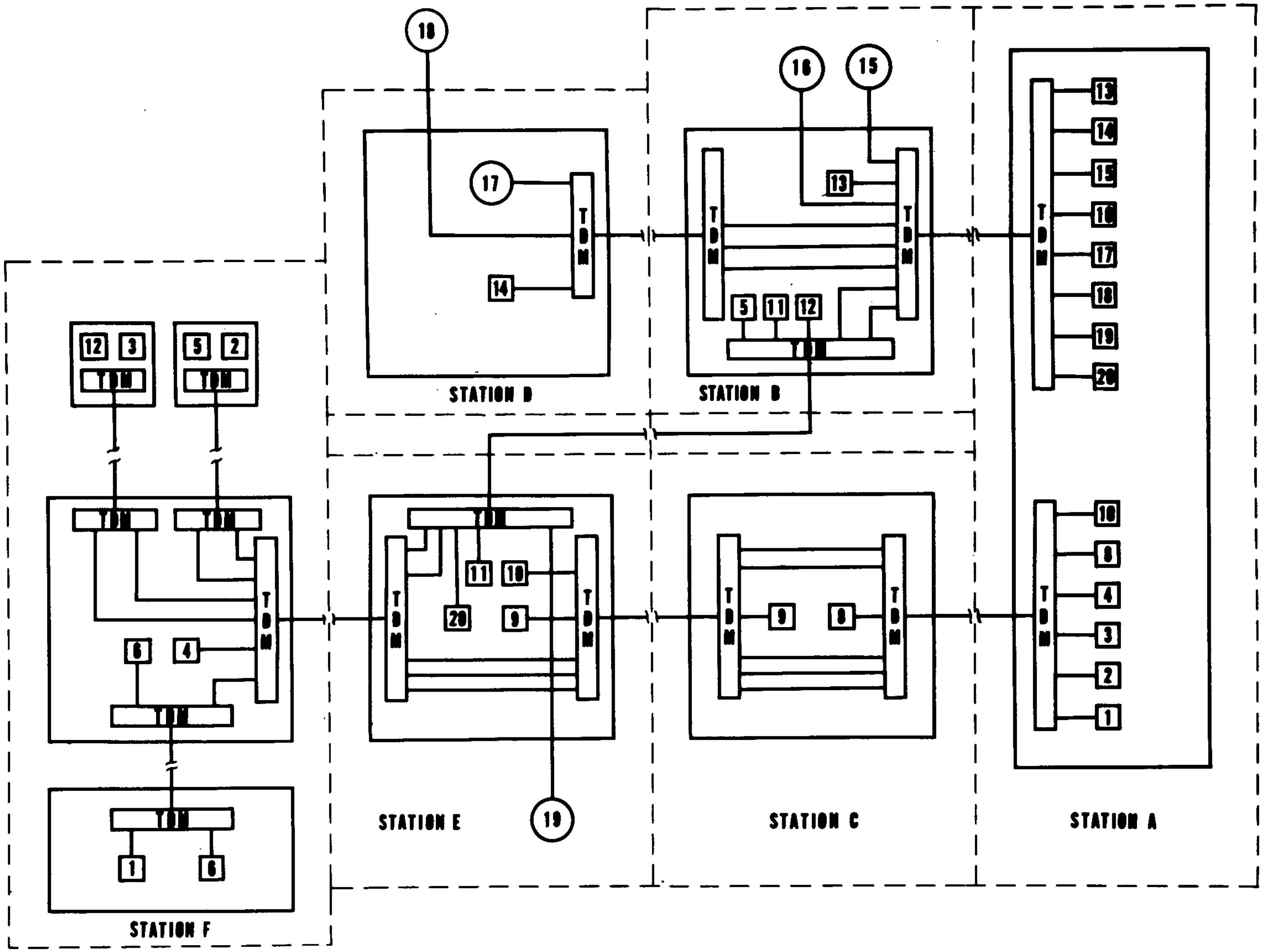


Figure 1. WORLDWIDE DIGITAL NETWORK

one can trace from Station F on the left a link from a time division MUX (TDM) port 2 through Station E to C to A.

In the early fifties, it was learned that the typical 50-baud telegraph channel did not behave quite as a lot of us assumed. HF radio paths were recognized to change in path absolute delay as one shifted from night or day frequencies or when the paths, due to propagation, etc., tended to switch between single and multiple hops.

In Europe "Multipath," for example, was most often on 600- to 1000-mile links, a matter of a few milliseconds and at most confined to one or two bits at 50 baud.

A most disturbing problem was that a telegraph channel operating on leased cable or microwave would abruptly change absolute delay by several hundred milliseconds. One had learned to expect a few milliseconds' shift for HF radio multipath but multipath also had habits which helped to spot it, in that it was not a stable shift and there would be seconds, minutes, or even hours when the path delay changes were not shifting fortuitously. It was noted that a path might suddenly, that is, essentially instantaneously grow shorter or longer by perhaps 5 bits at 20 milliseconds a bit. The path might remain at this absolute delay for a period of several hours to as much as a day or more.

