

# Network Timing/Synchronization for Defense Communications

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**Abstract**—The designers of synchronous switched digital communications networks have a large number of possibilities from which to choose a timing/synchronization system. Various combinations of the timing/synchronization system features described here can be used to characterize these possibilities. Advantages and disadvantages of employing different timing/synchronization features are examined, and their relationships to the more commonly discussed mutual and master-slave methods of network timing/synchronization are described. The need for particular timing system options is dependent on system applications. Significant differences in needed capability result from differences between civilian and military application. These differences are discussed, and the relationship between timing/synchronization requirements of a wartime worldwide synchronous switched digital military communications network and timing system features is explored.

## I. INTRODUCTION

IN a digital communications network employing time division multiplexers and/or time division switches, each bit must be available at the right time to fill its assigned time slot in the multiplexer or switch. Since the bits to be interleaved at any switch or multiplexer can originate at many locations throughout the network, it is important that their sources be adequately synchronized. Variations in the transit time of the signal from one node to another due to environmental conditions can be accommodated by temporarily storing bits in variable storage buffers placed in all received bit streams. These buffers can also accommodate small errors in the nodal clocks that determine the timing of transmitted signals.

To avoid a network synchronization problem while taking advantage of the economy of digital transmission, it has been common practice for the telephone companies to provide analog-to-digital conversion at the lowest level multiplexer and to employ pulse-stuffing at higher levels of multiplexing [1]–[11]. In this pulse-stuffing process, extra “stuff” bits are added to each of the bit streams to bring them all to the correct rates for interleaving into a higher rate bit stream. The location of the “stuff” bits is communicated to the other end of the link where the extra bits are removed to return the streams to their original rates; however, some pulse jitter is introduced by this process [12]. If switching is provided so that a channel originating at any user in the network can, upon demand (dialing), be connected to any other user in the network, then channel groupings continually change as new paths through the network are selected. Telephone companies commonly provide for synchronizing the channels in these new groups by returning all signals to analog form at all switches and redigitizing them after switching. This is inconvenient and expensive when digital

switching is used because of the need to convert each analog channel to a digital form synchronous with the switch. Where there are military requirements for encrypted digital voice channels, returning to analog form not only involves the additional equipment for digital-to-analog and analog-to-digital conversion but also considerable additional expense to provide decryption/encryption equipment for all channels at every switch. This decryption and reencryption also reduces the level of security. 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. In addition to digital voice communication channels, there are integrated communications concepts, which combine digital voice channels with digital data packets, that can also benefit by good methods of synchronizing network transmitters [13], [14].

## II. NETWORK TIMING/SYNCHRONIZATION SYSTEM FEATURES

Studies of various synchronization approaches, identified only by traditional names (such as mutual, master/slave, time reference distribution, external master reference, or independent clock systems) have been criticized because the “right” set of optional features was not used for one particular approach or another [15]. To relieve that problem, a list of system features are defined from which a large number of possible timing systems can be selected by using various combinations of these features. The reader should recognize that the present state of technology, especially microprocessor technology, will permit them all to be conveniently and economically implemented.

### A. Directed Control (DC)

With this feature, the clock at only one end of a communications link is permitted to take corrective action in response to an indication of a timing error between the two ends of the link. Although timing information might pass in both directions over the link, the timing reference passes only in one direction. The feature can be applied in such a way as to avoid closed feedback paths.

### B. Double-Ended Timing (DE)

A switched digital communications network is normally made up of duplex digital transmission links which interconnect the nodes of the network. Synchronization codes allow the receivers to be synchronized to the received signals. If the timing information for the local clock is obtained only by comparing the arrival time of the received signal's synchronization code with the local clock, the system is said to be single-ended. If timing error information is exchanged be-

Manuscript received June 12, 1979; revised April 8, 1980.

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tween the nodes at both ends of a communications link, it is called double-ended, and the phases of the clocks at the two ends of the link can be directly compared; without the effects of signal transit time.

In one double-ended approach, the local clock controls the timing of all transmitted synchronization codes. The arrival time of all received synchronization codes is measured relative to the local clock. This measurement includes the signal transit time and any difference between the two clocks. The measurement is communicated to the other end of the link. Subtracting the measurement made at one end of the link from that made at the other end and dividing by two gives the error between the two clocks. This is shown in (1) where  $T_B - T_A$  represents the time difference between the two clocks,  $D_{AB}$  represents the signal transit time from node  $A$  to node  $B$ ,  $D_{BA}$  represents the signal transit time from node  $B$  to node  $A$ ,  $\Delta_A = T_A - (T_B - D_{BA})$  is the measurement at node  $A$ , and  $\Delta_B = T_B - (T_A - D_{AB})$  is the measurement at node  $B$ .

$$T_B - T_A = \frac{\Delta_B - \Delta_A}{2} + \frac{D_{BA} - D_{AB}}{2}. \quad (1)$$

### C. Self-Organization (SO)

When, without manual intervention, the communications system selects (and reselects when needed) a network master clock and a preferred timing hierarchy, it is called self-organization. Two methods are described here. In both self-organization methods, each network clock is given a unique rank which is used to determine the order of ascension to network master clock. Both methods are distributed, i.e., based on local decisions made at the individual nodes. In both methods each node receives the small amount of information needed to make the decisions from its immediate (directly connected) neighbors with no need to communicate with more distant nodes.

