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AN EVALUATION OF OPTIONAL TIMING/SYNCHRONIZATION FEATURES TO SUPPORT SELECTION OF AN OPTIMUM DESIGN FOR THE DCS DIGITAL COMMUNICATION NETWORK

D. B. Bradley, J. B. Cain, III, and M. W. Williard
Harris Corporation, Melbourne, Florida

ABSTRACT

This paper reports the results of one of the tasks of a study performed by Harris Corporation for the Defense Communications Agency (DCA). The task was to evaluate the ability of a set of timing/synchronization subsystem features to provide a set of desirable characteristics for the evolving Defense Communications System (DCS) digital communications network. The set of features relate to the approaches by which timing/synchronization information could be disseminated throughout the network and the manner in which this information could be utilized to provide a synchronized network. These features, which could be utilized in a large number of different combinations, include mutual control, directed control, double ended reference links, independence of clock error measurement and correction, phase reference combining, and self organizing. Some additional secondary features include smoothing for link and nodal dropouts, unequal reference weightings, and a master in the mutual control network. The set of desirable characteristics used in the evaluation of the features includes but is not limited to, frequency and phase accuracy, minimized propagation of disturbances in the network, slip free communications as a normal mode of operation, survivability under stressed conditions, interoperability with other networks, monitorability, precise time availability, minimized overhead requirements and cost effectiveness.

The utility of each feature (and combinations thereof) in providing the desirable characteristics was evaluated by means of combined analysis and computer simulation. One underlying assumption was that of a microprocessor based nodal synchronizer which implemented a second order digital phase locked loop with an extended range linear phase detector. The nodal microprocessor was also utilized in distributed control of the timing/synchronization subsystem network.

Some of the features of the simulation model included: 1) a single network topology of 20 nodes and 29 interconnecting links (a mixture of cable, satellite, microwave, and tropo), 2) normal variations which included an initial startup transient, normal path delay variations, natural clock frequency drifts, and link and nodal measurement jitter, 3) three sets of stress scenario and 4) sixteen combinations of the timing/synchronization subsystem features.

Nodal loop parameters used in the simulation were not optimized but were a compromise of several conflicting goals. These included maximizing utilization of the available reference information, providing for rapid entry into the network, coasting through reference outages and minimizing the effects of transient and steady state reference perturbations. A continuing portion of the study from which this paper was abstracted aims at optimizing these parameters.

The relative abilities of each of the sixteen combinations of the subsystem features in providing each of the desirable characteristics is presented in tabular form for easy comparison. Although this study is particularly concerned with the DCS application, the information developed could be applied to any extensive network.

I. INTRODUCTION

A large switched digital communications network gives rise to a set of desirable characteristics for its timing/synchronization subsystem. This set of desirable characteristics is identifiable from the mission of the communications network. There are a number of features which may be applied to the timing/synchronization subsystem in various combinations to provide the identified set of desirable characteristics to varying degrees.

This paper reports the results of one of the tasks of a study performed by the Harris Corporation for the Defense Communications Agency (DCA). The purpose of the task was to evaluate the ability of several timing/synchronization subsystem features to provide a set of identified desirable characteristics for this subsystem. Although the study was performed specifically for the future DCS digital communications network, many of the findings are also applicable to civilian digital communications networks. The approach used in the evaluation was combined analysis and computer simulation.

The set of identified desirable characteristics for the future DCS digital communications network timing/synchronization subsystem are discussed in some detail in [1]. For this reason, and since they are somewhat particular to the DCS network but primarily self explanatory, the set of desirable characteristics are merely listed in Section II. Since the set of features range from the exceedingly familiar to the possibly never-heard-of, a fairly detailed explanation of what they are is given in Section III. Attributes of the simulation model are given in Section IV. The results of the evaluation are discussed in Section V.

II. THE DESIRABLE CHARACTERISTICS

The set of desirable characteristics against which the features were compared included the following:

1. Frequency and phase accuracy.
2. Freedom of clocks from being disturbed by perturbations occurring further from the master than the local node.
3. Freedom from propagation of clock errors except that of the master.
4. No harmful propagation of a disturbance due to path delay variations or link dropouts.
5. Slip free as a normal mode of operation.
6. Survivability of the timing function.
7. Minimum overhead communications.
8. Precise time availability.
9. System level monitorability (functional as opposed to equipment monitoring).
10. Compliance with Federal Standard 1002.
11. Cost Effectiveness.
12. Interoperability of the digital communications system with other digital communications systems employing different synchronizing techniques.
13. Capability to automatically select a new network master.

III. THE FEATURES

There are several optional features which can be included in various combinations in the DCS timing/synchronization subsystem. Some of the features, however, preclude incorporation of certain other features. Also, some combinations of the features are more synergetic than others.

1. Independent Clocks (IC)

Figure 1 shows the form of this feature. This feature precludes the attainment of a truly synchronized communications network due to the unavailability of ideal clocks. However, it provides a basis for many comparisons and it is also a natural fall back configuration for the directed or mutual control features, when in times of stress, all references are temporarily lost. It is spoof proof, its set up time minimal, and for a tactical military communications mission it may very well be the best choice. It is conceptually simple from the standpoint of the timing subsystem itself but it is not necessarily the simplest from the standpoint of the digital communications equipment designer or user, because lack of a truly synchronized network implies occasional resetting of communications buffers, as well as an increasingly complex system of pulse stuffing to accommodate growing multiplexing and switching needs. For a given quality of communication it is not necessarily the lowest cost system due to the higher implied quality of nodal clocks. Also, to the degree that survivability is reflected in the probability of bit slips and the ability to monitor the system for impending failures, it does not necessarily provide as survivable a network as certain combinations of the other features, all of which are precluded by independent clocks. Since independent clocks do not lead to a synchronous network it was not included in any of the simulations and will not be further considered in this paper.