It was also noted that some paths seemed to grow longer or shorter on a predictable basis. A path that changed in delay in this fashion immediately warned that the synchronous terminal equipment was not being properly clocked. As a result of the discovery that a telegraph channel could abruptly change absolute delay by many milliseconds, a device was developed for use with synchronous transmission systems. Records kept from 1958 through 1964 on 25 long-haul cable, microwave and HF radio, 61.1-baud telegraph channels showed typical abrupt delay changes of 30 to 125 milliseconds.

The device was a simple shift register that inserted 21 bits of additional delay between the incoming line and the synchronous receiver input.

(Twenty-one bits at 61.1 baud is approximately 1300 milliseconds.) A front panel control calibrated in terms of plus 10 to minus 10 bits delay was provided. The operational procedure is for the operator to set the delay to zero (bit position number of 11). The synchronous system was then started and, if the path delay then changed, the operator simply advanced or retarded the delay control until he regained synchrony (approximately 85 percent of the attempts did recover synchrony). If he did not regain synchrony, the device was either zeroed or returned to the last delay setting and the cause of the problem sought elsewhere.

Now we come to the heart of the matter: How did the crypto operator, in effect, measure changes in the path absolute delay? Perhaps the following explanation will help those not familiar with synchronous cryptographic devices.

One can think of a synchronous cryptographic device as having a memory that is arranged such that each bit that is to be transmitted from the crypto is programmed into it by the key setting. The mating receive crypto has a similar memory that performs in precisely the same manner. There is one and only one point at which the transmit and receive key will precisely mate and, therefore, if the relative phases of the transmitter and receiver crypto are not precisely maintained, the data will not be decrypted.

If the two devices are started they will run predictably and typically without error for as long as they are supplied timing, etc. If the timing is slewed at transmit and receive cryptos identically, they will also follow in synchrony and in the same predictable fashion. In typical operation the transmit and receive devices are provided a given key setting. The transmitter emits a precise starting sequence that propagates over the comm link with an absolute delay that is determined by the given link; the receiver is in effect "unlocked" by the "start" sequence which means that, if a successful start occurs and the timing is correct and the path delay does not shift, the receiver will continue to run in synchrony with the transmitter offset in phase by the absolute path delay. If the path fails the receiver will continue to run in synchrony with the transmitter for a period determined by the relative drift between the transmit and receive crypto timing. With a good timing scheme, if the path is restored normally, the crypto will be found to be "in set" and the data can pass without restarting the crypto system.

If the path absolute delay changes one can advance or retard the receive key in the receive crypto until the "set" is picked up or one can use the device mentioned earlier to cope with delay changes. Having operated both schemes, it is suggested that the artificial delay approach is more realistic in a large TDM network. The reasons for this will be explained shortly.

In the fifties and early sixties most low-speed synchronous cryptographic systems were operated on their own internal timing. The receivers recovered phase correction data from the incoming line transitions and corrected their internal timing accordingly.

This system suffers from the fact that channel perturbations, FOX TEST, intermod from adjacent channels, cyclic distortion, etc., too often modify the receive timing to the point that synchrony is lost and the entire system must be restarted.

Recognizing this fact, and knowing that, contrary to popular thought, telegraph channels did not always remain at a given absolute delay, a program was initiated to place station timing sources at a large number of sites throughout the world. The initial objective was to obtain a relative coherence among these timing sources such that a drift not greater than plus/minus 25 percent of the duration of the unit interval at the applicable modulation rate for 100,000 consecutive seconds would be obtained. In most cases in 1960 this was 6-2/3 milliseconds for a 75-baud circuit (approximately 140 microsecond per hour worst case drift). It was quickly proved, for example, that the channel suppliers could not drive the receive crypto out of synchrony by inadvertently placing FOX TEST on the circuits or by patching a 50-baud terminal to a 75-baud terminal, etc. The 100,000 seconds were a little over 24 hours, or one radio day. It was found that dramatic circuit improvements were obtained from operating on station rather than recovered clock. On one circuit operated on recovered clock the typical availability for traffic was less than two hours per 24 hours. After converting to station clock the circuit availability was typically better than 22 hours a day.

Over the years the station clocks have been brought closer and closer into coherence. At first one did not need to worry about the coherence since the basic timing sources were close enough even at their worst relative drift to run for 100,000 consecutive seconds at 75 baud without drifting outside of one bit.

The relative coherence of the station timing has improved network-wide to approximately 3 to 15 microseconds per hour relative drift. In a few stations with Loran-C the stations are now able to hold within approximately 100 nanoseconds relative drift. Those stations with VLF tracking and manual updating do well to meet the 3 to 15 microseconds per hour relative drift.