In the classic self-organization method described by Darwin and Prim [16], three pieces of information are frequently passed from each node to its neighbors: 1) the rank of the node used as the ultimate master reference for the local clock; 2) the demerit rating of the transmission path over which timing information is passed from the ultimate reference clock to the local clock (each node gets this information by adding the demerit of the link between itself and the neighboring node from which it receives its reference to the corresponding information provided by that neighbor); and 3) the rank of the local clock. The time reference is taken from the neighboring node which uses the highest ranking clock as its ultimate reference. If any two or more neighbors are using the same highest ranking ultimate reference, the local node selects from among them the one with the lowest demerit path to that highest ranking ultimate reference. If two or more neighboring nodes are using the same highest ranking reference with the same lowest demerit path from that reference, the local node selects from among them the one with the highest ranking local clock. By repeatedly following this procedure at all nodes of the network for every exchange of information, the highest ranking clock in the network is selected as the ultimate master for the

network, and the best path from each node to that master is also selected.

A study at Clarkson College [17] found that under certain system failure conditions, obsolete information remaining in the network could cause a "ring around" condition, preventing the system from reorganizing itself. To avoid the condition, the affected nodes would have to self-reference (i.e., use their own free-running clocks) for sufficient time to allow the obsolete information to be purged from the network. To assure that adequate but not excessive time is allowed for this, a fourth piece of information is added to those that each node provides to its neighbors [17], [18]. This is the status of the node's update counter. After the best tentative reference has been selected by the procedures described above, the update counter information is used to determine when to begin using the tentative selection as the local node's actual reference. Following each information exchange, if the tentative best reference for a given node is self-reference, the node uses its own clock as reference and reduces its update counter by one unless it is already zero. If the count at a neighbor, selected as the tentative reference, is less than the count at the local node, the local node takes its reference from that neighbor and sets its update counter to a count just one greater than the neighbor's. If a neighbor with a count equal to or greater than the count at the local node is selected as the tentative reference, the local node continues to self-reference and increases its update counter by one. This procedure is repeated until the desired network organization is established.

The other self-organization technique organizes the timing/synchronization system into tiers [19], [20]. All nodes with the same minimum number of links between themselves and the ultimate master are assigned to the same tier. Two pieces of information are transmitted by each node to its immediate neighbors: 1) the rank of the clock used as the ultimate master time reference for the local clock; and 2) the number of links between the local node and its ultimate master time reference. If one or more neighbor's reference clocks outrank the local clock, the node selects from among them those neighbors referencing the highest ranking ultimate reference for use in determining its own time reference. That same highest ranking ultimate reference then becomes the ultimate reference for the local clock. The number of links between the local node and its ultimate master is greater by one than the least number for those neighbors referencing the same ultimate reference as the local node, unless the local node is not exceeded in rank by the ultimate reference used by any of its neighbors, in which case, the number is zero. As each node makes use of this information to update the information supplied to its own neighbors, the network automatically arranges itself into tiers. The highest ranking node is automatically selected as master and it is the sole occupant of the top tier. All nodes directly connected to the master share the second tier. All nodes connected to the second tier nodes but not to the master will share the third tier, etc. This method of self-organization does not require an update counter because it does not have the same susceptibility to obsolete information. Waiting a couple of information exchange periods is always adequate to remove obsolete information. This type

of self-organization is useful for applying the phase reference combining feature described in subsequent paragraphs.

#### D. Independence of Clock Error Measurement at any Node from Correction of a Clock at any Other Node (IMC)

For timing/synchronization systems using very good clocks, bandwidths in the region of a few microhertz might be used in phase-locked loops controlling the nodal clocks causing considerable time delay between the measurement of an error and the actual correction of the clock. A timing reference passing from node to node without the benefit of this feature accumulates time delays. Also, without this feature any change of an intervening clock due to external causes can result in perturbations of other clocks which get their reference via the intervening clock. A simple procedure can avoid such perturbations, and reduce the accumulation of time delays [20], [21].

The double-ended feature provides a measurement of the difference between the local clock and the neighboring clock at the other end of the link which is serving as an immediate reference for the local clock. If all nodes, including the master, transmit their measured but uncorrected (known) errors to their neighbors, any node wishing to use a particular neighbor for time reference information can use this information from that neighbor, along with the measured difference between its own clock and that of the neighbor, to determine its own measured but uncorrected error. Changing a clock at any intervening node will change its measured but uncorrected error, and it will also change the difference between its clock and that of any node which references it. For nodes using a timing reference from the intervening node, these two changes cancel one another and there is no net change to their measured but uncorrected error.

#### E. Phase Reference Combining (PRC)

If a system with the preceding four features uses the second method described for the self-organizing feature, then without introducing closed feedback paths, each node can optimally combine timing reference information from all directly connected nodes which are higher in the hierarchy than its own level. By taking the precautions described below, a node can also combine timing information from neighboring nodes in its own level of the hierarchy without introducing closed feedback paths [19], [20].