2. Directed Control (DC)

The form of the directed control feature is shown in Figure 2. It consists of a tree network of selected communications links over which timing information is passed from master node to all immediate neighbor nodes. These immediate neighbor nodes in turn pass timing information from their nodal clocks to their immediate neighbors who are farther removed from the master. The timing information only flows in one direction of the duplex links, i.e., away from the master. This is the central idea of a master slave network which is a particular case of directed control. Since there are no closed loops in the network, this feature has no network stability problems. It is a widely used feature in military and civilian networks [2,3,4]. It results in a synchronized network in which all nodes have the same average frequency. When combined with elastic communications buffers of sufficient size, short term perturbations will not cause bit slips. Thus the network should be able to support communications without slips or scheduled resetting of communications buffers for an indefinite period of time.

3. Mutual Control (MC)

Figure 3 shows the form of the mutual control feature. It is the antithesis of directed control. Each node takes a weighted sum of the phase error of its local clock relative to that of signals received from all of its immediate neighbors to determine a correction signal to apply to its local clock. Since there are numerous closed loops in the network, care must be taken in the selection of error signal processing parameters at each node in order to insure network stability. The network frequency under mutual control is a function of the weighted average of the individual nodes natural frequencies and the path delays of the network. This feature has been widely studied from a theoretical standpoint, mainly to investigate the questions of network stability and the sizes of transient and steady state phase errors in the system [5,6,7,8,9,10,11,12,13,14] but no major network has selected this feature. It's most touted attribute for a military mission is its survivability.

4. Double Ended Reference Links (DE)

Figure 4 shows a model for double ended reference links. This feature provides the capability to remove the effects of transmission delay time in the time reference information. Each node in the timing hierarchy transmits to each of its immediate neighbor nodes its clock reading as well as the difference between its clock and that received from its immediate neighbor. This is sufficient information to remove the propagation time from the reference information. To see how this works, let $K_A = T_A - T_B + D_{BA}$ be the difference between node A's clock reading and that of node B. Notice that the propagation time from B to A has been explicitly accounted for by the term D_{BA}. Similarly, let $K_B = T_B - T_A + D_{AB}$ be the difference between the reading of node B's clock and that of node A with propagation time from A to B explicitly expressed by D_{AB}. Now node B may determine the error of its clock relative to that of node A to within one-half the asymmetry of the duplex link propagation times by computing

$$\frac{K_A - K_B}{2} = (T_A - T_B + D_{BA}) - (T_B - T_A + D_{AB})$$

$$= (T_A - T_B) + (D_{BA} - D_{AB})/2.$$

The asymmetry $D_{BA} - D_{AB}$ of a duplex link is expected to be quite small if similar equipment and the same transmission medium is utilized in the forward and reverse paths.

5. Independence of the Clock Error Measurement at Any Node from the Correction of Clock Error at Any Other Node (ICEM&C)

This is a feature which may be used to remove the effects of phase errors in clocks intermediate between the local node and the network master. This is accomplished by passing measured but uncorrected errors down the timing chains. Figure 5 shows how this is accomplished. When this feature is used in conjunction with double ended reference links and directed control, each node of the network is effectively tied to the network master. This feature cannot be effectively applied with the mutual control feature because in general there is no definit hierarchical path from the local node back to an ultimate reference.

6. Phase Reference Combining (PRC)

Figure 6 shows a model for the phase reference combining feature. This is a feature applicable for use in conjunction with DC, DE and ICEM&C which tends to reduce the effects of cumulative measurement errors in reference information arriving at nodes far removed from the network master. This is done by combining reference information received at a particular node over the parallel paths from the network master. It is designed to make good use of all the available reference information while carefully avoiding closed loops in the network. Two classes of two types of information are passed through the system when this feature is utilized. The two types of information are the actual measured values of the reference information and an estimate of the statistical variance in the measured value of the reference information. The statistical variance is obtained from design parameters of the network components. It is used to determine how to weight the measured reference information received over the various parallel paths. The two classes of information are called class 1 and class 2. At a particular node class 1 information of both types is obtained from neighbor nodes strictly above the local node in the network hierarchy. It is combined and used to discipline the local clock. The combined class 1 information is also passed to neighbor nodes not lower in the hierarchy than the local node. The class 2 information is obtained from neighbor nodes not lower in the network hierarchy than the local node. It is combined and passed to neighbor nodes lower in the hierarchy than the local node. The method used to combine the reference information is to weight it inversely proportional to the estimated variance.

This feature also provides for an elaborate monitoring capability.

7. Self Organizing (SO)

This feature is concerned with a scheme for distributed self organization of the network hierarchy. In a system that does not utilize the PRC feature the implementation is very similar to that described by Darwin and Prim [15]. Each node is assigned a rank with the network master being assigned a higher rank than any other node. The first alternate master is assigned a rank lower than the master but higher than any other node, etc. Each link is assigned a demerit number depending on the quality of the link. The object of the scheme is for each node to reference the highest ranking node through the highest quality path. It is shown in [15] that a network will actually do this in a stable manner when all rules are utilized.

For networks using the PRC feature as described by Stover [16] the link demerit information is essentially contained in the variance information so it is only necessary to know the number of intervening nodes between each node and the master reference, as well as the nodal rankings.

8. Master in Mutual System (MIM)

One of the disadvantages of the mutual control feature is that the network frequency may take random walks. This may be avoided by allowing one node to be the master, i.e., this master node does not reference any other node of the network. The result is that the long term average frequency becomes that of the master node.