Experience has shown that the satellite paths tend to be better in all aspects save one than the transoceanic cable channels. Satellites have one technical parameter that must be dealt with if tandem operation of synchronous time division multiplexed links are to be successfully employed. That technical parameter is the change in absolute path delay over a 12-hour period. This change is caused by the suborbital movement of the satellite on a north/south path with relationship to the equator. The relative change is as predictable as the rise and fall of the tides and it can therefore easily be dealt with.

Figure 2 shows Intelsat III, Flight 7 on 28 July 1971. Reading left to right we see a change in path absolute delay between midnight and noon on the 28th of approximately 1390 microseconds, and from noon to midnight

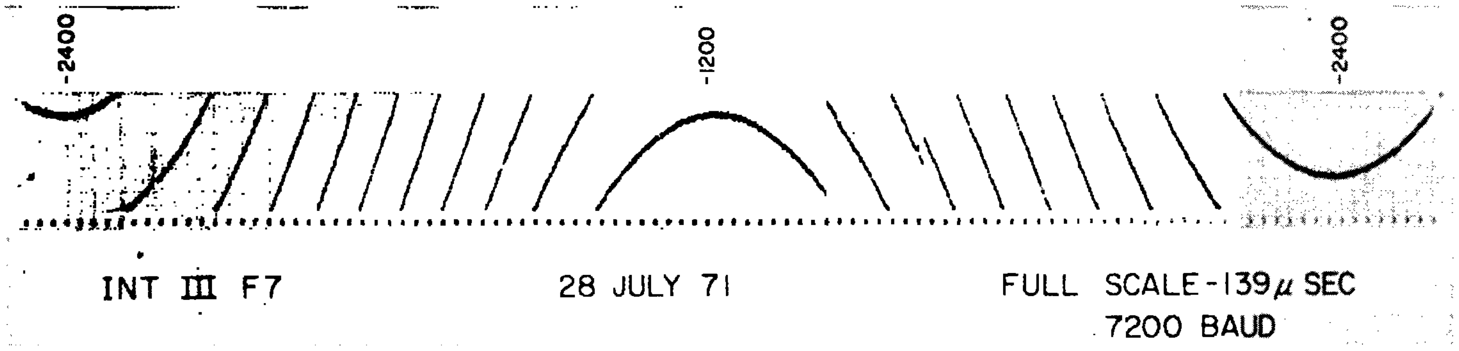


Figure 2. INTELSAT III, FLIGHT 7 ON 28 JULY 1971

a change in path absolute delay of approximately 1180 microseconds. The difference of approximately 210 microseconds between the first 12 hours and the second 12 hours is an indication of the relative drift of the station timing between the two multiplex terminals. This equates to approximately 8.75 microseconds per hour relative difference between the two stations.

At 7200 baud the duration of the unit interval is approximately 140 microseconds. Assuming no change in path delay an 8.75 microseconds/hour relative drift will cause synchrony to be lost in approximately 8 hours, if no phase correction is accomplished. The change in path absolute delay cannot be ignored however, and synchrony will be lost depending on the relative position of the satellite in its orbit anywhere from once in four hours when the satellite is slowing down and reversing its direction relative to the equator to once every half hour during the remainder of its orbit. This can quite easily be seen by referring to the trace displayed in Figure 2. The steeper the slope on the graph, the faster the rate of change. It might also be noted that each time the trace completes a transit from one edge of the chart to the other, this is comparable in time to one unit interval at the data modulation rate. It is quite easy therefore to estimate by observation of the chart how often and when synchrony will be lost. This display is not only a useful engineering tool but also a very useful tech control and maintenance technician guide. The recording is a comparison between modem recovered timing and the local station clock. Figure 3 has been prepared to bring out other important aspects of this phenomenon: One, the rate and amount of change is determined by a given satellite and its effect on the digital signal is proportional to the modulation rate. Doubling the signalling speed halves the time to loss of synchrony. Two, the suborbital movements of satellites change, as shown in Figure 3. On 29 May Intelsat IV, Flight 2 the change in path absolute delay was approximately 361 microseconds in 12 hours whereas the same satellite on 15 August 1971 had slowed down to approximately 70 microseconds per 12 hours. Seventy microseconds is approximately one-half the duration of the unit interval