It is desirable to avoid having timing information repeatedly passed back and forth between two nodes or repeatedly passed around a closed loop consisting of several nodes. Such a process, without the introduction of new or better information, cannot improve the information and can only add noise (measurement error) each time it traverses a transmission link. One approach to avoiding closed feedback paths while combining timing information received over multiple paths is for each node to combine only timing information coming from neighboring nodes higher in the hierarchy than itself. Better performance can be achieved if useful information from neighboring nodes at the same level is also combined without introducing closed paths. This is accomplished by maintaining two classes of timing information at each node and passing this information to neighboring nodes. Class 1 timing information

(clock error measurements and inaccuracy values for those measurements) is based only on information received from neighboring nodes higher in the hierarchy than the local node, while Class 2 timing information is based on information from all neighboring nodes not lower in the hierarchy. When deriving its own Class 1 information, each node combines only Class 2 information from directly connected neighboring nodes higher in the hierarchy than itself. When deriving its own Class 2 information, it also combines Class 1 information from neighboring nodes of its own hierarchical level. This prevents closed feedback paths while making better timing information available.

By comparing its own level in the hierarchy (determined by the second piece of information exchanged) with that of each neighboring node, a node determines from which neighbors to use Class 2 information and from which neighbors to use Class 1 information for the combined information. If several measurements of the local clock error are available for independent paths between the local clock and the master, and the statistical variance for each measurement is known, then the best estimate of the true error is a weighted sum of the measurements made for the different paths. This weighted sum is shown in (2) where the weighting factors  $W_p$  are those given by (3).

$$M_c = W_1 M_1 + W_2 M_2 + \dots + W_n M_n \quad (2)$$

$$W_p = \frac{\frac{1}{\sigma_p^2}}{\sum_{i=1}^n \frac{1}{\sigma_i^2}} \quad (3)$$

$M_p$  = a measurement value for the "p" path

$W_p$  = the weighting factor for the "p"th measurement

$\sigma_i^2$  = the variance of the "i"th measurement path.

The resulting measured value has a variance given by (4):

$$\sigma_c^2 = \frac{1}{\sum_{i=1}^n \frac{1}{\sigma_i^2}} \quad (4)$$

The variances used in the denominators of (3) and (4) are obtained by adding the variance due to the link between the local node and each neighboring node to the variance information provided by the corresponding node.

If all different paths passing timing information between the master and each local node were independent, the above procedure should provide an optimum estimate of the true clock error at the local node. However, since different long paths between two nodes are likely to share some common transmission links, independent paths do not always exist. The degradation due to the path dependencies should generally be acceptable. It is the assumption of independence that makes possible the use of simple distributed computation, with each node's computation based only on simple information with no need for any node to communicate timing information beyond its immediate neighbors.

This phase reference combining feature makes possible a quantitative system self-monitoring capability. Each local node has variance information for each measurement received from a neighboring node. Its own combined measurement information also has a computed variance. A variance for the difference between the measurement for any path and the combined measurement for the node can be computed. If the difference between the error measurement for any received signal and the local combined error exceeds a computed standard deviation for that difference by a predetermined factor, an alarm is activated.

When using this feature, the node serving as ultimate master reference should always reference its own clock and inform its neighbors that there are zero nodes between itself and its master. Every node connected directly to the master should inform its neighbors that it has one link between itself and the master. If any neighboring node using this same highest ranking master informs the master that there is other than one link between itself and the master, the master can interpret this as detection of a problem. For every node in a stabilized operating system, either each neighboring node should be reporting the same number of links between itself and the master as the local node, or it should be reporting one more or less than the local node, otherwise a problem exists and corrective action should be taken.

All variance information is introduced initially as variance of the error measurement process associated with a particular transmission link. The receiving node adds the variance for that particular link to the variance information provided by the neighbor at the transmitting end of the link. In most cases, for line-of-sight (LOS) microwave links, the primary contribution to the variance will be due to the phase tolerances on the transmitters and receivers at the two ends of the link. Therefore, the variance of the clock error measurement is relatively independent of the length of the LOS path, and the same variance could be used for all LOS links with the same number of repeaters using this grade of microwave equipment. The most degrading transmission medium (if we completely neglect those where the ionosphere is significantly involved) is the tropospheric scatter medium. Although investigation has shown that accurate time transfers can be made even over this very difficult medium [22], [23], it might be desirable to introduce a path length factor when this medium is used. Since only a small number of tropospheric scatter paths will be used in large communications networks, it might be treated as a special case.

#### *F. External Time References*

If the clock at each node has its phase directly related to a widely available suitable reference external to the network, such as coordinated universal time (UTC), the network will be synchronized, and the buffers should not overflow.

