TIME AND FREQUENCY FOR DIGITAL TELECOMMUNICATIONS

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Time and frequency (T&F) are fundamental and pervasive parameters of telecommunication technology. Advancing development of digital communications using data modulation rates above 2400 baud and time-division multiplex in complex network configurations is now requiring more accurate and precise T&F reference information for efficient operation of telecommunication systems. Past papers that I have presented addressed the concept of T&F facilities at telecommunication stations in the field[1] and a system concept for distribution of T&F reference information via telecommunication and navigation systems to users in the field.[2] The question that is most often asked, "Why is T&F reference information necessary for the operation of digital telecommunication systems?" I will answer this question by discussing here the fundamental ideas of processing binary digital signals, the operation of time-division multiplex, and digital network synchronization.

A schematic diagram of a general communication system as conceptualized by Shannon and Weaver[3] is shown in Figure 1. This diagram is very general and can depict any type of communication. The information source selects a specific message which is encoded and sent through a communication channel. Enroute, the signal is subjected to perturbations from environmental noise. The received signal is then decoded and delivered to its destination. Through the process, the message may undergo many spurious changes, resulting in a loss of information content in the delivered message as compared to the original selected message. In digital telecommunication systems, loss of information content of the signals can be attributed to noise, distortion of waveshape, and loss of synchronization.

Digital signals are basically a series of binary digits (bits) occurring at a fixed rate of time. As shown in Figure 2, each bit represents one of two possible logical states (1 or 0) and is held for an equal time interval (t). The sequential combinations of logical states represent

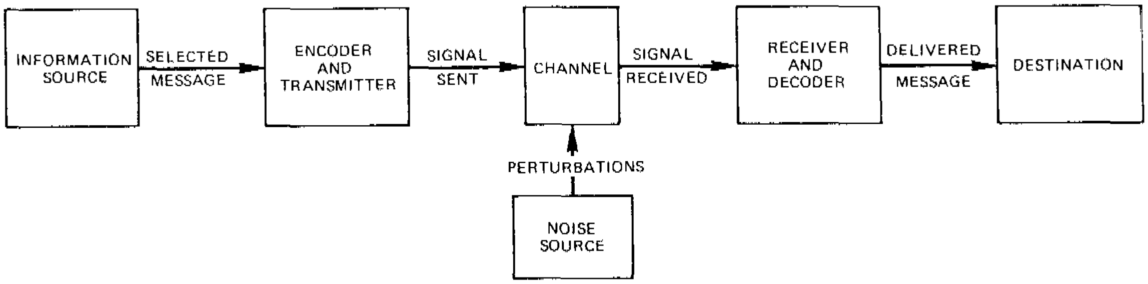
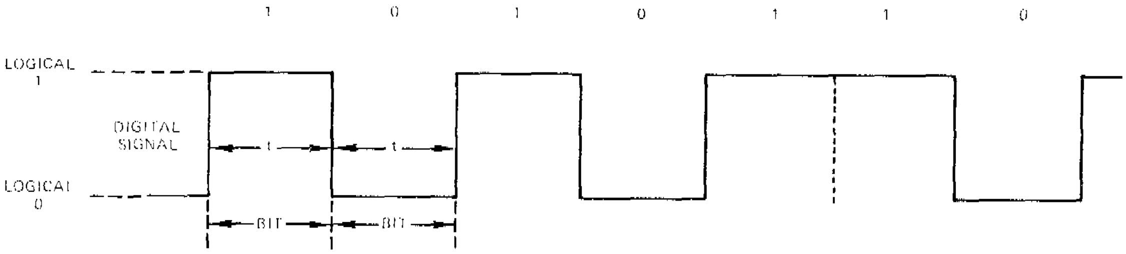


Figure 1. Schematic diagram of a general communication system.



BIT = BINARY DIGIT
t = TIME INTERVAL IN SECONDS
$\frac{1}{t}$ = DIGITAL SIGNAL MODULATION RATE IN BAUDS

Figure 2. Basic digital signal.

the encoded information of the selected message. The reciprocal of the time interval of a bit gives the modulation rate in bauds for transmission of the digital signal.