9. Smoothing for Link Dropouts and Reference Switching (SLD&RSS)

The technique most commonly used to discipline the local clock is a second order phase locked loop. A step change in reference phase at the input to such a device results in a spike in output frequency whose peak amplitude is equal to $2\zeta\omega_n\Delta\phi$, where ζ and ω_n are parameters of the phase lock loop and $\Delta\phi$ is the reference phase change. This frequency spike can have a large peak amplitude and is quite undesirable. Fortunately,it can be avoided.

In a network using mutual control dropout smoothing consists of remembering the value of phase error relative to each reference immediately before the dropout. The remembered value is then applied through a decaying multiplier for a period of time sufficient to allow the remaining reference errors to slowly readjust, thereby avoiding the large spike in output frequency.

In a directed control network utilizing a second order loop of the integral plus proportional type the integrator voltage may be adjusted to exactly compensate for the difference between the old and new reference errors. Since the integrator has a long time constant the output frequency changes very slowly to compensate for the difference in phase references.

IV. THE SIMULATION MODEL

A computer simulation model was developed to help evaluate the ability of the set of features described in Section III to provide the set of desirable characteristics listed in Section II, though primarily for characteristics 1 through 6. This model consisted of the following:

- A nodal synchronizer
- A network topology
- A set of normal link and nodal variations
- A set of stress scenarios
- A set of feature combinations

1. The Nodal Synchronizer

Figure 7 shows a simplified functional block diagram of the nodal synchronizer. The weight and sum function is utilized in mutual control systems as well as directed systems utilizing the PRC feature although the implementation will be considerably different for the two cases. Under mutual control all available references are normally selected except that failed references must be deselected. Provisions are made for either a VCXO which is directly controlled by the loop filter output or an atomic clock whose output is indirectly controlled by means of an outboard phase stepper. The phase detector(s) was modeled as an extended range linear device. The loop filter was one of two types, having transfer function $\frac{a}{s+a}$ or $\frac{s+a}{s}$. The phase locked loop employing a loop filter of the first type results in a type 1 loop while one employing a loop filter of the second type results in a type 2 loop. The type 1 loop tracks a constant frequency offset (local clock's natural frequency offset from reference frequency) with a constant nonzero error signal out of the phase detector. The type 2 loop tracks a constant frequency offset with a constant zero error signal out of the phase detector. In order to avoid network instability problems only the type 1 loop was utilized with the mutual control feature. Either the type 1 or type 2 loop may be used with the directed control feature but the simulations were run almost exclusively with the type 2 loop because its performance is clearly superior to that of the type 1 loop. Figure 8 shows a baseline model for the phase locked loop. For a detailed explanation of such devices see tutorial papers [17] and [18]. From this model the following transfer functions for the type 1 and type 2 loops can be derived:

$$\text{Type 1:}\quad \frac{\theta_o(s)}{\theta_i(s)} = \frac{\omega_n^2}{s^2+2\zeta\omega_n s+\omega_n^2}$$

$$\text{where } \omega = \sqrt{ak_v} \text{ and } \zeta = \sqrt{a/4k_v}$$

$$\text{Type 2:}\quad \frac{\theta_o(s)}{\theta_i(s)} = \frac{2\zeta\omega_n s+\omega_n^2}{s^2+2\zeta\omega_n s+\omega_n^2}$$

$$\text{where } \omega_n = \sqrt{ak_v} \text{ and } \zeta = \sqrt{k_v/4}$$

Table 1 shows the loop parameters used in the simulation.

TABLE 1

Loop Parameters for Simulation

	ζ	ω_n (rad/s)
Type 2-DC-Quartz	4	5.6×10^{-5}
Type 2-DC-Cesium	2	1.12×10^{-5}
Type 1-DC&MC-All	1	1.52×10^{-3}

2. Network Topology

The topology of the network used in all simulations is shown in Figure 9. It was chosen to represent a skeleton of the DCS network in that link distances were chosen similar to those that will actually be utilized in the DCS network The four gateway nodes were assumed to connect between the North American and European continents.

3. Normal Link and Nodal Variations

The normal link variations were modeled as sinusoidal length variations about the nominal length. All except the tropo links were modeled with a period of one day. Measurement jitter terms were added for each link and each node for some of the simulation runs. Initial frequency offset was assumed for each clock to give an initial transient. Quartz clocks were given a linear drift in natural frequency. These variations are summarized in Table 2.

4. Stress Scenarios

The stress scenarios consisted of selected link failures, node failures, and clock frequency changes occurring at various times throughout the simulation runs. Each run represented an elapsed time of 300,000 seconds. The three sets of stress scenarios were called General, Low Level, and High Level. The General stress scenario was designed to measure how closely nodal phases and frequencies at various points of the network would hold together under a variety of disturbance events. The Low Level scenario was designed to measure any upward propagation in the network hierarchy. The High Level scenario was designed to measure propagation either upward, laterally, or downward. The General stress scenario is shown in Table 3.

5. Feature Combinations

A total of 16 feature combinations were selected for incorporation into a simulation run. These are shown in Table 4.

V. THE RESULTS AND CONCLUSIONS

Results:

Simulation runs were made for each of sixteen combinations of features and three stress scenarios for a total of 48 simulation runs. Each simulated run was for a duration of 300,000 seconds. Outputs consisted of plots of absolute frequency error and phase error relative to node 1 of Figure 9. Figures 10-15 show samples of these plots. The means and standard deviations of the frequency and phase errors were also obtained for each of the monitored nodes over the duration of the simulation run. The output plots and statistical data were then compared manually for those desirable characteristics which could be evaluated by this technique (primarily characteristics 1 through 6 of Section II). The other seven desirable characteristics were somewhat amenable to analysis in light of the broad understanding of the overall problem that was gained through the process of developing the simulation model. From this narrow simulation data and the broad problem understanding, relative rankings of the ability of each of the 16 feature combinations to provide each of the desirable characteristics was obtained. These rankings are shown in Table 5. In order to distinguish

Table 2

Normal Link and Nodal Variations

LINKS:

Link Type	1σ Measurement Jitter	Normal Link Variations
Microwave	10	$\Delta L = 10^{-5} x L_0 x \sin(\omega_d t+\phi_r)$
Cable	10	$\Delta L = 3x10^{-6} x L_0 x \sin(\omega_d t+\phi_r)$
Satellite	30	$\Delta L = 5.04x10^{-5} x L_0 x \sin(\omega_d t+\phi_r)$
Tropo	20	$\Delta L = 10^{-8} x L_0 x \sin(\omega_x t+\phi_r)$ $(10^{-4} x L_0 x \sin(\omega_d t+\phi_r)$ $+2x10^{-5} L_0 x \sin(8.7x10^{-4} t)$

where $\phi_r=0$, $\omega_d=7.3x10^{-5}$ rad/s, $\omega_x=3.5x10^{-3}$ rad/s and L_0=nominal link distance

NODES:

Node Numbers	1σ Measurement Jitter
1,2,13, & 14	10
3,4,5,6,7,8,15 & 16	20
9,10,11,12,17,18,19, & 20	30

Nodal variance and weighting factor calculation

$$\sigma^2 = \sigma_N^2 + \frac{1}{\sum_{i=1}^{n}\left(\frac{1}{\sigma_i^2+\sigma_{Li}^2}\right)} \; ; \quad \omega_i = \frac{\frac{1}{\sigma_i^2+\sigma_{Li}^2}}{\sum_{j=1}^{n}\left(\frac{1}{\sigma_j^2+\sigma_{Lj}^2}\right)}$$

where σ_i^2 or σ_j^2 is the input variance from reference i or j, σ_{Li}^2 is the variance associated with the link between the reference node and the local node and σ_N^2 is the nodal variance.

Table 3

General Stress Scenario

- Apply initial transient to all nodes
- Apply normal link delay variations to all links
- Apply clock drifts to all quartz clocks

50000 s - Node 6 clock starts ramp increase in frequency of 1.16×10^{-14} x fo per second and continues until 75000 seconds.

60000 s - Node 13's clock makes step decrease in natural frequency of 3×10^{-11} x fo.

75000 s - Node 6's clock begins ramp decrease of 1.16×10^{-14} x fo per second and continues until 100000 seconds.

100000 s - Node 13's clock makes step increase of 3×10^{-11} x fo in natural frequency.

150000 s - Link 6-5 fails.

Node 5 free runs until 150300 seconds and then references Node 7 if self-reorganizing.

Node 5 free runs until 160800 seconds if nonself-reorganizing..

200000 s - Link 1-2 fails.

Node 2 free runs until 200300 seconds it references Node 6 if using self-reorganization, it free runs to 210800 seconds for nonself-reorganization.

250000 s - Node 13 fails.

Node 16 free runs until 250300 seconds at which time it references Node 15 if using self-reorganization.

It free runs to 271600 seconds if using non-self reorganization.

Monitor: Nodes 5, 6, 7, 2, 11, 13, 16, 17, 15, and 3

Links 7-5, 1-6, 1-7, 6-2, 5-11, 1-13, 13-16, 16-17, 14-15, and 2-3.

Table 4

Feature Combinations for Simulations

1. Directed control with Type 1 loop (mutual sync loop parameters).
2. Directed control with Type 2 loop.
3. Mutual control with equal weighting.
4. Mutual control with unequal weighting.
5. Mutual control with a _master_ and equal weighting.
6. Mutual control with a _master_ and unequal weighting.
7. Mutual control with dropout _smoothing_ (and equal weighting).
8. Directed control with Type 2 loop and _double-ended_.
9. Mutual control with equal weighting and _double-ended_.
10. Mutual control with a master, unequal weighting, dropout smoothing, and double-ended.
11. Directed control with double-ended and _independence of measurement and correction_.
12. Directed control with double-ended, independence of measurement and correction, and phase reference combining.

SELF-ORGANIZING RUNS

13. Directed control with Type 2.
14. Directed control with double-ended.
15. Repeat Run No. 11.
16. Repeat Run No. 12.

Table 5 - Summary of Results

Characteristic / Feature Combination	1 Frequency Accuracy	2 High Level Clocks Not Disturbed by Perturbations at Lower Levels of Network	3 Clock Errors Do Not Harmfully Propagate to Other Nodes	4 Path Delay Variations and Dropouts Do Not Harmfully Propagate to Other Nodes	5 Slip Free	6 Survivable
1. DC-1-SE	13	1	3	--	--	--
2. DC-2-SE	12	1	3	10	2 (63)	9
3. MC-EW-SE	15	8	4	14	4 (100)*	14
4. MC-UEW-SE	16	5	4	15!	4 (100)*	12
5. MC-M-EW-SE	9	7	3	12	4 (100)*	11
6. MC-M-UEW-SE	10	6	3	13	4 (100)*	10
7. MC-DOS-EW-SE	14	4	4	11	4 (100)*	13
8. DC-2-DE	7	1	3	8	1 (13)	6
9. MC-EW-DE	8	3	4	9	3 (73)*	7
10. MC-M-UEW-DOS-DE	3	2	2	7	3 (73)*	3
11. DC-2-DE-ICEM&C	6	1	1†	6	1 (13)	5
12. DC-2-DE-ICEM&C-PRC	5	1	1†	5	1 (13)	4
13. DC-2-SE-SO	11	1	3	4	2 (63)	8
14. DC-2-DE-SO	4	1	2	3	1 (13)	3
15. DC-2-DE-ICEM&C-SO	2	1	1†	2	1 (13)	2
16. DC-2-DE-ICEM&C-PRC-SO	1	1	1†	1	1 (13)	1

In "Slip Free" column numbers in parenthesis indicate buffer sizes needed to avoid slips.