One source of such information is the 100 kHz Loran-C radio navigation system which is synchronized to UTC [24]-[28]. The pulsed signals of Loran-C generally permit timing measurements to be made on the groundwave prior to the arrival of the sky-wave signal. Loran-C stations are monitored by the Naval Observatory and controlled to provide an ac-

curacy of a few microseconds within the groundwave coverage range of about 1000 mi. In addition to the possible drawback of dependence on an external timing source, three limitations to the use of Loran-C for synchronization of a global military communications network such as the DCS are: 1) coverage only exists for about 75 percent of the northern hemisphere with no stations in the southern hemisphere; 2) the limited number of Loran-C stations serving a given area could be a target for enemy destruction; and 3) the signal propagation conditions in this frequency range permit the signals to be jammed by a transmitter located a long distance from the station and the characteristics of the signal make it susceptible to interference. Another source of timing external to the communications network will be the NAVSTAR satellites of the global positioning system (GPS) [29]-[31]. With 24 satellites in orbit, this system will avoid, to a considerable extent, the difficulties listed above for Loran-C and is expected to be much more accurate, but the receivers are expected to be relatively expensive.

#### *G. Precise Free-Running Clocks*

Precise free-running clocks capable of providing slip-free synchronous operation of a digital communications network for a period of a day or two might not seem to be a proper selection as a feature of a synchronous communications network, because the buffers will eventually either overflow or empty and require resetting. However, the use of precise free-running clocks, with periodic resetting of the buffers to avoid overflow, has been selected by the Joint Tactical Communications Office as the primary method of network synchronization for tactical switched digital communications systems [32]. It is also a desirable backup mode of operation for many other systems.

Failures of the timing/synchronization system are expected only rarely, and only a small percentage of maintenance personnel are expected to be skilled in the maintenance of the synchronization system. It might also be expected that the wartime maintenance and repair function for a military network would be intentionally impeded by the enemy. Free-running clocks can keep the communications system operating for extended periods of time at the expense of occasionally interrupting the traffic in order to reset buffers.

#### *H. Free-Running Prediction*

If the first five features listed above are used in the normal mode of operation, an accurate history of local clock performance relative to the ultimate master reference for the network can be kept at each node. This clock performance history could be used by the nodal microprocessor to predict the performance of the local clock for those periods of time when a reference external to the node is not available. This prediction could be used to compensate for the systematic free-running errors of the local clock until a network reference can be re-established.

The possibility of predicting the future performance of free-running quartz crystal clocks if a good measurement history were available might make it feasible to replace expensive cesium clocks at selected locations with less expensive quartz

clocks equipped with the necessary computational and compensational capability. Recognizing this possibility, DCA asked the Naval Observatory to study the predictability of high-quality quartz crystal oscillators. The study is presently being conducted.

### III. COMBINATIONS OF FEATURES IN MUTUAL AND MASTER-SLAVE SYSTEMS

#### *Mutual Synchronization*

A technique which has been very widely studied, but which has had little application to date, is called "mutual synchronization" [33]–[55]. In mutual synchronization, 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 phase of all signals received from its neighbors. Although it does not have the directed control feature, several of the other features are optional. It could be either single-ended or double-ended. It is usually considered to be inherently self-organizing, but corrective action is needed to prevent bad information from a failed part of the network from being used in the averaging process. It might also be desirable to change some system parameters following a failure in the network. A system using mutual synchronization could be provided with a master node simply by assuring that the node designated as master does not have its phase or frequency dependent on any of its neighbors. If it has a master, then self-organization requires provision for assigning a new master when required. Because of closed loops involved in mutual systems, it is impractical to employ the IMC feature. Mutual systems do combine phase references at the nodes; however, in mutual systems, this combining involves closed paths which tend to introduce additional noise as compared to the precision phase reference combining described earlier. There is no procedure in mutual systems for automatically optimizing the combining process during operation.

For mutual synchronization, a type-one control loop is usually employed [56]. Stability analyses for mutual synchronization systems, e.g., [34], have shown that in order for a mutual synchronization system to be stable, it requires a closed loop phase response that satisfies inequality (5). It has been indicated [56] that type-two loops with proportional-plus-integral filters

$$\left| \frac{\phi_o(j\omega)}{\phi_i(j\omega)} \right| = |H(\omega)| < 1, \quad \omega > 0 \quad (5)$$

of the form  $F(s) = \alpha(1 + a/s)$  do not satisfy this condition. Note from the corresponding expression for the magnitude of the closed loop function, given in (6), that for the natural frequency,  $\omega = \sqrt{\alpha a}$ , the inequality (5)

$$|H(\omega)| = \sqrt{\frac{\alpha^2 a^2 + \alpha^2 \omega^2}{(\alpha a - \omega^2)^2 + \alpha^2 \omega^2}} \quad (6)$$

is not satisfied. Phase jitter at the natural frequency will be amplified resulting in system instability. This restriction to the use of a type-one system can have disadvantages. In general, the type-one system provides less accuracy in the control

of a nodal clock than a type-two (or higher) system will provide. Although it provides an accurate frequency correction for an offset in the natural frequency of the local clock, the type-one system does so at the expense of a steady-state phase error. One company selected a digital, proportional-plus-integral, phase-locked loop for their master-slave system because it produces no steady-state phase error in the presence of a steady frequency offset and it can remember its past operating frequency after the input to the loop is removed [57]. If one or more clocks in a mutual system have unidirectional frequency drift, the type-one control loop limitation of mutual systems can cause a steady state frequency error [51]. Phase errors will accumulate with time (at a rate dependent on the frequency drift rate of the oscillator), and the buffers will eventually overflow. In systems with type-two control loops (must be master-slave systems), an oscillator with a frequency drift will produce a phase error proportional to the rate-of-drift (it will not accumulate with time). Oscillator frequency drift in a type-three system will not produce a phase error; at least one master-slave system was implemented with a third-order loop so that it would remember the oscillator drift rate when the input to the loop was removed [58], [59].