There are also digital signals that may contain bits of different time intervals for identification of groups of bits as information characters. This is normally associated with conventional low-speed electromechanical teletype operation and has no significance in this discussion. Under consideration here are the serial digital signals with bits of constant time interval as normally used for data communications at a modulation rate of 2400 baud or higher.

The generation of a digital signal requires a source of time-interval reference information (often called *clock*) for timing the signal at a given modulation rate. Normally the timing-signal modulation rate is twice that of the associated digital signal. The relationship of the timing and digital signals is shown in Figure 3. The timing signal is a series of alternating logic states of equal time interval. One timing period consisting of a "1" and a "0" determines the interval duration of one bit in the digital signal. The logic state of the encoded information is detected by the "0" to "1" transition of the timing signal. This state is then reflected as one bit in the resulting digital signal for the duration of one timing period.

The detection of a digital signal also requires a source of time interval reference information. As shown in Figure 4, the received timing signal is normally twice the modulation rate of the digital signal and in the same phase relationship as at the digital signal source. However, the sampling of the digital signal is accomplished by the "1" to "0" transition of the timing signal, which is coincident with the center of the bit. This portion of the bit has the least probability of being perturbed by the transmission channel. Therefore, the chance of detecting the wrong logic state is minimized.

Now it becomes readily apparent that if the time interval (or frequency) of the timing signal is different from that of the received digital signal there will be a relative continuous change in phase between the two signals. Therefore, the point of detection will shift either toward the leading or the trailing edge of the bit. Eventually the detection point could change over

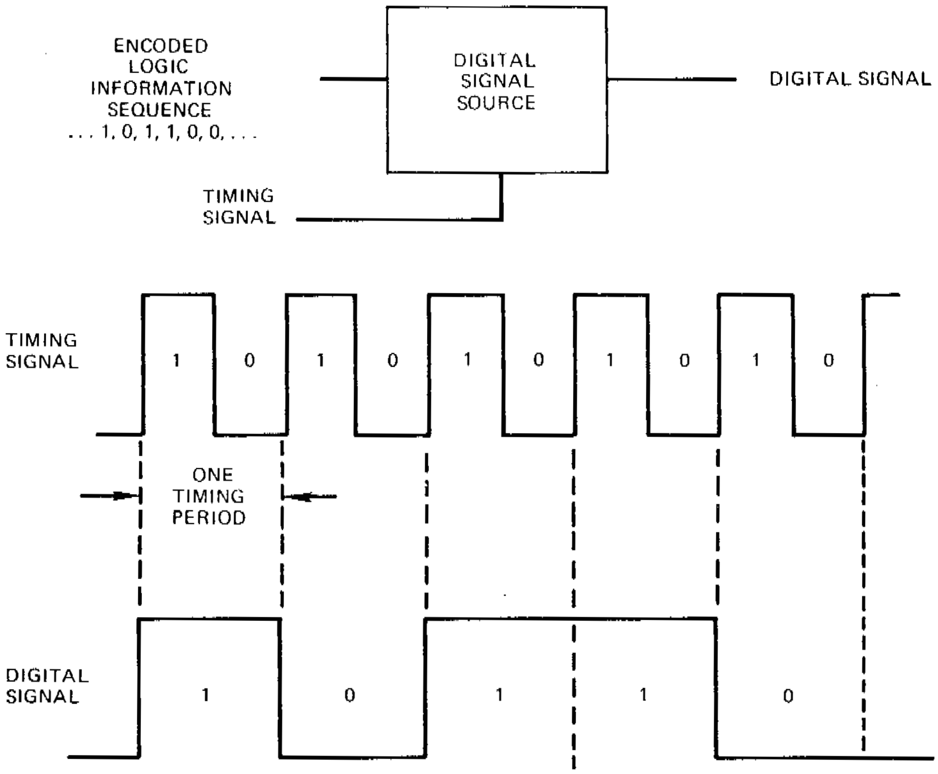


Figure 3. Generation of a digital signal.

to an adjacent bit. This would cause what is known as loss of bit-count integrity and result in loss of the information content of the signal. Even before loss of bit-count integrity, as the sampling point drifts into a perturbed portion of the data bit, the wrong logic state may be sensed.