* Requires special provisions with quartz clock to cancel accumulated phase error every 100 days.

† Not harmful according to criterion.

! Potentially harmful according to definition.

Table 5 - Summary of Results
(Continued)

Characteristic / Feature Combination	7 Overhead Requirement (Bits/Sec)	8 Precise Time Available	9 Monitorability		10 Federal Standard 1002	12 Inter-Operability	13 Selects New Master	11 Cost Effective	
			Incre-Mental	Overall				Time (% Of 8080A)	Space (Bytes)
1. DC-[illegible]-SE	--	No	Fair	Good	Fair	Fair	No	0.77	395
2. [illegible]SE	--	No	Fair	Good	Fair	Fair	No	0.77	395
3. MC-EW-SE	--	No	Poor	Good	Poor	Poor	No	7.20	594
4. MC-UEW-SE	--	No	Poor	Good	Poor	Poor	No	7.20	594
5. MC-M-EW-SE	--	No	Poor	Good	Fair	Fair	No	7.20	594
6. MC-M-UEW-SE	--	No	Poor	Good	Fair	Fair	No	7.20	594
7. MC-DOS-EW-SE	--	No	Poor	Good	Poor	Poor	No	7.20	594
8. DC-2-DE	63	Yes	Good	Good	Fair	Fair	No	2.24	731
9. MC-EW-DE	63	No	Poor	Good	Poor	Poor	No	10.55	1045
10. MC-M-UEW-DOS-DE	63	Yes	Poor	Good	Good	Good	No	11.60	1164
11. DC-2-DE-ICEM&C	126	Yes	Very Good	Good	Good	Good	No	2.42	802
12. DC-2-DE-ICEM&C-PRC	171	Yes	Very Good	Good	Good	Good	No	10.65	1847
13. DC-[illegible]-SE-SO	76.5	No	Good	Good	Fair	Fair	Yes	1.46	702
14. DC-2-DE-SO	139.5	Yes	Very Good	Good	Good	Good	Yes	2.93	1009
15. DC-2-DE-ICEM&C-SO	202.5	Yes	Excellent	Very Good	Very Good	Very Good	Yes	3.11	1109
16. DC-2-DE-ICEM&C-PRC-SO	247.5	Yes	Excellent	Very Good	Very Good	Very Good	Yes	11.34	2154

harmful versus non-harmful propagation of disturbances, a criterion of harmful propagation was derived. This was primarily concerned with the probability that a disturbance (clock or link) would cause a bit slip in the input communications clock recovery loop (different from the output nodal clock) of a node down stream from the disturbance. This was predicated on our knowledge of the parameters of the clock recovery loops in existing DCS equipments. New equipments can be designed to handle disturbances of a given size and speed by selection of these parameters, albeit at a possible signal to noise ratio penality. The criterion is listed below:

$\left\|\frac{\Delta\omega}{\omega_o}\right\| \geq 10^{-7}$	Definitely harmful.
$10^{-9} \leq \left\|\frac{\Delta\omega}{\omega_o}\right\| < 10^{-7}$	Potentially harmful and it causes SNR degradation.
$10^{-10} \leq \left\|\frac{\Delta\omega}{\omega_o}\right\| < 10^{-9}$	Unlikely to cause observable problems.
$\left\|\frac{\Delta\omega}{\omega_o}\right\| < 10^{-10}$	No effects on slip rate or SNR.

Using this criterion against the desirable characteristic "clock errors do not harmfully propagate to other nodes" one clock error of 10^{-9} p-p was judged to be potentially harmful to some node of the network under each set of feature combinations except the ones indicated. In the "precise time availability" column the YES entries do not mean that precise time is automatically provided by this combination of features but rather indicate that the essential ingredients are provided to support an add-on unit to the nodal synchronizer which gives precise time. In the column titled "selects new master" the mutual control systems utilizing a master node (Runs 5,6, and 10) had no provisions for automatic selection of a new master and therefore were marked with NO. However, a real implementation of this combination of features would almost certainly require provisions for automatic selection of a new master.

Conclusions:

All features tend to do the things which they are logically designed to do. They all provide contributions to the attainment of subsets of the desirable characteristics.

Directed and mutual control tend to provide for a synchronized network with long term frequency averages at each node the same as or very close to the network frequency. Additionally, directed provides for long term zero average phase error and contains disturbances in the branch in which they occur and only propagates them downward.

Double-ended removes path delay variations.

Smoothing removes undesirable large frequency spikes due to step changes in reference phase.

Master in mutual system provides definite network frequency. Unequal weighting in mutual system tends to improve short term accuracy but can cause larger transients with link and nodal failures.

ICEM&C removes disturbances due to independent clock errors in a branch of nodes.

Phase reference combining is effective in combating measurement jitter and also decreases expected percentage of time that nodes may be without a reference during periods of stress.

- The simulations were performed with limited network size and connectivity and for very limited run time. With larger networks and connectivity and much longer run time the expected benefits from the additional features will be accentuated.
- Provisions for additional features (over and above mutual or directed control) does not seem excessive in that overhead data requirements are quite small and processor time and storage space is small in comparison with the capabilities of presently available microcomputers.
- The most striking of the additional features is the double-ended reference links.
- Although, according to the definition of harmful transient, most of the disturbances due to clock errors or path delay variations and dropouts experienced in the simulation were judged to be non-harmful these events were mostly isolated and their amplitudes were chosen to represent typical events. In a real stressed environment it is possible that several such events could occur closely enough together in time and at the correct points in the network to be harmful. The tabular summary

indicates the combinations of features least vulnerable to such threats.

- Precise time can be provided as an add-on feature to any scheme of control that has a master and utilizes double-ended links. The add-on does not affect the manner in which the nodal synchronizer controls the local clock's phase and frequency. Additional features may be used to improve the accuracy of disseminated time.