A network with single-ended mutual synchronization "breathes" with the environmental conditions. That is, the network is elastic and phase bulges occur in parts of the network, and unless it has a system master, the phase and frequency of the entire network can float around. With the phase and frequency of every node, both influencing and being influenced by the phase and frequency of all other nodes in the network (including the effects of interconnecting transmission links), there is no fixed reference from which to make measurements concerning malfunctions of the timing system. A disturbance in one part of a network with mutual synchronization can propagate throughout the network; however, the double-ended feature, when employed, can greatly reduce these disturbance effects.

#### *Master-Slave Synchronization*

Perhaps the simplest and most obvious of all communications network synchronization methods is the simple master-slave technique in which all nodes have their clocks slaved, either directly or through intermediate nodes, to a system master clock. This is accomplished by phase locking each nodal clock to one of the received signals. It has been widely recommended for civilian application [59].

Master-slave systems always employ directed control. Unlike mutual system features, there are no restrictions on the application of any of the other system features. Also in contrast to mutual systems, there are no restrictions on the type of clock control that can be used at a node. The system designer of a master-slave timing synchronization system has greater flexibility in choosing system parameters and configurations than the designer of a mutual system. Master-slave systems with both the self-organization feature and the double-ended feature have been called *time reference distribution*. If both the IMC feature and the phase reference combining feature are also included, it has been referred to as the *improved time reference distribution technique*.

The use of a microprocessor at each node to implement an automatic self-organization function is an attractive (and highly desirable in military applications) alternative to manual reorganization. Once available at a node the microprocessor can also be employed for other features and functions.

Of the various timing system features, the double-ended feature can have the greatest impact on transmitting and receiving equipment. Although little cost is added to newly designed equipment by also carefully specifying phase tolerances for *RF* portions of transmitting and receiving equipments, and by specifying desirable types of frame synchronization equipments and codes, these precautions can add considerable precision to the comparison of phases between clocks at different nodes. Simulations have shown that the double-ended feature contributes more than any other features to the frequency and phase stability of nodal clocks throughout the network [60], [61]. (This is true for both mutual and master-slave systems.) If a microprocessor is used for implementing a self-organizing feature, the same microprocessor can be used for processing the double-ended measurement information and converting the results to standard units of time, e.g., microseconds.

Whereas in a mutual system disturbing the frequency or phase of a clock affects every clock in the network, in master-slave systems such a disturbance can only affect those nodes receiving their timing reference either directly or indirectly from the disturbed node. If each node informs its neighbors of its measured but uncorrected error, some simple additional programming of the microprocessor used for implementing the second and third features can be used to provide the fourth feature, i.e., the independence of measurement and correction. This feature minimizes the propagation of a clock error in any direction from the node. This feature will rank second only to double-endedness in contributing to the phase and frequency stability of nodal clocks throughout the network [60], [61].

The fifth feature, i.e., phase referencing combining, can also be implemented in a master-slave system through the use of the same microprocessor. It gives promise of additional accuracy and stability, and is compatible with the second method of self-organization, which can have advantages over the first method.

Whatever combination of other features is selected, it will usually be desirable to provide the seventh feature, i.e., a precise free-running independent clock, as a backup mode of operation. It is preferable to interrupt communications traffic occasionally to reset the buffers rather than to have communications disrupted by a failure in the system used to synchronize the clocks. If the first five features are all provided it should be advantageous to provide the eighth feature, free-running prediction, which is an important extension to the backup capability provided by the seventh feature.

#### IV. DIFFERENCES BETWEEN CIVILIAN AND MILITARY APPLICATIONS

In a survey made for DCA, engineers for several civilian wide-band digital communications networks, without taking into consideration special military requirements, recommended application of a simple master-slave system, i.e., a

single-ended system without self-organization and without double-endedness [59], [60]. None of them felt that their customers would accept an occasional interruption of traffic to reset the buffers (required by the independent clock approach) if such an interruption could easily be avoided. Such interruptions are also undesirable for military applications, but the independent clock approach has been selected as the principal method of synchronization of tactical switched digital communications. Tactical systems operate under less than ideal conditions, and they can be expected to have many interruptions of traffic for reasons other than buffers overflowing or emptying, but buffers can be reset during these interruptions. However, interruption of traffic solely to reset the buffers is generally undesirable for military digital communications (particularly for long-haul communications), and it is not difficult to avoid this requirement. Another consideration is that cesium clocks used at major nodes of independent clock systems in order to reduce the frequency with which the buffers must be reset are quite expensive.