A number of digital signals can be combined into a single digital signal by a time-division multiplexer (TDM). This is accomplished by reducing the time duration of the bits of the input signals and interleaving the bits (or groups of bits) into a single serial signal of a higher modulation rate. The rotating selector shown in Figure 5 functionally illustrates the process of time-division multiplexing. Rotating at a rate of one revolution per input-channel-bit time interval, the selector samples each channel sequentially for one quarter of a revolution. The resulting output signal has a modulation rate of four times that of the input channels. The first four bits of the multiplexed signal are the first bits of each input channel in the order that they are sampled. This sequence is then repeated as the selector continues to rotate.

Demultiplexing the signal is just the reverse of the multiplexing process. Functionally, a rotating selector in synchrony with the multiplexer distributes the bits of the incoming multiplexed signal to their respective output channels.

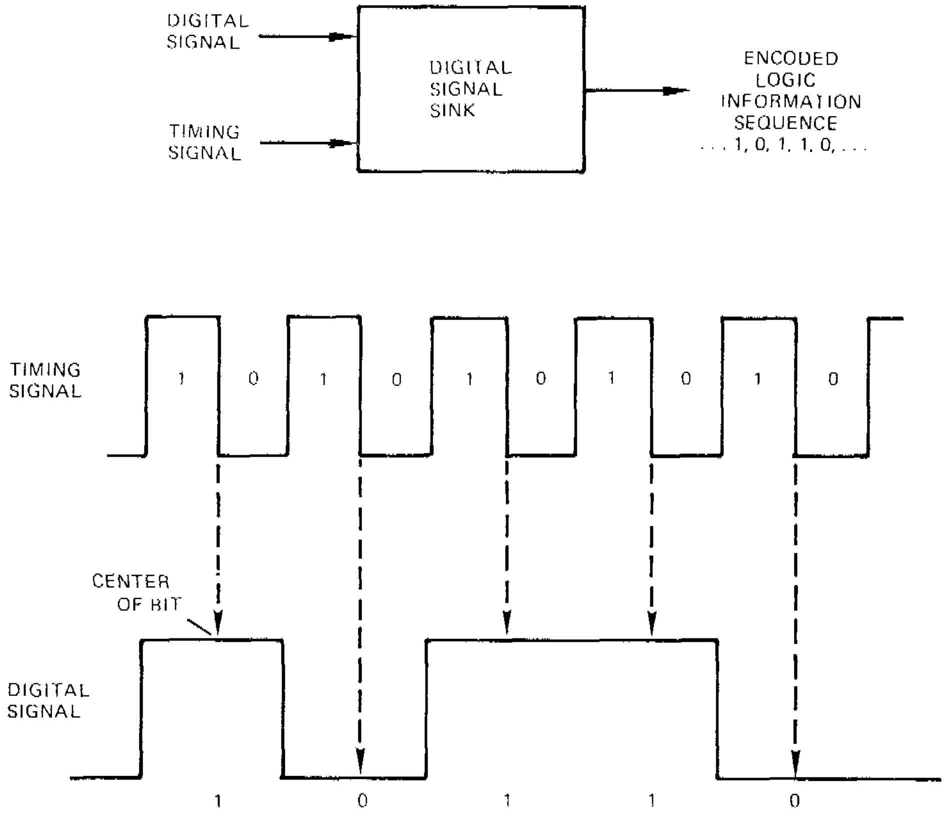
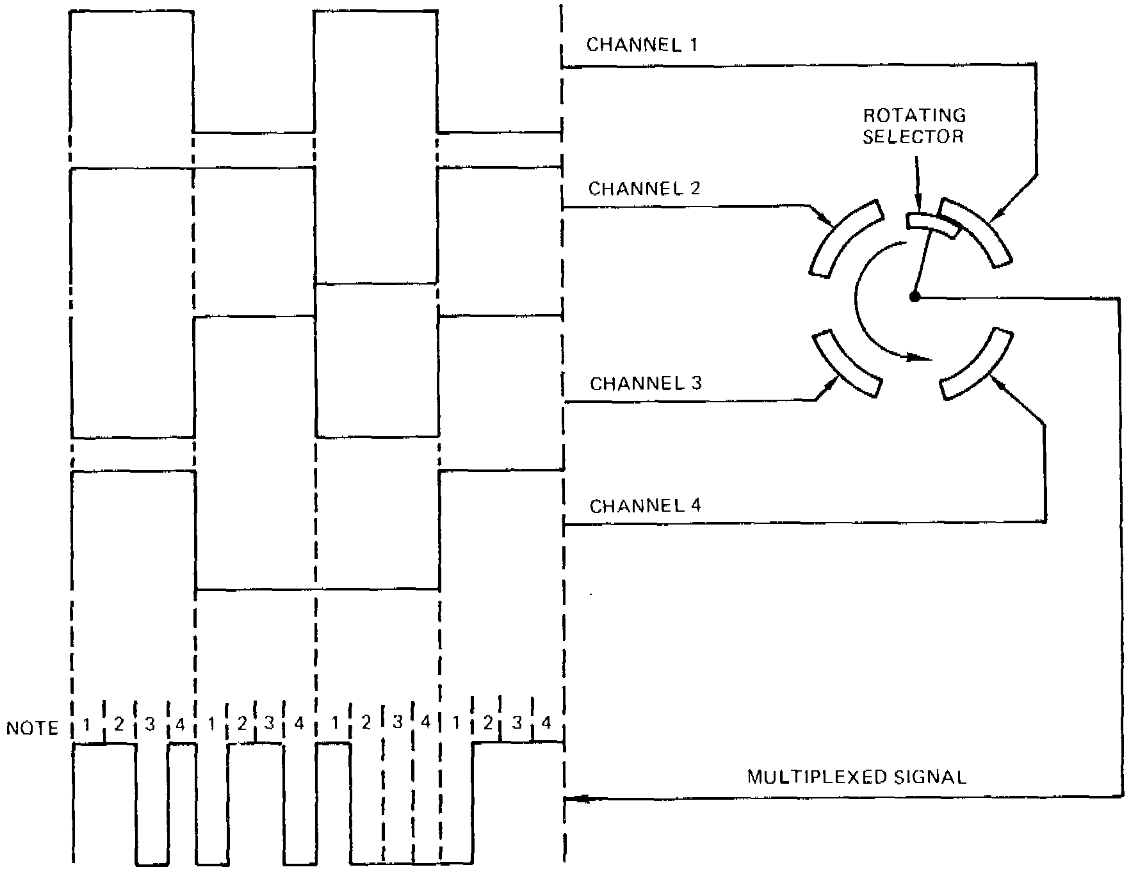