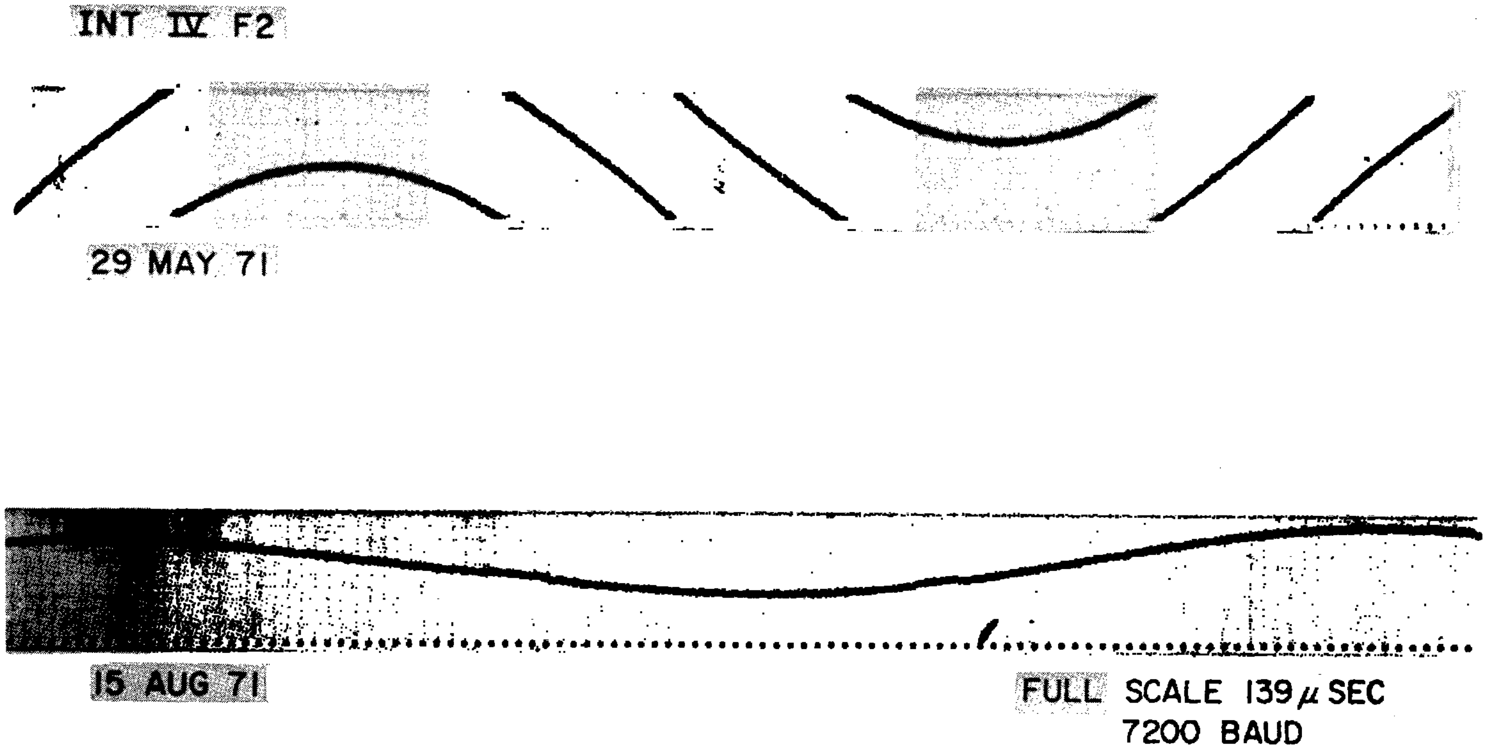


Figure 3. INTELSAT IV, FLIGHT 2 ON 29 MAY 1971

at 7200 baud; therefore, synchrony would not be just on a 7200-baud circuit over a 24-hour period on this path.

Figure 4 shows the typical Defense Communications System point-to-point configuration wherein recovered clock from the modem is utilized to time the crypto and data terminal equipment.

In this configuration any perturbation or phase shift in the recovered timing is passed to the crypto and to the data terminal devices(s), etc.

Figure 4 also indicates the difference in phase between station timing and recovered timing.

Figure 5 shows the method wherein the incoming data is retimed to station clock time such that shifts in phase in the recovered clock do not appear at the crypto or data terminal. Note that in Figure 5 data are retimed to clock, whereas in Figure 4 clock was retimed to data. Figure 6 shows the addition of storage that permits one to deal with path absolute delay changes greater than one bit.

Figure 7 is intended to remind us that when path absolute delay changes it affects not only the crypto but all the associated devices. In other words, if the shift in absolute delay is permitted to propagate through the input device then all the equipment can also lose synchrony with their mating terminals.

In conclusion, Figures 8 and 9 are intended to indicate a path can get longer or shorter. In Figure 10 the relationship of station timing in a worldwide network must be made independent of the changes in absolute delay. The dotted lines in Figure 10 are intended to indicate how the timing sources may be directly related in a large network. Figure 11 is intended to indicate the path absolute delay changes in a large network that must be dealt with if tandem digital link operation is to be effective. An effective way of dealing with this problem can be the insertion of additional absolute delay between the nodes of the network. The objective

