SURVEY OF TIMING/SYNCHRONIZATION OF OPERATING WIDEBAND DIGITAL COMMUNICATIONS NETWORKS

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ABSTRACT

In order to benefit from experience gained from the synchronization of operational wideband digital networks, a survey was made of three such systems: Data Transmission Company, Western Union Telegraph Company, and the Computer Communications Group of the Trans-Canada Telephone System. Additional information was obtained from AT&T relative to their Switched Digital Network.

The focus of the survey was on deployment and operational experience from a practical (as opposed to theoretical) viewpoint. The objective was to provide a report on the results of deployment-how the systems performed and wherein the performance differed from that predicted or intended in the design. It also attempted to determine how the various system designers would use the benefit of hindsight if they could design those same systems today.

No conclusions or evaluations of the network performance are provided in the report. However, some of the differences in requirements between the commercial networks surveyed and those of strategic, survivable networks, such as the Defense Communications System, are noted.

INTRODUCTION

There are (were) several sideband digital communications networks operating which incorporate synchronization systems. Most of these networks were originally conceived and developed in the late sixties and early seventies, and initially deployed in the early seventies. This paper describes the results of a survey which attempted to learn of practical aspects and experiences in the design, deployment and operation of these networks.

Three specific systems surveyed are the switched digital network developed by the Data Transmission Company and now operated by SP Communications (hereafter called the Datran System); the digital network deployed and operated by the Computer Communications Group of the Trans-Canada Telephone System (Dataroute) and a digital system developed by the Western Union Telegraph Co. (hereafter called the WU system). With the

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exception of the WU System, these networks are in service today. The Western Union system was put into operation in late 1971 and field trials conducted for several months. The system was never put into service, and has since been dismantled.

A brief description of each major subsystem of the three networks is given. It is followed by a set of questions which were posed to personnel associated with each of the networks in the development and early operational phases. These questions were posed during meetings with the personnel for each of the systems. Original plans were to include a section on the private-line Digital Data System (DDS) deployed by American Telephone and Telegraph. However, due to pending litigation, AT&T personnel were unable to provide information on DDS. An interview was substituted which covered Bell's planning for timing and synchronization of the network of No. 4ESS switching centers referred to as the Switched Data Network (SDN).

The paper concludes with a summary of the survey and a general comparison of timing/synchronization (T/S) considerations for the commercial networks described with those for a strategic military network such as the DCS. Many of the features important to a military system such as the DCS need not be considered in a commercial system. Survivability may be of interest to a commercial network, but not enough to dominate design trade-offs. Thus, while the engineering, planning, and design of the commercial networks, along with the operational experiences, are of interest in planning military networks, the two applications have distinctions that can heavily sway design trade-offs and decisions in different ways.

Questions posed to the technical personnel associated with the three digital systems (WU, Datran, Dataroute) were as follows:

A. Fundamental Reasons for Choosing Timing and Synchronization (T/S) As Implemented.
   1. What were criteria used for selecting T/S system?
   2. Were other types T/S system considered?
   3. On what basis was final choice made-performance analysis; cost analysis; O/M analysis; simulation; other?
   4. Is system reference to UTC or other standard necessary and/or desirable?
   5. How was compatibility with other systems (international, military, other common carriers, etc.) a factor in the system selection/design?

B. Theoretical Design of Chosen T/S System
   1. What were the main criteria in specifying the T/S system? Did it have to "marry" existing hardware, etc.?
   2. Specifications of Hardware

(a) Stability - long/short term
(b) Reliability
(c) Jitter reduction
(d) Cost goals
(e) O/M aspects

3. What were driving criteria on timing distribution waveforms, interfaces, etc. "downstream" from clocks, i.e., between MUX's, from MUX's to user, etc.?

C. Practical Design/Engineering Considerations
   1. Were any unusual obstacles met in the design/development of hardware?
   2. Were specifications as finally met tighter or looser than original specifications?

D. Initial Field Deployment, Testing, O&M
   1. In the field trials and early operation of the network, were any unusual problems encountered?
      (a) Were craftsmen able to install, test, troubleshoot, or was system so foreign that engineers were needed?
      (b) Was elaborate/non-routine test equipment needed?
   2. Are there any changes to system design that, in retrospect, would enhance or otherwise favorably influence initial field deployment and testing?

E. System Operations Experience
   1. Has system operated as expected? If not, what has arisen that was unexpected?
   2. Is performance adequate in retrospect?
   3. Is reliability adequate in retrospect? Is redundancy used?
   4. Is maintainability adequate in retrospect? What have been MTTR experiences?
   5. Is flexibility for growth/change acceptable in retrospect? Are any future requirements now foreseen that would have influenced design?

F. Any Other Information Useful to U.S. Government/DoD in Planning for the Defense Communications System (DCS)?

WESTERN UNION DIGITAL NETWORK

The Western Union Telegraph Company network in this survey was operated as a testbed until it was dismantled in late 1973 or early 1974. The system utilized line-of-sight microwave as the basic trunking medium and provided point-to-point data services. The system, while only deployed over a limited area (Cincinnati to Atlanta) was conceived and designed to be eventually expanded on a nationwide basis.