Figure 4. Detection of a digital signal.

A major problem in the design of digital communications is synchronization of the TDM and the terminal equipments. The synchronization problem for point-to-point operation as most commonly used up to this point in time, is relatively simple. However, this problem becomes acute with the evolution of complex network configurations.

Point-to-point synchronization requires only that the receiver be synchronized with the transmitter. This is typically achieved as shown in Figure 6 by recovering the time interval information from the received signal to phase lock a local oscillator which provides the timing for sampling the incoming digital signal. The receive timing is, therefore, slaved to the send timing, but contains any timing perturbations that may have occurred to the digital signal during transmission through the communication channel.

This basic scheme, however, is not adequate for network timing. All major nodes shown in Figure 7 must be synchronized with each other. Within a nodal facility, the digital signals must be exactly synchronous in order to allow interchange of signals between channels of various interconnecting routes. The synchronization must be accomplished in a manner that will prevent any instability throughout the network resulting from feedback of timing perturbations through network loops.



NOTE: NUMBER INDICATES CHANNEL
ASSOCIATED WITH EACH BIT OF
MULTIPLEXED SIGNAL

Figure 5. Time division multiplexer.

There are two basic factors that create the problems in synchronization. The first is that of maintaining a frequency coherence between the transmit-timing signals and the receive-timing signals. As discussed earlier, a difference in the time interval (the reciprocal of frequency) between the receive timing and the receive digital signals can cause the point of detection to drift into adjacent bits, resulting in a loss of bit-count integrity.

