N79-24746

OVERVIEW OF TIMING/SYNCHRONIZATION FOR DIGITAL COMMUNICATIONS SYSTEMS

Harris A. Stover
Defense Communications Engineering Center, Reston, Virginia

ABSTRACT

Digital technology is being applied to communications at a very rapidly increasing rate. Use of digital communications (transmission, multiplexing, and switching) results in a timing/synchronization problem not encountered in analog communications systems. This overview explains the need for timing/synchronization of digital communications systems in general, and switched systems in particular. It points out some of the criteria that greatly influence timing/synchronization subsystem design for a military communications network but have little or no significance for civil systems.

The results of previous studies by DCA and its contractors are summarized and the rationale for the current study being reported in other presentations in this session is provided. In this approach, timing techniques are evaluated in terms of fundamental features. Different combinations of these features would cover most possibilities from which a synchronous timing system could be chosen. Although the studies described in this session were intended for application to the Defense Communications System, the problems of an extensive worldwide military communications system tend to encompass the problems of other digital communications systems, both military and civilian.

INTRODUCTION

The communication of information in digital form is expanding at a very rapid rate. There are many reasons for this: (1) to accommodate information that originates in digital form; (2) economic advantages of digital multiplexing and switching equipment; (3) improved quality provided by digital telephone systems (noise and distortion do not accumulate along the path); (4) need for communication to, from, and between digital computers; (5) requirement for encryption of communications; (6) available techniques to provide resistance to signal jamming; (7) reduced maintenance costs for digital systems, and (8) the trend whereby developing technology continues to further enhance the advantages of digital communications. There are timing/synchronization requirements that must be satisfied in order to reap the

advantages of digital communications. As will be discussed in the following sections, the timing/synchronization requirements encountered when digital communications are organized into networks can be satisfied by many different approaches. Information presented in the four papers of this session of the meeting should help to choose from among them.

DIGITAL COMMUNICATIONS

In digital communications, transmission is in the form of discrete pulses, each with a finite number of allowable states. For pulses with two states (e.g., two phases), each pulse represents a single bit of information; for four states (e.g., four possible phases), each pulse represents two bits; for eight states, each pulse represents three bits, etc. The number of bits is equal to the logarithm to the base 2 of the number of allowable states.

For a one-way digital point-to-point communications link, it is only necessary that the receiver be correctly synchronized to the received signal. However, since a different type of meaning can be applied to different pulses in the sequence--e.g., the most significant digit in a large number has a different meaning than does the least significant digit, or different pulses may represent data with different origins--a capability must be provided to identify particular pulses. This is normally done by grouping the bit streams into frames of a selected number of bits. Frame synchronization codes are used to identify the beginning of the frames. These frame synchronization codes are chosen so as to be unlikely to occur in the communications stream. This is accomplished by selection of unique patterns or by transmitting the code with greater regularity than it would randomly occur.

Most digital communications systems, other than simple telemetry systems or one-way command systems, provide transmission in both directions. By itself this does not impose much of a synchronization problem. Two-way transmission is effectively two one-way links in opposite directions. However, advantage can be taken of the two-way transmission to improve timing precision in more complex systems.

MULTIPLEXING

For economy, a number of lower capacity channels are multiplexed onto a single higher capacity transmission link. In digital transmission, this is done by interleaving the pulses from several lower rate channels into a single higher rate stream, i.e., time division multiplexing. In order to accomplish this without problems, the signal pulses must be available at the correct time to fill their assigned time slots in the multiplexed pulse stream, i.e., some form of synchronization must be provided.

PULSE STUFFING

One procedure for multiplexing digital communications streams, that may have clock rates that are slightly different, adds extra (dummy) pulses to each pulse stream to bring them all to a common higher rate compatible with the rate of the multiplexed transmission. At the other end of the transmission link, where the channels are demultiplexed, the extra pulses are removed to return each channel to its original rate. This technique, referred to as "pulse-stuffing," is quite effective for individual transmission links, but it does introduce some pulse jitter. In order to reduce the cost of pulse stuffing, it is common practice for telephone companies to group analog voice channels together in groups of 24 channels (30 channels in some countries) for digitizing at a common clock rate. When this is done, the pulse stuffing is only needed for time division multiplexing these groups of 24 channels into higher capacity transmission links. For this use, the cost of any single stuffing-destuffing operation is shared among all 24 channels. For more complex networks, where at any particular node previously multiplexed channels are demultiplexed, separated and remultiplexed with other channels on each of several links leading to different nodes, the requirements of pulse stuffing and destuffing are much more complex.