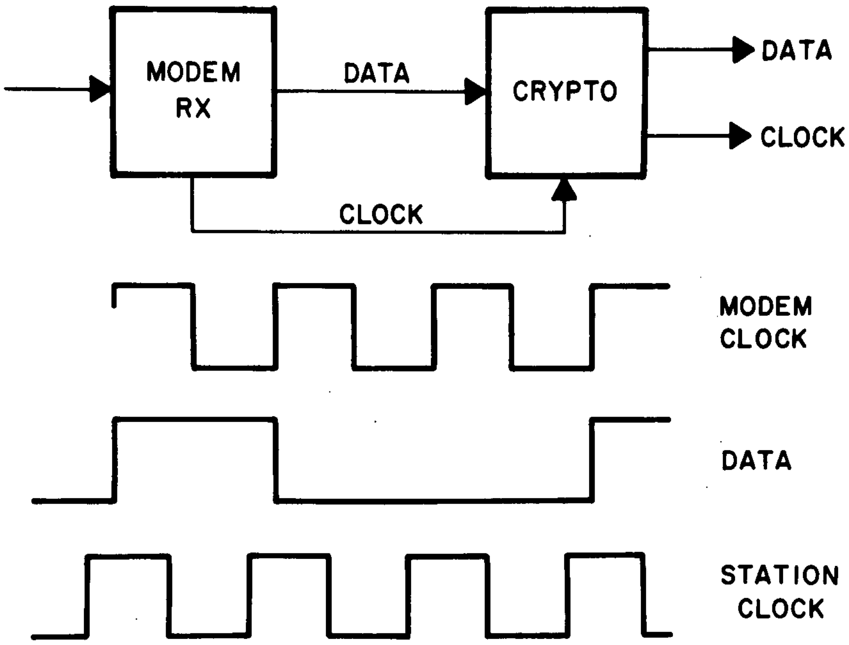


Figure 4. DEFENSE COMMUNICATIONS SYSTEM POINT-TO-POINT CONFIGURATION

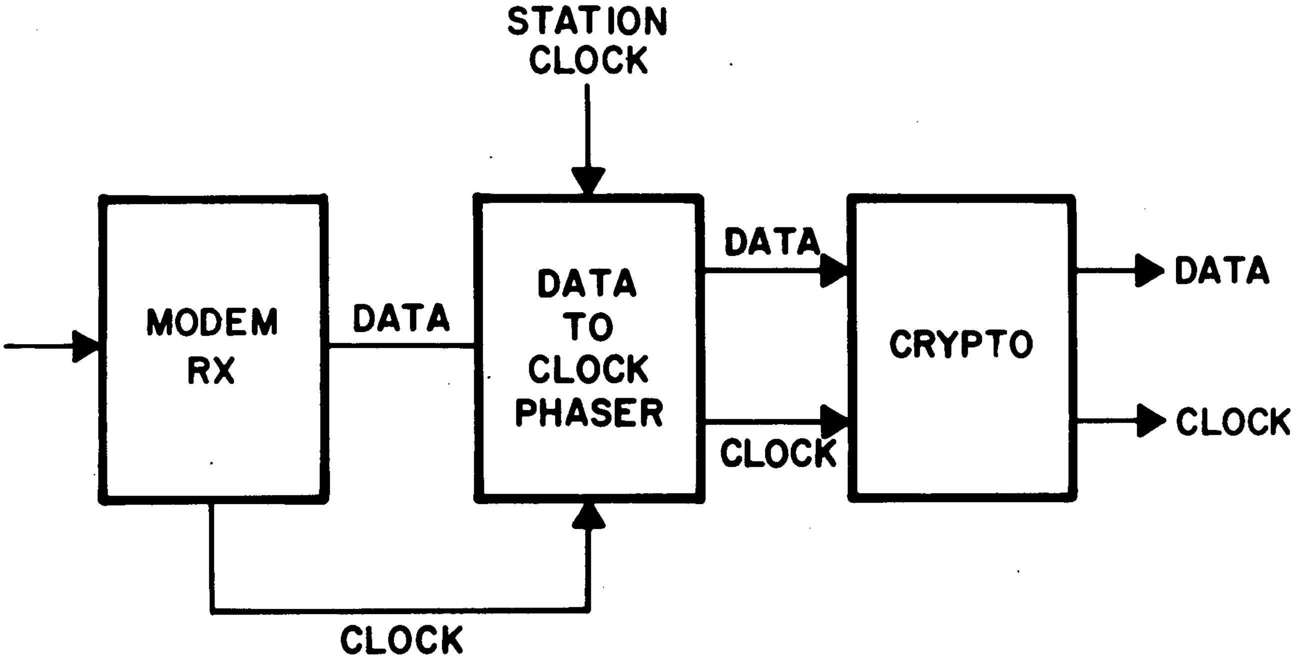
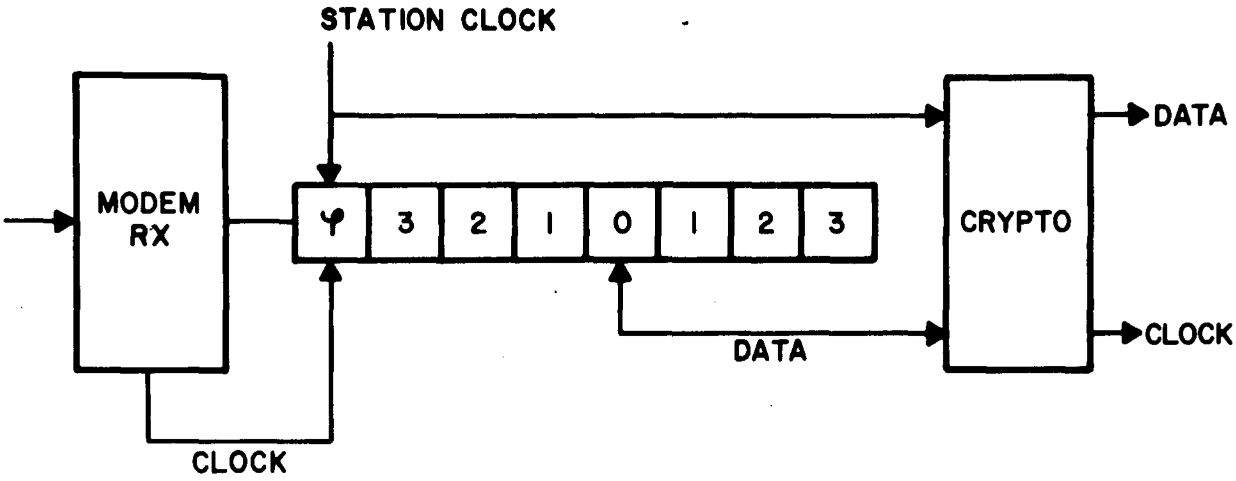