Planners of civilian systems recommended the master-slave technique because of its simplicity of design and operation. Since excellent crystal oscillators were available, there was no need for the mutual system's ability to work with inaccurate oscillators. One of the major advantages ascribed to mutual synchronization has been that it is "administration free." Studies mentioned by representatives of one company indicated that this simply was not true for their system and that mutual systems would require more administration than some other approaches [59].

Each of the civilian timing/synchronization systems surveyed had been planned for excellent reliability because loss of timing was considered to be potentially catastrophic. Operational experience from those systems, where available, showed failures to be very rare. In civilian networks, the failures are unlikely to occur simultaneously in widely separated geographical areas. Free-running clocks could be expected to provide satisfactory service for a considerable period of time following a failure. Required reorganization of the network timing function in such a civilian network could be manual (or at least manually initiated) under the control of a few specialists at a central location, and these same specialists could supervise all maintenance of the timing function for the network. For these reasons, in civilian networks, extensive redundancy and alternate timing paths were not considered necessary, and the self-organization feature might not be needed.

Military networks have a different situation. For a military communications network, any location where an important function (such as control and maintenance of the timing function) is centralized becomes an attractive target for the enemy. Whereas, in civilian systems prompt repairs can be expected before a failure to a timing system can lead to serious communications outages, the maintenance and repair function for a military network might be intentionally impeded by enemy action. Access to locations where repairs are needed might be severely restricted by the wartime situation, and the required skilled personnel might not be available when needed. In the military network, extensive damage might occur to widely separated areas simultaneously, thereby putting severe strain on the maintenance function. Therefore, the timing/synchroni-

zation system for military communications should be automatically self-organizing with no need for human intervention, and every communications path should be capable of supporting the timing function. The self-organization function should be distributed rather than centralized. Then, it will not present a particularly lucrative target for enemy action. The timing/synchronization function for a military digital communications system should also include a very effective self-monitoring and self-diagnosis capability, and a well-engineered maintenance manual in order to reduce the repair function to the simple replacement of the modules. This capability should be designed to permit all timing system maintenance to be performed by personnel not specializing in the timing function, and it should permit repairs to be made without disruption of service.

Of the four civilian systems surveyed, only one was newly conceived, designed, and built as a digital system, while the others were digital overlays to existing analog systems which were already employing pulse stuffing equipment for digital transmission between nodes of the analog networks. It is probably for this reason that only the newly conceived system used synchronous digital operation at all levels of multiplex. In the other systems, only the lowest levels of multiplex (group level or lower) were operated synchronously while the higher levels of multiplexing employed pulse-stuffing. This design, using asynchronous (pulse-stuffing) operation for the higher level multiplexers, minimized the need for high-speed variable storage buffers (probably unnecessary today because of technological advances). Variable storage buffers were only required for synchronous operation at the lower speeds of lower multiplexing levels. There could be some concern about applying self-organization in those civilian systems using pulse-stuffing at the higher multiplexing levels because of the number of lower level signals from which a timing path must be selected at a given node. Obviously, for very large communications systems with large switching nodes, this could contribute some complexity if the choice must be made from among all possibilities. However, considerably fewer choices are involved at the highest level of multiplex than at lower, and the choices are quite reasonable for the number of links at a node in military applications. It should be pointed out that the phase comparisons used for determining the control of the local clock can be made at the highest level of multiplex, and the buffers could still be placed at the low levels if the systems designer so chooses. This would permit using the higher accuracy that can be accomplished at the higher rates while allowing lower speed buffers to be employed.

The addition of a good reference from which measurements can be made can considerably simplify maintenance. This is one reason for referencing everything to a standard time, but there are other reasons also [21]. If all measurements are made relative to a standard time so that craftsman can use familiar concepts of a clock being either fast or slow by a particular amount, it has no mysteries except for being much more precise than familiar experience.

When the civilian systems were implemented, the very versatile, low-cost microprocessors of today were not available. Attempts were made to keep hardware simple. With today's microcircuits, where complexity is mostly on the chip, inter-

connections between microcircuits are relatively simple, concern for complexity takes on a new dimension. The microprocessor can be programmed to provide the information to the craftsman in the form that is most useful to him, rather than requiring him to adapt to what seemed to be a simple way to provide the hardware.

The actual condition avoided through the application of the timing/synchronization system is the overflow or emptying of the variable storage buffers. This depends on whether too many or too few bits have been received, which corresponds to a phase shift at the bit rate. Use of time variation rather than phase variation is preferred when referring to the timing/synchronization function so that it will be independent of the bit rate. The actual frequency error is of little concern so long as it does not exceed system bandwidths (except for its contribution to the phase errors). For this reason, specifications and standards for timing/synchronization systems should be written in terms of time (microseconds of allowable error) rather than frequency.

Military communications systems are subject to enemy jamming. A major method of resisting jamming is the use of spread spectrum signals produced by high rate pseudorandom phase shifting of the signal. Systems using wideband spread-spectrum signals for this purpose must be capable of rapidly synchronizing 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 acquisition search window. Similarly, military communications systems have a need for the extensive application of encryption. This adds another device that must obtain and maintain synchronization. Unfortunately, some of the different levels of synchronization in military systems must be obtained in sequence, which can further increase the time required to acquire synchronization; and although this time is usually small, it can increase greatly under jamming or other abnormal conditions. An extremely stable timing system that is immune from perturbation will help to satisfy these needs of a switched digital military communications system.