The system utilized partial response digital signals in the lower baseband portion of an existing analog microwave radio system. Simultaneously, 600 FDM voice channels occupied the upper baseband.

The system was originally planned and designed around a five-level time division multiplex hierarchy. The fifth level of multiplexing (20 or 40 Mb/s output) was never implemented.

Both the planned and implemented systems employed a hybrid synchronizing arrangement wherein the first (or lower) two levels of multiplexing were synchronous system-wide while the top two (or three) levels of multiplexing employed pulse stuffing. This design, using asynchronous operation for the higher level multiplexers, minimized the use of high speed elastic stores, or buffers. Path length changes and other multi-bit delay variations were taken care of by the pulse-stuffing capability. Thus, the network was a hybrid, i.e., it was not purely synchronous or asynchronous.

The timing and synchronization system likewise was a hybrid in that it was conceived as a mixture of both master-slave and independent master types of systems. The segment of the planned system which was deployed between Atlanta and Cincinnati was basically operated as a master-slave system, but had the hybrid capability.

The timing and synchronization subsystem of the Western Union network was built around a set of redundant Disciplined Oscillators and a corresponding Interface Unit. The Disciplined Oscillators are basically phaselocked loops (PLL's) and the Interface Unit is a control circuit which selects the reference source to which the PLL's are locked.

For master-slave operation of the network, a highly stable oscillator such as a rubidium standard is fed into the Interface Unit at the master station. All other station clocks in the network then receive their reference from one or more of the 56 kb/s synchronous data channels emanating down from this master. At these slaved stations, the Interface Unit selects which 56 kb/s signal is to be used as the reference.

For independent master operation, each node in the system where timing is derived has a Loran-C receiver subsystem. This subsystem receives a ground wave signal from the Loran-C system and integrates it for a long period to provide a highly stable 1 MHZ signal to the Interface Unit and thence to the Disciplined Oscillators. All stations deriving timing from the Loran-C system are thus synchronized.

The Disciplined Oscillators are the heart of the Western Union timing and synchronization system. They were designed using a voltage-controlled crystal oscillator and a third-order feedback loop with three time constants. The third time constant of approximately 200,000 seconds provides a highly stable output for several days in absence of an input reference. The third order loop remembers the rate of change of the difference in frequency between the internal VCXO and the reference frequency. When the input signal is removed, the feedback loop continues to correct for this difference. Thus, if the reference has remained unchanged, when it is reapplied, the drift rate of the VCXO will have been compensated as if the reference had not been lost. The other two time constants are 50,000 seconds for the second loop and (switch selectable) 5, 25, or 500 seconds for the first loop.

Because the Western Union system was never made fully operational, some of the questions asked were not directly answerable as noted below.

A. Fundamental Reasons for Choosing WU T/S System as Implemented

There were several criteria used in selecting the Western Union system as implemented. Cost was a primary consideration in choosing a synchronous system in that it was felt that the relatively large numbers of lower level multiplexers could be much simpler. The reason for choosing asynchronous higher level multiplexers was to avoid the relatively large costs of high speed elastic stores. A synchronous mode for the lower level multiplexers would also allow switched circuit operation, and this was the primary reason for selecting a synchronous network.

The master-slave technique, augmented by an independent master capability, was chosen for its simplicity of design and operation. At the time, it appeared that this technique, along with independent clocks, was well within the state of the art and achievable in practice, whereas systems such as mutual synchronization were considered (by Western Union) as unproven and questionable.

The independent clocks system was also considered, but it was concluded that the cost of avoiding periodically overflowing buffers was low enough to be well worthwhile. Programmed, or scheduled, error bursts associated with resetting buffers was judged unpalatable from a marketing point of view.

The final system choice was made on the basis of engineering judgment about practical aspects and associated technical risks. Implicit in this judgment was a performance, cost, and maintainability assessment. Simulations were not used.

Some brief consideration of using the network T/S system to distribute precise time was given. It was judged, however, that no market existed to justify the expense. Being able to synchronize the system to another system was judged desirable and was a factor in choosing the master-slave technique. It was felt at Western Union that eventually it would be desirable to synchronize with (slave to) other U.S.

common carriers.

B. Theorectical Design of WU T/S System

Several important aspects were considered when specifying the Western Union T/S system. It was initially planned to use a data signal-below-analog technique on existing analog radio systems and/or group band modems and/or leased T-1 facilities as the transmission media between nodes. Thus the system design, including the T/S equipment, had to be compatible with these transmission methods. The capability of the Interface Unit to accept 56 KHz, 1.544 MHz and 1 MHz reference signals reflects this requirement.