The other problem is due to a phenomenon associated with the transmission media. As discussed by R. Day[4] last year, communication circuits "breathe" by effectively changing length over a period of time. This produces a doppler effect on the signal by increasing or decreasing its frequency. This problem is most acute with satellite circuits where a few milliseconds of cyclic drift over a period of 12 hours may be experienced due to the movement of the satellite. On cable or microwave circuits, this may be only a few microseconds at the most. When operating at modulation rates in the megabaud range, however, this could cause a slip in the detection of several bits in the digital signal.

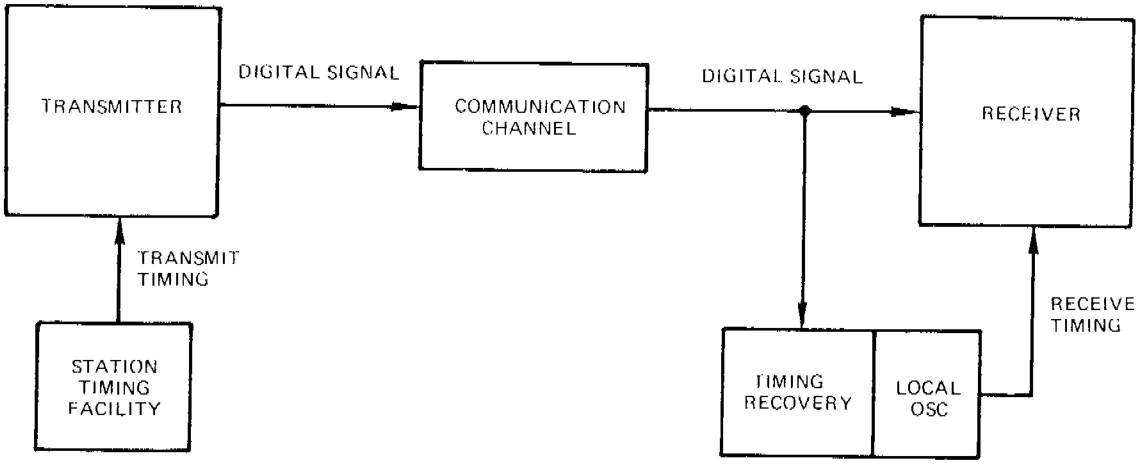


Figure 6. A typical point-to-point synchronization scheme.