## V. CHARACTERISTICS NEEDED FOR A MILITARY APPLICATION

In this section, a number of characteristics needed for the timing/synchronization of switched digital communications networks are identified, discussed, and associated with the combinations of features described in preceding sections. (Another discussion of this topic, presented from a somewhat different viewpoint and in greater detail is found in [62] which lists eleven suggested attributes for timing in a digital defense communication system and provides reasons why each of those attributes is needed.)

### *Survivability*

The ability of the digital communications function to survive enemy actions is related to the ability of the timing/synchronization function to survive. The ability to acquire synchronization of spread-spectrum signals rapidly under jamming conditions is related to the accuracy and stability of the nodal

clocks which determine the size of the acquisition search window. This is one reason that nodes of the defense satellite communications system (DSCS) are equipped with cesium clocks which are maintained within a few microseconds of UTC(USNO). Because of the accuracy provided through application of clock disciplining corrections coordinated by the Naval Observatory, these clocks free-run most of the time with infrequent corrections to phase and/or frequency..

For survivability of the timing function, every communications link should also have the capability of being a timing reference link. To make the most effective use of this capability, a self-organization capability should also be provided. Then, only when failures of nonredundant equipment occur and/or communications with all neighboring nodes have been lost will it be necessary for the node to free-run. The stability of the nodal clock, phase and frequency error of the clock when entering the free-running period, and the ability to compensate for clock drift all contribute to determining the errors that accumulate during the free-running period. These errors in turn affect the rapidity with which synchronization of all elements of the communications system can be restored following a communications outage—particularly for acquisition under signal jamming conditions. Double-endedness, independence of measurements and correction, and phase reference combining, in that order, are important features for enhancing this capability.

Taking corrective action when a problem occurs is another aspect of survivability. The discussion of monitorability and self-diagnosis in a subsequent section indicates that self-organization, double-endedness, and independence of measurement and correction are each important features for this function. All of them are required for a good quantitative functional monitoring capability at every major node.

### *Reliability*

Reliability is closely related to survivability since timing system characteristics that help one will frequently help the other. Survivability generally refers to the ability to survive enemy action or natural disaster, while reliability refers to freedom from loss of service due to random failures in the equipment or facilities. A good network timing synchronization system should be designed to minimize failures and to be tolerant of those that do occur. For reliability, as for survivability, network operation ideally should not depend on the continued operation of any particular node or transmission link. The simple master-slave system, without self-organization, has the possibility of losing the master node or its connecting transmission links without provision for backup. For an external time reference, such as Loran-C, there is the possibility of losing the reference due to transmitter failure, station destruction, or signal jamming. Mutual systems are subject to reliability problems because of the network-wide propagation of errors and poor system monitoring capability.

### *Monitorability, Self-Diagnosis, and Maintainability*

In addition to making the network tolerant to failures, failures must be detected, isolated, temporarily accommodated by operational procedures (automatically where possible), and

repaired. It is important to detect pending timing failures long before any interruptions to communications traffic occur. Many types of failures that can affect the operation of a timing system cannot be detected by simply monitoring equipment voltages and currents. In some systems, buffer fill at the local node is the only information (other than monitoring voltages of local equipment) that is available for timing system monitoring. Such a timing system provides very little help in the detection or isolation of faults.

Since the effects of a fault in a mutual system can propagate throughout the network, isolating the cause can be difficult. In general, the effects of a fault in master-slave systems are restricted to particular timing paths, making the detection and isolation of the fault somewhat easier. In time reference distribution systems, particularly those using the independence of measurement and correction feature in addition to the self-organizing and double-endedness features, comparison of time reference signals from different paths can help identify a particular error measurement that differs significantly from those of other paths to the same node. The accuracy provided by these features permits the determination of significant trend information from the measurements which can be useful in predicting pending future problems. If the phase reference combining feature is also included, quantitative evaluation of the system errors also becomes possible, giving this approach much better information on which to base self-monitoring and self-diagnosis capabilities.

### *Accuracy and Stability*

In engineering terminology, the word "stability" has two common applications. One is the feedback control meaning which relates to a condition where an unstable system either breaks into oscillation or one of its parameters continues to increase (or decrease) until some other, usually undesirable, limit condition is reached. Of the various timing systems, only the mutual system is known to have the possibility of such instability, and it can be avoided in that system by good engineering design. Hence, the "stability" of primary concern in this section refers to the ability to continue without change, as is applied to the frequency stability of oscillators. The frequency stability and phase accuracy of the network significantly contributes to the capability to operate without slip in the free-running mode for extended periods of time. It also contributes to the ability to detect and identify pending failures by monitoring clock error trend information. It increases the precision with which other network timing monitoring and fault diagnosis capabilities can be applied, and, therefore, significantly contributes to their dependability. By essentially removing the signal transit time from the comparison of clocks at two nodes, the double-endedness feature prevents environmental conditions, which change the speed of signal propagation, from contributing inaccuracy or reducing the precision of clock error measurements. The independence of measurement and correction feature, permits the error in the clock at any node in the network, except the master, to be removed (within measurement tolerance) from the measurement of the clock error at any other node. Phase reference combining uses information from several paths to help to compensate for equip-

ment errors, in addition to providing further help in removing time-varying inaccuracies. Therefore, these three features are very significant for improving the accuracy and stability of the system. In a system with free-running clocks, the accuracy and stability of each node depends entirely on the characteristics of the nodal clock oscillator, while any system with a master has its mean frequency determined by that master with the amount of frequency and phase variation about that mean determined by the parameters of the system.