Figure 5. METHOD OF INCOMING DATA RETIMED TO STATION CLOCK TIME



φ = PHASER

Figure 6. ADDITIONAL STORAGE FOR PATH ABSOLUTE DELAY CHANGES GREATER THAN ONE BIT

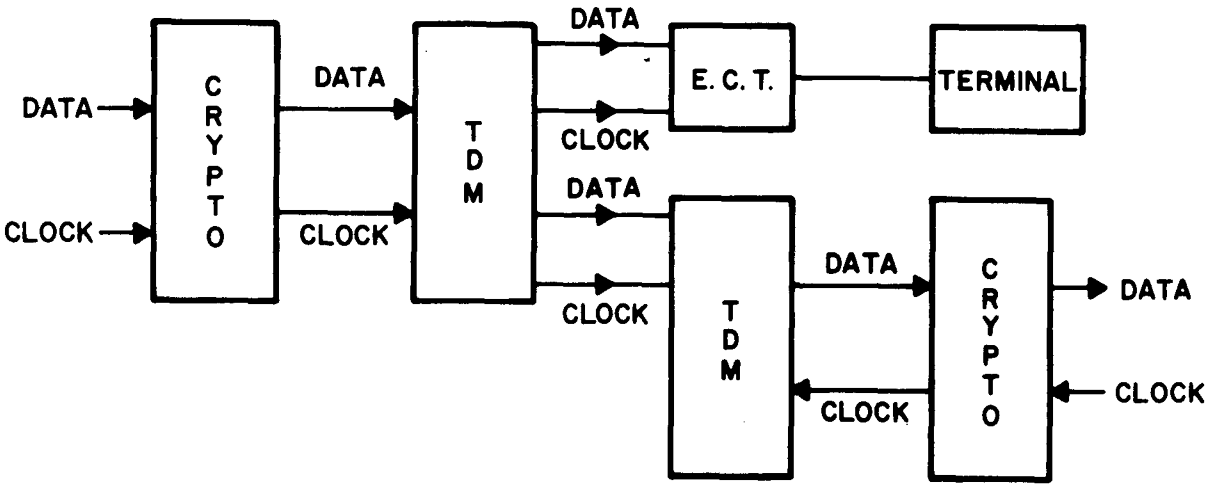


Figure 7. CRYPTO AND ASSOCIATED DEVICES AFFECTED WHEN PATH ABSOLUTE DELAY CHANGES

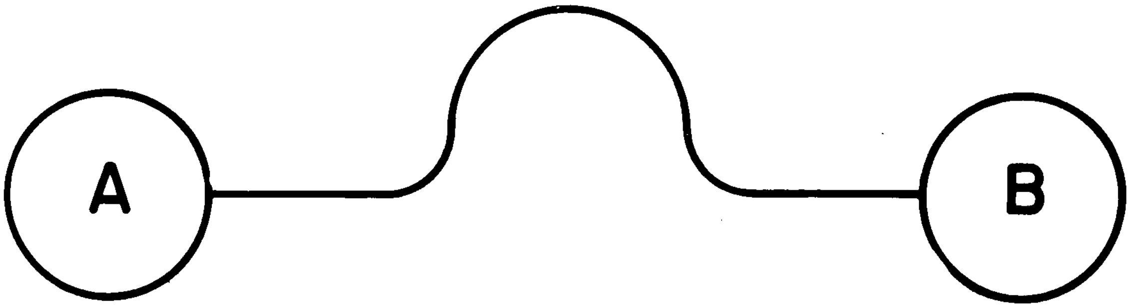


Figure 8. LONGER PATH ABSOLUTE DELAY

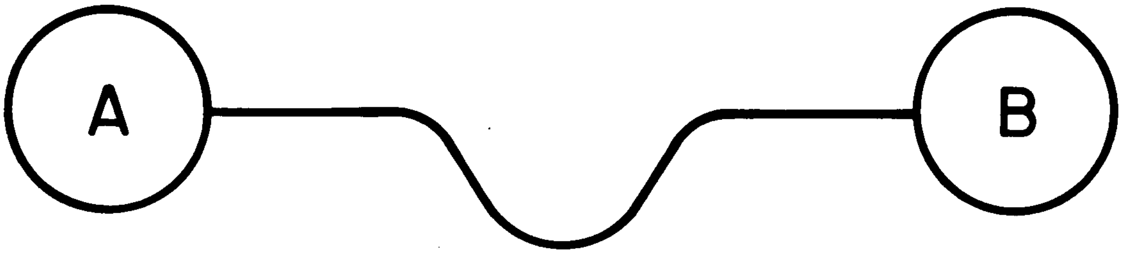


Figure 9. SHORTER PATH ABSOLUTE DELAY

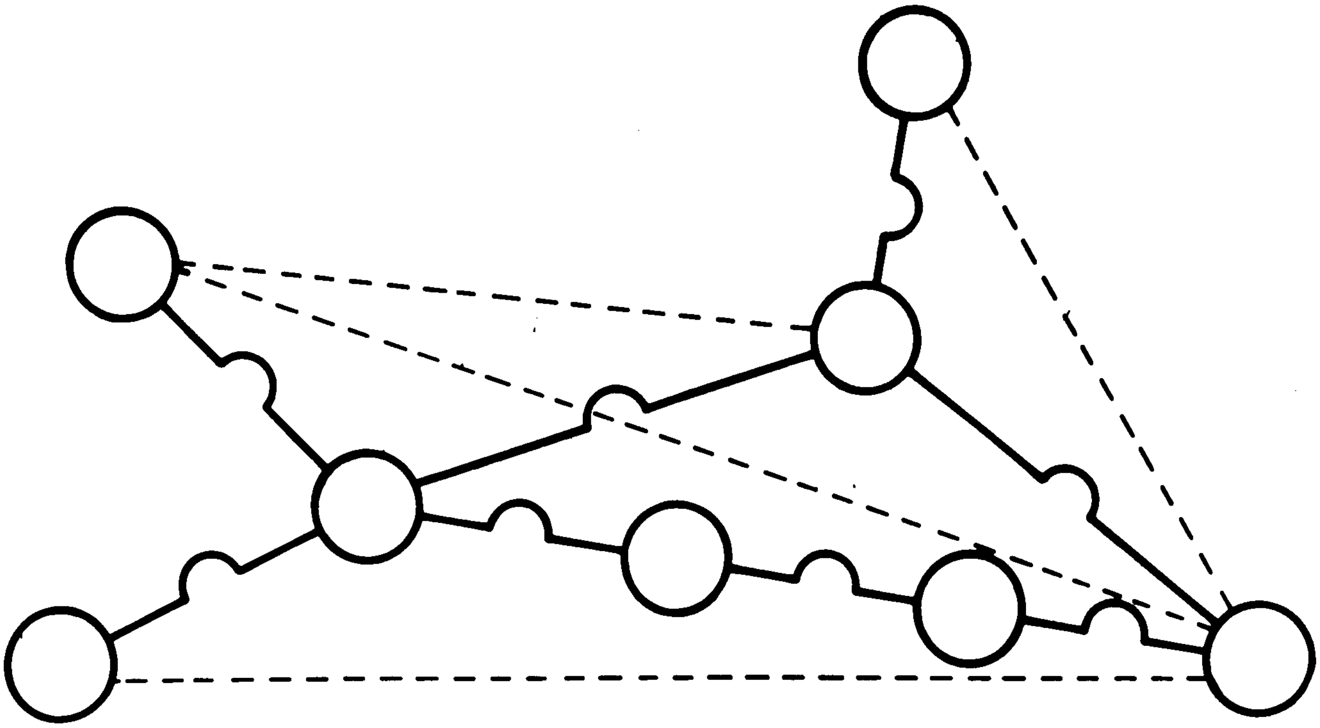


Figure 10. RELATIONSHIP OF STATION TIMING IN A WORLDWIDE NETWORK VS CHANGES IN ABSOLUTE DELAY

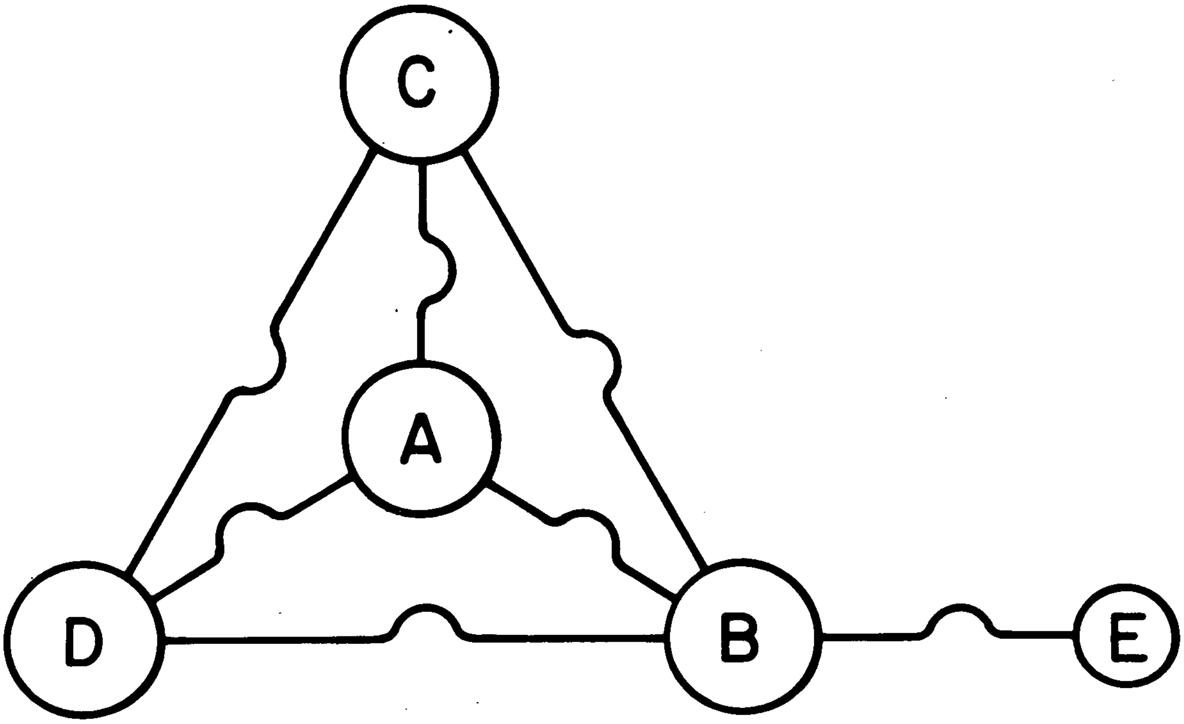


Figure 11. PATH ABSOLUTE DELAY CHANGES IN A LARGE NETWORK

would be to make each link appear to the terminal equipment as having a fixed delay. One might call this the "brick wall" approach. What is meant is that by providing excellent station timing and isolating path delays one can stop the propagation of the path delay changes through the network. Once one has the path delays under control one can then patch incoming links to outgoing links without the need for complicated and expensive buffering equipment on each link. One is also then able to avoid sequential resynchronization of each terminal equipment every time a path delay shifts.

DISCUSSION

DR. REDER: Do you have any idea what causes the large delays or delay changes in cables?