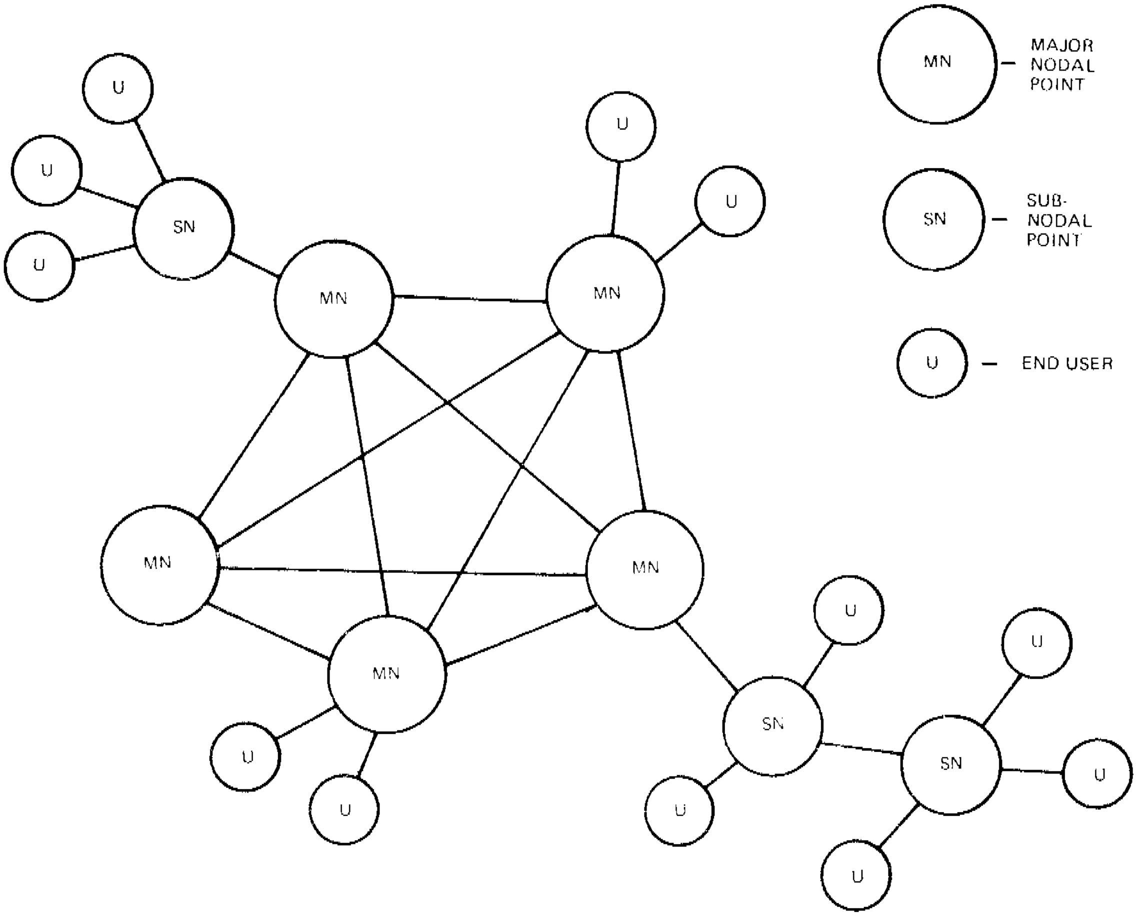


Figure 7. Typical communications network.

There have been several synchronizing techniques proposed,[5,6] but there has been no general agreement as to the best approach to be taken. The various proposals include use of nodal precise timing facilities tied into a T&F distribution subsystem, digital buffers, atomic clocks, pulse stuffing, frequency averaging, and discrete control correction.

The solutions to the synchronizing problems can be considered to fall into two categories, corrective and compensative. The solution to the difference in time interval of the transmit and receive timing signals can be one of a corrective nature, although it could also be one of compensation. The cyclic breathing of a communication channel requires a solution of compensation, since little is understood of this phenomenon and no practical corrective solutions are known. Another fundamental consideration is that the breathing phenomenon has a limit which can readily be determined for any particular application. The breathing is cyclic over a period of time and will average out to a mean value. The difference in the frequency of the transmit and receive timing signals, however, creates a continuous drift in time which does not have a limit.

A corrective solution to the timing signal frequency difference problem can be realized through the implementation of a T&F distribution subsystem[2] with precise T&F facilities at each nodal point in the network. This will ensure maintenance of timing coherence throughout the network, while each node is independent of each other node for its reference information. By retiming the digital signals at each node, timing perturbations are blocked and cannot propagate through to other nodes. Therefore, stability will be maintained throughout the network because feedback through network loops will not be possible.

A compensative solution to the timing perturbations due to the transmission media can be achieved by using digital buffers, adaptive queues, or elastic store devices. These devices are essentially the same in operation. The incoming digital signal is "written" into a temporary storage device by timing recovered from the received signal as shown in Figure 8. During initial synchronization the storage capacity is generally allowed to fill halfway. At this midpoint, the timing signal from the local station source "reads" the digital signal out