SWITCHING

If switches are provided in the network so that a channel originating at any user of the network can, upon demand (dialing and right number), be connected to any other user located anywhere in the network, the network is being reorganized nearly continually. The particular channels that are multiplexed together continually change. This means that every individual communications channel must be capable of being switched and/or multiplexed anywhere in the network on an individual channel basis. The telephone companies commonly provide this individual channel capability for transmission involving pulse-stuffing by returning all signals to analog form at all switches and redigitizing the signals after switching. This approach is relatively expensive. For encrypted digital voice signals, returning them to analog form would require considerable additional expense for encryption/decryption equipment at all switches. This decoding/encoding would also reduce the security provided by the encryption. An economical alternative, permitting the signals to remain in digital form throughout the network, is to synchronize the entire network and all of its users. That is, instead of only synchronizing the receiver to its received signal for each transmission link, the transmitters throughout the network are all synchronized with one another.

VARIABLE BUFFERS

In synchronizing the digital communications network, variations in

the signal transit times (time it takes for the signal to travel from one node to another) on the various transmission links must be accommodated. Even if the transmitters were perfectly synchronized, these variations could cause changes in the time that received signals would be available to fill their assigned time slots. The transit time variation can be accommodated by providing each receiver with a variable storage buffer (or stack) into which each bit is placed when it is received. It is removed by the local clock at the correct time to fill its assigned time slot. By enlarging these buffers over the size needed for the path length variations, they can also accommodate some error in the local clocks.

THE INDEPENDENT CLOCKS TECHNIQUE

If very stable clocks are used at each node, and variable buffers (or stacks) of sufficient size are employed, then the clocks can free run for a useful period of time before the buffers either overflow or empty. When this capability is coupled with provision for occasionally interrupting communications traffic to reset the variable buffers (or stacks), the timing/synchronization technique known as "independent clocks" results. This technique has been chosen for use at major nodes in U.S. tactical communications. It is also being used as a backup mode of operation in other systems, and it is generally recommended for backup use.

MASTER-SLAVE TECHNIQUE

Although pulse stuffing is widely used on an individual link basis, it is not normally used where the signals must remain in digital form throughout the network. In North America most commercial communications systems in which signals remain in digital form throughout the network use some type of master-slave system. This is also true of civil systems in many other parts of the world. In these systems, all nodes of the network are slaved either directly or indirectly to a master by phase-locking the local clock at each node to a selected received signal. It is a very obvious and straightforward technique.

MUTUAL SYNCHRONIZATION

A technique which has been widely studied, but has had little application to date, is called "mutual synchronization." In it, each node adjusts the frequency of its clock in such a way as to reduce the phase difference between itself and some weighted average of the phases of all signals received from its neighbors.

EXTERNAL TIME REFERENCES

If a time reference for synchronizing each nodal clock is obtained from a source external to the communications network, it is referred

to as the "external time references" technique. Several timing sources could be used. These include such systems as Loran-C, the NAVSTAR Global Positioning System (GPS), etc.

TIME REFERENCE DISTRIBUTION

In the time reference distribution technique, all nodes are kept within a specified time tolerance of the master node. Time reference information is transferred between all connected nodes with the effects of transmission time removed. There are three major functions that must be performed by the time reference distribution technique: (1) selection of the paths over which the time reference is distributed through the network, including selection of a new master when necessary; (2) measurement of the local clock's time error; and (3) correction of the time error in the local clock. The technique is generally considered to have the features (defined later in the paper) of directed control, double endedness, self-organization, and independence of the clock error measurement at one node from the clock error correction at any other node except for the master. Some of these features can also be used in some of the other techniques as will be discussed later.