- Without a master the network frequency of the mutual control system may wander which makes interoperation difficult. Provision of a master would then dilute "claimed" survivability of this method of control. Overhead is also required to automatically select alternate masters.

- A disturbance occurring anywhere in the mutual control network propagates to all nodes of the network.

- In order to ensure network stability in a mutual control system limitations are placed on the type of nodal loop. The disadvantages are as follows:

  1. Type 1 loop tracks constant frequency offset with non-zero phase error.
  2. Type 1 loop tracks constantly drifting clock with non-zero frequency error and constantly increasing phase error.
  3. The above two characteristics tend to degrade the short term accuracy of the network.
  4. Characteristic 2. above indicates need for special provisions for drifting clocks, size buffer for lifetime operation, periodic adjustment of natural frequency, or other means.

- Error history at each node in mutual control system is a complex function involving network topology, reference weightings, stress events, and individual clock performance at all other nodes of the network. This makes it more difficult to devise a control strategy during intervals when a reference is not available. Thus, survivability is decreased. This complex history also lessens the utility of monitored parameters at each node.

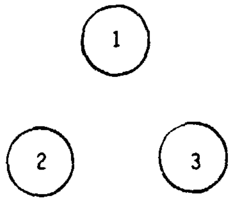


Fig. 1: Independent Clocks Network Model

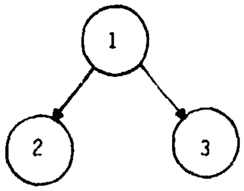


Fig. 2: Directed Control Network Model

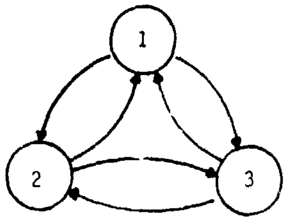


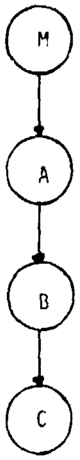
Fig. 3: Mutual Control Network Model

$$T_a, K_a = T_a - T_b + D_{ba}$$

$$T_b, K_b = T_b - T_a + D_{ab}$$

$$\frac{K_a - K_b}{2} = T_a - T_b + \frac{D_{ba} - D_{ab}}{2}$$

Fig. 4: Double Ended Reference Link Model



$$\Delta T_{AM} = T_M - T_A$$

$$\Delta T_{BM} = T_A - T_B + \Delta T_{AM}$$

$$\Delta T_{CM} = T_B - T_C + \Delta T_{BM}$$

Fig. 5: Independence of Clock Error Measurement and Correction Model

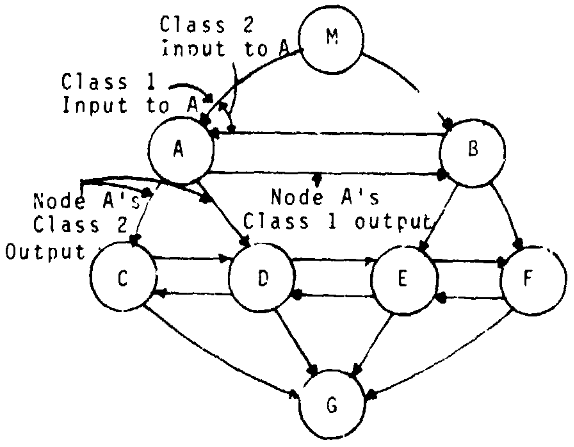


Fig. 6. Phase Reference Combining Model

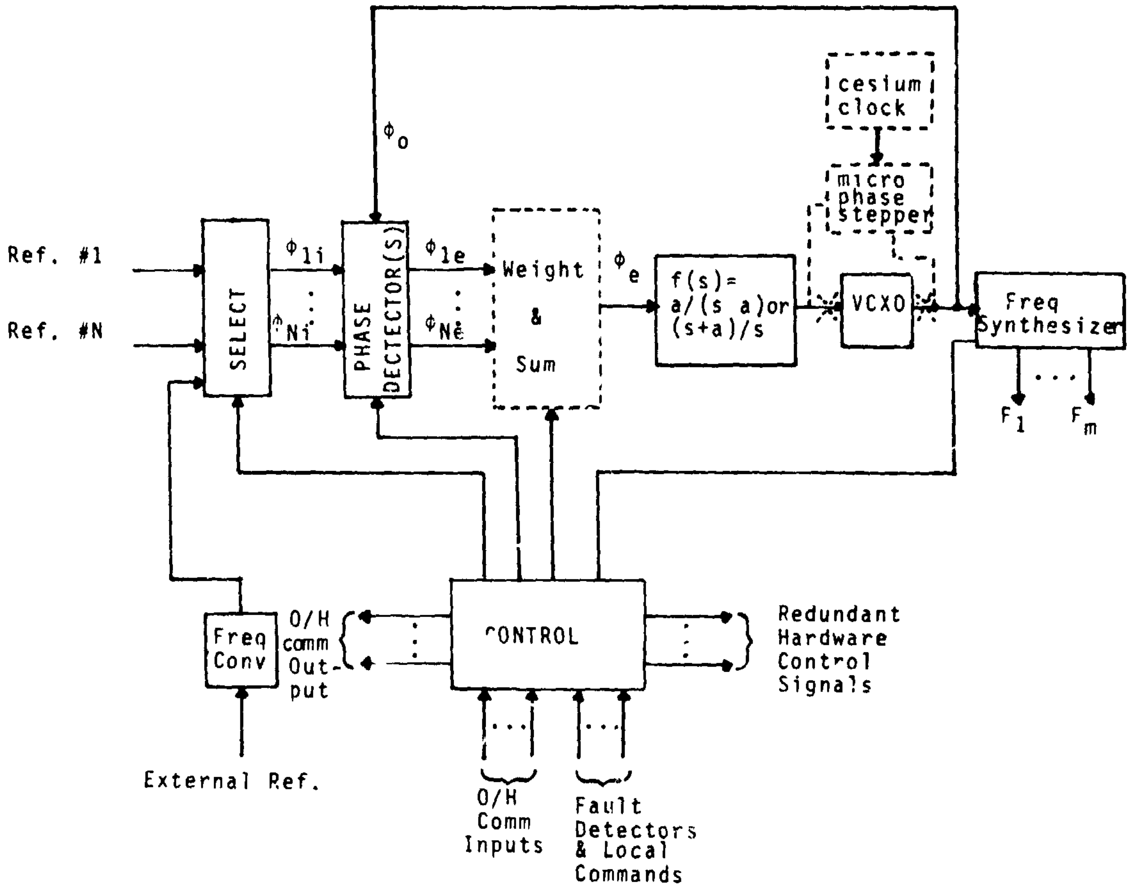


Figure 7: Functional Block Diagram for Nodal Synchronizer

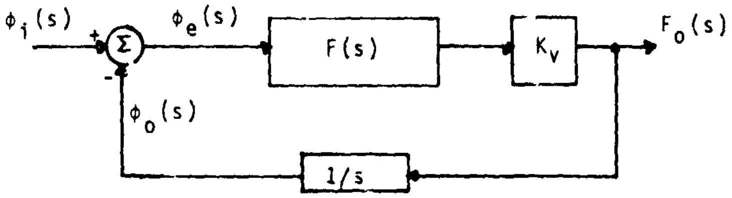
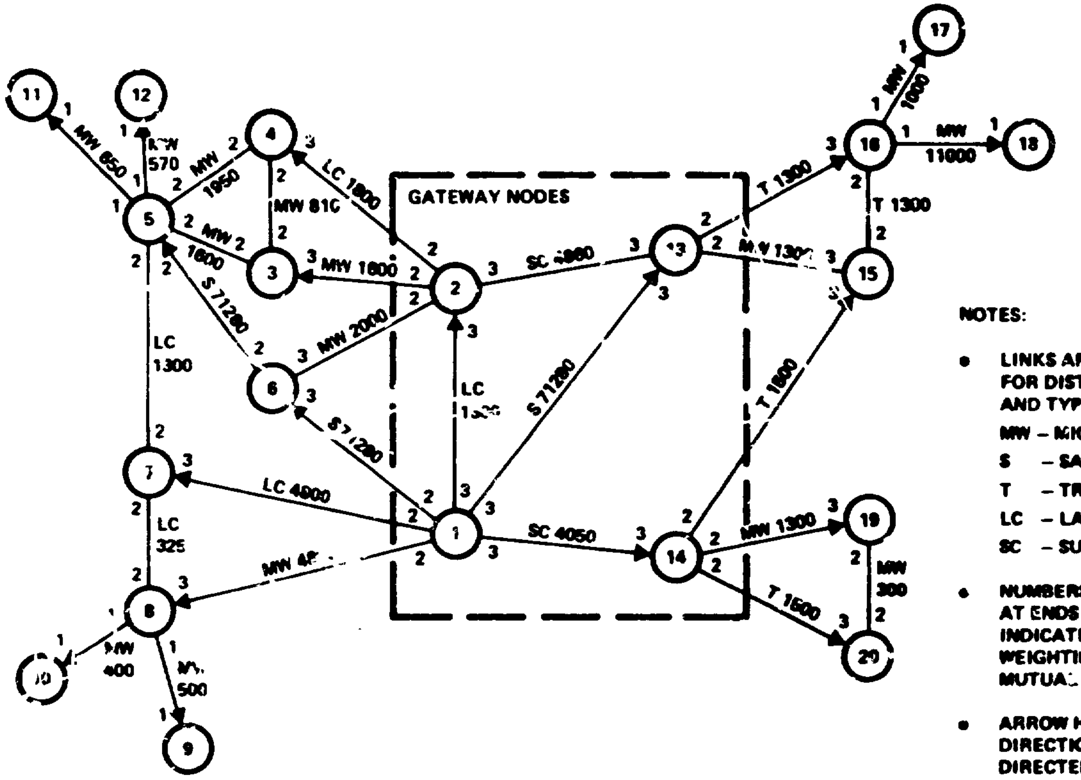


Figure 8: Baseline Phase Locked Loop Model



NOTES:

- LINKS ARE MARKED FOR DISTANCE IN km AND TYPE AS FOLLOWS.
  MW – MICROWAVE
  S – SATELLITE
  T – TROPO
  LC – LAND CABLE
  SC – SUBM RINE CABLE
- NUMBERS 1, 2, AND 3 AT ENDS OF LINKS INDICATE SIGNAL WEIGHTINGS FOR MUTUAL CONTROL
- ARROW HEADS INDICATE DIRECTION FOR DIRECTED CONTROL

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Figure 9: Network for Si

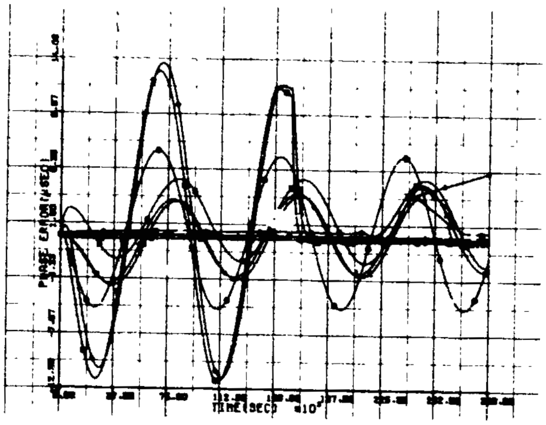

Figure 10 - Phase plot for directed control with type 2 loop and without drop-in smoothing and coating. General stress scenario.