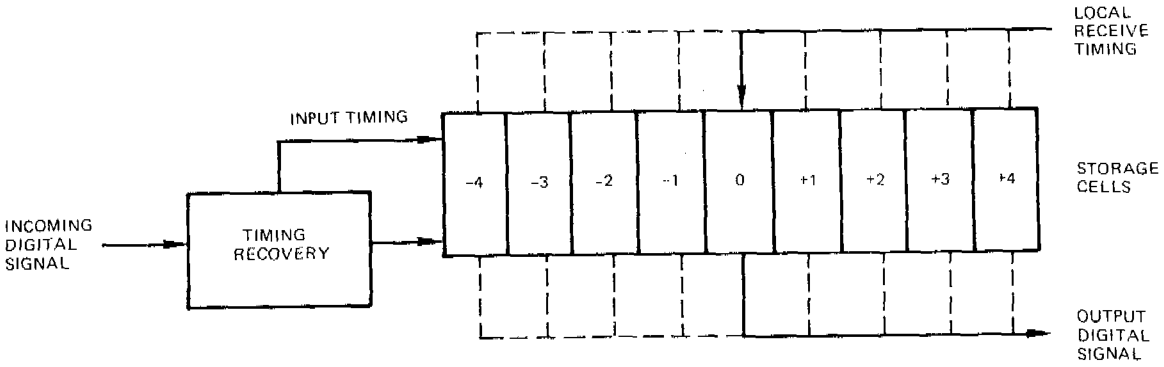


Figure 8. Digital buffer.

the storage to the receive equipment. As the input digital signal changes rate, the storage fill increases or decreases accordingly. The output sampling point then shifts to the appropriate cell to "read" the output signal at the correct time phase relationship.

The limit of timing variation that can be accommodated by the digital buffer depends on its storage capacity and the modulation rate of the signal. It is readily apparent that the dimension characteristic of the buffer naturally lends itself to compensating for the cyclic breathing phenomenon of transmission media. As long as the limits are not exceeded, there should be no requirement for periodic resynchronization. Further refinements have been incorporated into buffer devices to provide an adaptive queue which will compensate for any change in the transmission path over extended signal outages. Each time the circuit is restored a round-trip path-delay measurement is made to determine if an effective change in length has occurred. If so, the buffer fill is adjusted accordingly to allow reading the output from the correct cell.

If the digital buffer is also used to compensate for timing signal frequency differences, the change in fill of the storage cells will be continuous in one direction. This will eventually result in an overflow (or underflow) when the buffer limit is exceeded. In effect the mean point of the cyclic variation will shift in one direction until the storage capacity is exceeded. Thus periodic resynchronization will be required.

Most other synchronization techniques are compensative in nature, although some are a combination of corrective and compensative approaches. More complicated compensative techniques such as bit-stuffing require complex and costly logic circuitry. Also many of the bits in the digital signal are required for control, leaving only part of the signal to carry the actual message information. Once the modulation rates reach a level that exceeds the practical limit of coherent timing facilities, however, additional compensative techniques to ensure maintenance of network synchronization and stability will be necessary. Such a technique developed by R. Bittel[6] and called "discrete control correction" is a good example of what may be seen in the future.

Regardless of the type of digital-network synchronization technique used, a reliable precise source of T&F reference information will be required to ensure effective operation. The techniques are now available for economical distribution of T&F. Therefore, digital system designers must maintain cognizance of T&F technology for appropriate application in their discipline.

REFERENCES

1. H.C. Folts, "Precise Time/Frequency for the Defense Communications System," *Proceedings of the Third Annual Department of Defense Precise Time and Time Interval (PTTI) Strategic Planning Meeting,* Washington, D.C. November 16-18, 1971, pp. 83-190.
2. H.C. Folts, "Precise Time and Frequency is a Communication System," *Proceedings of the 26th Annual Symposium on Frequency Control,* Atlantic City, N.J., June 6-8, 1972, pp. 4-7.
3. C.E. Shannon and W. Weaver, *The Mathematical Theory of Communication,* Univ. of Illinois Press, Urbana, 1949.
4. R.A. Day, Jr., "The Effect of Changes in Absolute Path Delay in Digital Transmission Systems," *Proceedings of the Third Department of Defense Precise Time and Time Interval (PTTI) Strategic Planning Meeting,* Washington, D.C., November 16-18, 1971, pp. 195-209.
5. J.W. Pan, "Synchronization and Multiplexing in a Digital Communications Network," *Proceedings of the IEEE,* May 1972, pp. 594-601.
6. R.H. Bittel, *Network Timing and Synchronization,* Defense Communications Agency, Systems Engineering Facility, Reston, Va., Report 720.5-2, May 1972.