COMBINATIONS OF TECHNIQUES

The above techniques can be used in various combinations. The independent clock technique is an excellent backup for other techniques. However, in the applications to U.S. military tactical switched digital communications, the master-slave technique is used as a backup to the independent clock technique. The master-slave technique can be very effective at lower levels of the timing hierarchy when some of the other techniques are used at the higher levels. Another combination synchronizes the lower levels of the multiplex hierarchy (all users are synchronized) while using pulse stuffing at the higher levels of the multiplex hierarchy. This permits the use of lower speed logic for the buffers and for some of the other timing system hardware. However, it can greatly increase the complexity of some timing techniques because of the very large increase in the number of signals that must be separately synchronized as compared with synchronizing at the highest levels of the multiplex hiearachy.

MILITARY VS CIVIL REQUIREMENTS

Several characteristics of a digital communications network deployed for military communications can greatly influence timing/synchronization system design for such a military application, but have little or no significance for civil systems. However, careful examination of designs most capable of accommodating these characteristics might also show the approaches to be desirable for civil application. Among these characteristics is the need for extensive application of encryption to

military communications. Other such characteristics relate to action taken by an enemy to intentionally disrupt our military communications. A military digital communications network, including its timing function, must be capable of surviving such attacks. Resistance to signal jamming must be provided. Systems using wideband spread spectrum techniques for this purpose, (with their very short pulses arranged in a pseudo-random manner) must be able to rapidly synchronize their receivers to the received signals, even in the presence of jamming. The time needed to acquire such synchronization can be greatly reduced through the use of precise timing to reduce the size of the search window. An extremely stable timing system that is relatively immune from perturbation would help to satisfy the above requirements.

In normal operation, failures of the timing function will occur very rarely and would not be expected to be geographically extensive. Therefore, in civilian networks capable of free running for a period of time following failures, any required reorganization of network timing needed to accommodate failures can be manually controlled or initiated from a central location. However, in a military network, because of the importance of the timing function and the possibility of simultaneous attacks on many parts of the network, the reorganization of the timing subsystem should be highly automated and distributed throughout the network. (A required centralized function becomes an attractive target for enemy action.) Similar characteristics apply to the monitoring and maintenance functions for military network timing capability since they also may be intentionally impeded by the enemy.

Briefly stated, a military network must be able to endure: (a) physical destruction of parts of the network, (b) enemy capture of part of the network, (c) equipment failures, (d) enemy spoofing and/or jamming, and (e) deliberate obstruction of maintenance and repair operations. Under these conditions it must be able to maintain acceptable operations (both communications and timing) including operations within portions of the network which become isolated from the rest of the network. It must be able to interoperate with other digital communications networks that might use different techniques. It must be monitorable, primarily to permit the early identification of timing problems long before they can interrupt communications. It must also be versatile to provide easy compliance with modification of plans (such as the introduction of new technology) and to provide convenient application to future problems. The endurance, interoperability, monitorability, and versatility must be provided economically with low life cycle costs.

These and other characteristics of a military digital communications network have been considered in studies of communications network timing for the Defense Communications System.

STUDIES BY DCA AND ITS CONTRACTORS

Initial studies of network timing at DCA investigated DCS requirements and tradeoffs between several alternative techniques for meeting the requirements [1]. These initial studies selected a mutual system called Discrete Control Correction as desirable for use in the DCS. In it, the amount of occupied buffer storage is monitored for each link received at a node. At periodic intervals a weighted average of the information thus obtained is applied as a control signal for the correction of the local clock. Additional studies of the Discrete Control Correction approach were made by Clarkson College under a contract from the Air Force. These studies, employing both analysis and simulation, showed that proper selection of the weighting coefficients would bring the clocks to a common average rate with satisfactory damping of perturbations and the resulting freedom from spontaneous oscillations. The study participants were enthused by their findings which were described in a number of papers [2,3,4,5,6].