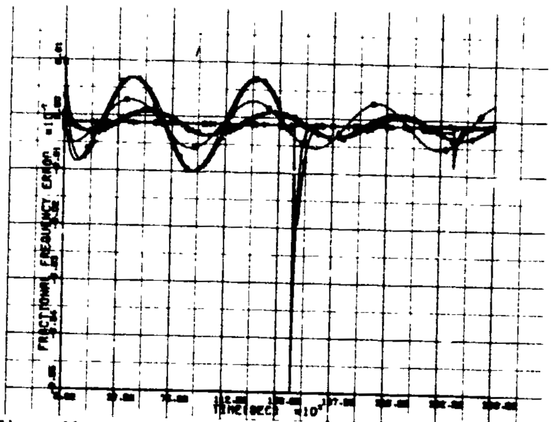

Figure 11 - Frequency plot for directed control with type 2 loop and without drop-in smoothing and coating. General stress scenario.

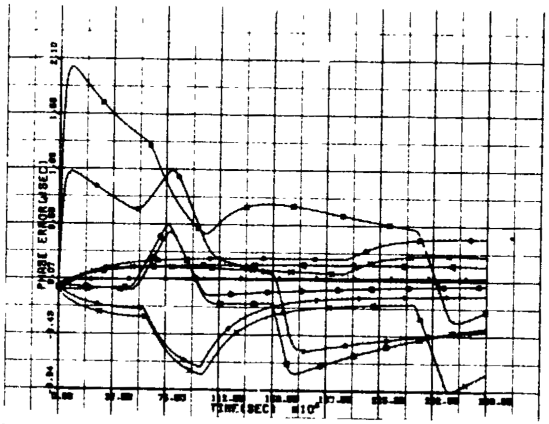

Figure 12 - Phase plot for directed control with type 2 loop and double-ended. General stress scenario.

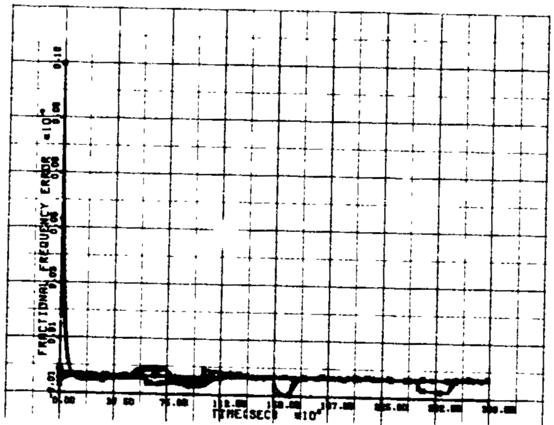

Figure 13 - Frequency plot for directed control with type 2 loop and double-ended. General stress scenario.

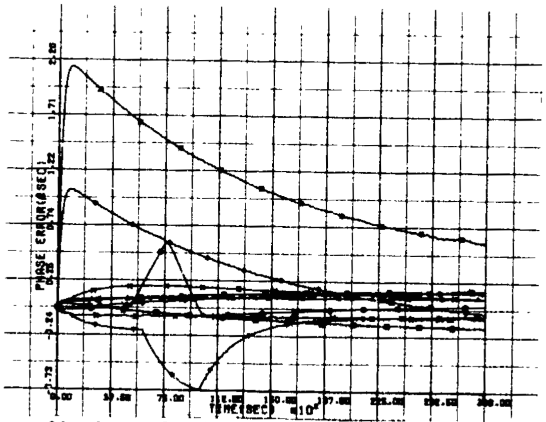

Figure 14 - Phase plot for directed control with double-ended, independence of measurement and correction, phase reference combining and self organizing. General stress scenario (with jitter).

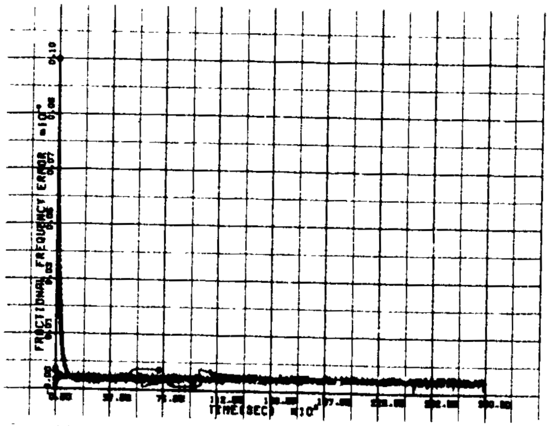

Figure 15 - Frequency plot for directed control with double-ended, independence of measurement and correction, phase reference combining and self organizing. General stress scenario (with jitter).

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QUESTIONS AND ANSWERS

MR. DAVID OWOLO, Western Union:

Most of the networks that both you and Ron touched on today used primarily terrestrial links for carrying either control or reference information to the various nodes, be they master or slave. What effects do satellite transmission links have on any of the systems you have discussed, and are there any special techniques that are more applicable to satellite linked networks than they are to terrestrial networks?

MR. WILLIARD:

I did touch on the fact in the first phase diagram I showed that there were satellite links assumed in three places in our network. The big phase variations, the 26 microseconds which I showed on that first phase plot, were essentially the result of the diurnal variations of the vertical drift of satellites in the directed control path to those nodes.

The use of double endedness can virtually eliminate those slow speed variations and not only the phase variations but the frequency variations also disappeared in that second set of graphs. The simple use of directed control will virtually eliminate the effects that satellites have upon the distribution and timing.

DR. HARRIS A. STOVER, Defense Communications Agency:

Now you have seen, I think, that the mutual is not the first choice probably, and whatever choice you make between directed control and mutual, it is generally beneficial to add the additional features after you have made that choice.