### *Flexibility*

Flexibility when applied to the communications timing system refers to freedom from timing system restrictions on the growth and extension of the network—growth not only in the number of users or the geographical area covered, but also in functional capability, including support of totally new functions. Since clocks accurately synchronized to UTC can support any of the functions that other timing approaches can support, and in addition many functions that other approaches could not support, such a system will provide the most flexibility in a communications timing system. Any features which enhance accuracy, therefore, enhance the flexibility of the timing system.

### *Interoperability*

A satisfactory timing/synchronization interface between any two digital communications systems where communications traffic originating in one of them must pass into or through the other is desirable. It is not likely that one communications system would accept a mutual timing relationship with a second system, giving that second system the possibility of generating undesirable perturbations in the first. The willingness of a communications system in one nation to slave its network timing to a communications system in another nation might be too much to expect, particularly for military communications systems. One approach that can be used in this situation is the plesiochronous approach (similar to independent free-running clocks) where each system internally uses whatever timing techniques best satisfy its own needs, but the clocks at the gateway nodes providing interfaces between the two systems are held to a frequency tolerance that assures that the buffers will not have to be reset more frequently than some acceptable rate.

Since UTC is an internationally accepted time standard, referencing communications systems to UTC would seem to be a logical readily acceptable choice for providing slip-free interfaces between communications systems in different nations. This would also provide additional redundancy by permitting communications systems to interchange timing reference with those navigation systems already referenced to UTC. At present, the DSCS contributes to the UTC coordination of some Loran-C navigation stations, and in turn Loran-C contributes to the synchronization of some DCS equipment.

## VI. ADVANTAGEOUS PRACTICAL TIMING SYSTEM FOR APPLICATION TO SWITCHED MILITARY DIGITAL COMMUNICATIONS NETWORKS

By providing a timing system with the properties listed below—survivability, reliability, monitorability, self-diagnosis,

maintainability, accuracy, stability, flexibility, freedom from propagation of errors, and interoperability with other systems—should be economically achieved.

1) Each node should be provided with an accurate and stable nodal clock from which all frequencies and phases for all transmitters are derived.

2) Each receiver's clock signal should be phase-locked to the received signal. Coordination between the receiver clock signal and the nodal clock is desirable. This can help to maintain synchronization during brief signal outages and to aid rapid reacquisition of synchronization after extensive outages and/or adverse signal conditions such as signal jamming.

3) The nodal clocks should be accurately coordinated with (synchronized to) coordinated universal time (UTC). When communications system use of UTC becomes widespread, it will permit slip-free (without planned interruption of traffic to reset the buffers) operation among different communications systems throughout the world. It can also enhance the survivability of the system by permitting compatible interaction with navigation systems which are referenced to UTC.

4) In coordinating the nodal clocks at major nodes, the timing system should employ all of the following features: 1) directed control, 2) double-endedness, 3) self-organization, 4) independence of clock error measurement at any node from correction of a clock at any other node, 5) phase reference combining 6) external references to UTC (at selected nodes only), and 7) precise free-running clocks as a backup mode of operation. It would also be desirable to use the information gathered during normal operation to predict clock performance during a backup free-running period and compensate for systematic drifts during that free-running period. The combination of all of these features would enhance accuracy and stability. They would also enhance monitorability, self-diagnosis, and maintainability, while reducing the propagation of errors. The increased accuracy and stability would enhance the flexibility. In addition to directly increasing the survivability and reliability of the network, the features would also provide secondary enhancement of these two characteristics through the improvements in accuracy, stability, monitorability, self-diagnosis, and maintainability.

As with most things, there are some situations where an exception is desirable. With satellite communications employing time division multiple access, an exception to property number 1 would permit the transmitter to be adjusted relative to the nodal clock. This is necessary because all signals, time sharing the satellite transponder, must arrive at the satellite at the correct time. It is therefore desirable to coordinate the timing of the signals as they arrive at the satellite with UTC; the flexibility provided by a system as described above would permit this. It is only necessary to provide buffers for transmitters in addition to those for receivers on these particular links, and the timing advantages to the overall communications system are still retained.

Although a timing system for a future switched digital communications network of the DCS has not been selected, a system employing all of the features discussed above is under active consideration.

The features listed above are advantageous for application at major nodes of military digital communications networks.

However, for those nodes with only one or two links to the rest of the network, a simple slave approach will be quite satisfactory in most cases.

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