While these studies were being conducted at Clarkson College, further studies at DCA indicated that distributing an accurate time reference through the communications network would have advantages not available to mutual systems. For military application, such an approach would be capable of self-reorganization following failures. In order to maximize its stability and minimize the propagation of errors through the network, it would have no closed loops. The effects of signal transit time (in comparing the time of clocks at neighboring nodes) would be removed to enhance accuracy and stability. A method for accomplishing this is called Time Reference Distribution [7]. The general concept of which was presented at this planning meeting in 1973 [8].

With two different concepts being considered for Timing/Synchronization of the DCS, the Clarkson College team was tasked to compare four synchronization techniques: Discrete Control Correction, Master Slave, Independent Clocks, and Time Reference Distribution. This study found that use of the Time Reference Distribution Technique at major nodes with slaving at minor nodes will best meet the DCS requirements. However, the study indicated that the use of independent clocks has considerable merit if it is acceptable to occasionally interrupt traffic to reset the variable storage buffers. But, the study also stated that the availability of monitoring capabilities renders the Time Reference Distribution Method superior to the Independent Clock Technique [9]. While this study was being conducted, work at DCA showed how easy it would be to make the measurement of the clock error at any node independent of the correction of the clock error at any other node by simply having each node inform its neighbors of its measured but uncorrected error [10, 11].

Because it was felt that an industrial contractor could add a degree of depth in the area of hardware implementation that could not be

provided as well by an educational institution, and because the Clarkson College report on evaluation modeling had recommended further study of some aspects of some of the timing techniques, the Harris Corporation was competitively selected for a "Study of Alternative Techniques for Communication Network Timing/Synchronization." The results of this study were in agreement with all previous studies that had considered the Time Reference Distribution Technique; i.e., that the Time Reference Distribution Technique should be used at the major nodes of the switched digital Defense Communications System, but that minor nodes of the network should be slaved [12]. There was criticism of the Harris Corporation report because it compared simple Master-Slave and Mutual systems with a Time Reference Distribution system that has many more features. The criticism pointed out that many of the features of the Time Reference Distribution Technique could be included in either the Master-Slave or Mutual Techniques. So long as too many of these features are not included, these systems will not actually be Time Reference Distribution Systems.

Simultaneously with this study, an Improved Time Reference Distribution Concept was being developed at DCA. This improved concept provides automatic selection of the highest ranking clock in the network as the master for the network; automatically arranges the network into a preferred timing hierarchy below that master; provides optimum combining of the timing information at each node for best accuracy while avoiding all closed paths; and provides independence of the clock error measurement at any node from a clock correction at any other node. This independence prevents changes or adjustment of any clock in the network--other than the master clock--from propagating to other nodes [13]. This is accomplished without requiring any node to communicate with any other node farther away than its immediate neighbors.

It had been planned that studies following the "Study of Alternative Techniques for Communications Network Timing/Synchronization" would optimize a selected system. However, as a result of the criticism of that study, it was decided that the follow-on study should include further comparisons. In order to avoid further criticism, the Statement of Work for the follow-on "DCS Synchronizing Subsystem Optimization/Comparison Study" was written to require a comparison of the capability of each of a number of basic subsystem features to provide each of a number of desirable characteristics. This would provide a basis of comparison for any combination of these features. These different combinations would cover nearly all meaningful possibilities for synchronization of digital communications systems. The features were to include as a minimum:

1. Directed Control: The clock at only one end of a transmission link is permitted to be changed as a result of the measured difference

between the clocks at the two ends.

2. Double Ended: information is exchanged between the two ends of a transmission link so that the clocks at the two ends can be directly compared independent of the time required for the signal to travel from one node to the other. (If the time required for the signal to travel between nodes is the same for both directions of transmission, this feature permits removal of the signal transit time from the comparison of the two clocks).

3. Self Organization: when the network is initially put into operation, or following a disturbance, the synchronization function of the network automatically organizes itself into an optimum configuration for all surviving facilities.

4. Independence of the clock error measurement at any node from the clock error correction at any other node: all clock error measurements are, in effect, made with reference to the master; and errors in any clock other than the master do not propagate through the network.