MR. DAY: We guess, we believe, we think--let's put it that way here--the channel supplier reroutes channels for routine maintenance checks, service restoration, and so on. That seems to be the real cause of it. We don't see any likelihood of it being stopped, or any advantage in having the channel supplier always reroute a certain facility in a certain way to control it. If you were to put that kind of limitation on the channel supplier, and if his first alternate failed, you'd be dead. So we feel that we just have to live with it, and the way to live with it is by putting delay external to the link.

DR. WINKLER: Regarding variations in cable, postulating cables has been interesting to telecommunications engineers since, I think, at least 1925 or 1930. There are many causes. A submarine cable, for instance, is subject to varying pressure depending on the tidal loading. If you figure out the length of that cable you get, very easily, variations of 1 part in 10^5, of the length, or 1 part in 10^4. A land line would be subject to atmospheric influences and temperature changes. But there is one more thing that we have observed in a relatively short link between NRL and the Observatory, which was used for several years to make use of the hydrogen masers which were at NRL. We had a dedicated line provided by the telephone company and we used a tuned 10-kilocycle channel. And we noticed sudden changes in phase delay, most likely caused by differences in capacity of loading. Also the channel did not go through switching centers. But apparently the condition in these switching centers changes abruptly from time to time, and I can imagine that, if you have a very long complicated system going through many of these centers, this can accumulate in a random fashion. It's clear, of course, that microwave links also are not perfectly stable. I will come to that fact a little bit later.

MR. DAY: I would like to make one additional comment on this. The abrupt changes of significant shift in milliseconds are very different than the breathing effects from temperature, atmospheric changes, and so on. We also know that the propagation velocity through a narrow band channel, for example in 75-baud telegraph channels, is around 18,000 kilometers a second. So a round trip between Tokyo and Washington is around 900 milliseconds, whereas I recall that some years ago we made some measurements on a voice band, Tokyo to Washington on a 3-kilohertz slot. It was 165 milliseconds around the loop, yet they were both essentially the same distance. So the bandwidth of the channel at the very narrow band does have some effect. But the thing that puzzles us is this abrupt, very large delay. We think it's probably maintenance-related.