5. Overhead: while not a feature as such, all systems (except for very low rate systems not considered here) regardless of features have timing subsystem overhead requirements for providing the frame synchronization signals (even the independent clocks technique). How much this basic overhead requirement is either increased or decreased by implementing the other features is of interest.

The desirable characteristics against which the features were to be evaluated included as a minimum:

1. Survivability of the Timing Function.

2. Slip-free operation, i.e., no interruptions of traffic to reset the variable storage buffers.

3. Frequency accuracy and phase accuracy.

4. Freedom of clocks from disturbance by perturbations at clocks or transmission facilities further from the master than the clock under consideration.

5. No harmful propagation to any other node of an error introduced at any node in the network except the master.

6. Compliance with Federal Standard 1002, "Time and Frequency Reference Information in Telecommunications Systems." (This requires referencing to UTC (USNO) or UTC (NBS).)

7. Monitorability at the system level (functional vs equipment

monitoring).

8. Minimum overhead communications.

9. Interoperation of the digital communications system with other digital communications systems employing different synchronizing techniques.

10. Cost effectiveness, i.e., maximizing the ratio of performance to cost.

11. Capability of automatic selection of a new master whenever there is a failure of the master through which the timing/synchronization subsystem is coordinated.

12. Availability of Precise Time (UTC) to users of the DCS without introducing any significant penalty.

The results of this work (2 tasks of the 11 task study) are reported in the third and fourth papers of this session.

EXPERIENCE WITH OPERATIONAL SYSTEMS

It is recognized that frequently much can be learned during the initial stages of implementing a system, and that this frequently includes valuable information that does not come to light during theoretical studies only involving analysis and simulation. Because of this, one task of current study required gathering information on the implementation and operational experience with timing/synchronization systems of operating digital communications networks. The results of this task are reported in the second paper of this session.

REFERENCES

[1] DCASEF Report 720.5-2 "Network Timing and Synchronization," R. H. Bittel, 17 May 1972.

[2] R. Mukundan et al, "Clock Synchronization Through Discrete Control Correction," EUROCON '74 Conf. Digest, Amsterdam, The Netherlands, April 1974.

[3] K. R. Krishnan et al, "Synchronization of a Digital Communication Network by Discrete-Control-Correction," IEEE IASACS '74 Proceedings, April 1974, pp 411-415.

[4] D. A. Perreault et al, "A Computer Simulator for Discrete Control Correction," Fifth Annual Pittsburg Conference on Modeling and Simulation Proceedings, Pittsburg, PA, April 1974.

[5] R. H. Bittel et al, "Clock Synchronization Through Discrete Control Correction," IEEE Trans. on Communications, 22, No. 6, June 1974, pp 836-839.

[6] K. R. Krishnan et al, "Discrete Control Correction for Synchronization of Digital Communication Networks with Different Correction Parameters at Different Nodes," IEEE ICC '74 Conf. Record, June 1974, pp 6C-1--6C-4.

[7] DCASEF TC 39-73, "Time Reference Concept for the Timing and Synchronization of the Digital DCS," H. A. Stover, July 1973.

[8] H. A. Stover, "A Time Reference Distribution Concept For a Time Division Communications Network," Proceedings of Fifth Annual NASA Department of Defense Precise Time and Time Interval (PTTI) Planning Meeting, NASA, Goddard Space Flight Center, Greenbelt, Maryland, December 4-6, 1973.

[9] RADC-TR-77-19 (AD-039-377) "Network Timing/Synchronization Evaluation Modeling," Clarkson College of Technology, April 1977.

[10] H. A. Stover, "Coordinated Universal Time (UTC) as a Timing Basis for a Digital Communications Network," EASCON 1974.

[11] DCEC TR 43-75 (AD-A021934) "Communications Network Timing," H. A. Stover, September 1975.

[12] Harris Corporation Electronic Systems Division, AD-A041004 "Final Report, Study of Alternative Techniques for Communication Network Timing/Synchronization," March 23, 1977.

[13] H. A. Stover, "Improved Time Reference Distribution for a Synchronous Digital Communications Network," Proceedings of Eighth Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, U.S. Naval Research Laboratory, Washington, D.C., November 30 - December 2, 1976.