Another important criterion in specifying the T/S system was the required mean time to loss of bit count integrity at a node when the source of timing reference was lost. It was felt that bit count integrity should be maintained for up to several days if possible. To provide this, a stability of one part in 10^9 per day was chosen as the design goal.

Cost was also an important design criterion. In conjunction with the necessary reliability it was decided that the master-slave system augmented with a back-up Loran-C receiver/monitor was the most cost effective way to provide station timing throughout the network. An overall goal of Western Union was to develop the digital system to permit service at rates below the corresponding analog derived channels. The station clock system cost approximately $25,000 in 1972 dollars which was felt to be compatible with overall cost goals.

The following specifications were used for the development of the Western Union T/S equipment.

a. Stability - long/short term.
   Design goal of $\pm 1 \times 10^{-9}$ hours
b. Reliability - no reliability numbers such as MTBF were used. However, Western Union engineers felt that the T/S equipment should be of such reliability that overall system reliability would be determined by the radio system's MTBF and propogation path availability.
c. Jitter Reduction - no jitter reduction specifications were given.
d. Cost Goals - an approximate capital expenditure goal of $25,000 per station clock was used , not including spares provisioning or maintenance costs.
e. O/M Aspects - no MTTR or other maintenance related goals were specified.

The design of the signal/clock waveforms between the T/S system and the multiplexers and between the various multiplexer levels was driven principally by the desire to be compatible with existing standards. In most cases, the standards were not formally specified in the early 70's but were de facto standards as perceived by the Western Union engineering staff. This basically led to using the T-1 bipolar format without separate clock signals wherever possible in the system.

C. WU Practical Design/Engineering Considerations

The only unusual or unforeseen obstacles encountered in the development of the Western Union system did not relate specifically to the T/S system. In the older radio system used between Atlanta and Cincinnati, some of the klystrons used as transmitter oscillators and as receiver local oscillators were microphonic. Mechanical vibrations were translated to electrical noise on the baseband in the lower frequency spectrum, which caused poor performance of the digital system. It was also found that phase and amplitude linearity of the radio system were critical, especially as the 600 channel voice system above the digital signal (on the baseband) was loaded with traffic. If the phase/amplitude characteristics were not very well aligned, intermodulation products from the voice signals fell in the baseband used by the digital signal and degraded performance.

All specifications on the T/S system were met in the design of the equipment. It is not known what margin was achieved, i.e., how much performance exceeded specification.

D. WU Initial Field Deployment, Testing, O&M

No unusual problems were encountered in field deployment other than those of the microphonic klystrons and the exacting phase/linearity requirements. The system was being operated as a test-bed, and engineers were used extensively to put it into operation. No legitimate measure of how well O&M craftsmen or other lower skill-level personnel could handle the system was obtained.

Digital test equipment was not widely available at the time, especially bit error rate test equipment, but these problems were not peculiar to the T/S system. Non-routine test equipment was not required for the T/S equipment, and in today's environment, one would not expect bit error rate equipment to present a problem.

In retrospect, no changes to the T/S system design which would enhance or otherwise favorably influence the field deployment and testing are known by the Western Union people.

E. WU System Operations Experience

The Western Union system did not go into regular commercial service so questions about operational experience generally are not answerable. Based on the several months of field trials, the system was judged to be performing as expected. Technical performance, reliability, and maintainability are felt to have been as designed and no readily obvious change would be apparent. No flexibility for growth or change requirements have been identified. When queried about requirements now foreseen that would have influenced design, the Western Union engineers responded that the deployment and growth of AT&T's Digital Data System (DDS) would probably influence any such system they would design today. For interoperability reasons, and for cost/simplicity considerations, a design today would probably take a timing/synchronization reference signal from DDS at one or more locations and then distribute this over the Western Union network in the master-slave fashion. The Loran-C capability would not likely be implemented.

F. Other Information Useful to DoD Planning of DCS

The Western Union digital systems design/deployment experience did not result in specific T/S information other than that described above. An opinion was ventured by the Western Union engineers with regard to overall digital system, however: if possible, DoD would be well advised to avoid trying a hybrid system such as the digital MUX's on an analog radio. They feel that the most cost-effective, least troublesome route to follow today would be to initiate any such system as a pure digital network, and not attempt to incorporate existing hardware.

CANADIAN DATAROUTE

The Trans-Canada Telephone System (TCTS) is an association of eight of the largest telecommunications companies in Canada. Within TCTS, the Computer Communication Group (CCG) is dedicated to data communications services. After initial experimental work in 1971 with a synchronous digital network, CCG announced the development of a much more expanded synchronous digital network called the Dataroute. The system provides point-to-point service to fifteen metropolitan areas in Canada. It is presently in service carrying customer traffic. Its timing and synchronization system is basically a variation of the master-slave technique.

The Dataroute system was designed to utilize existing long haul facilities of the member common carriers of TCTS. Most of the long haul facilities of these carriers are 5 GHz microwave radio systems. Group band (12 equivalent 4 kHz voice channels) modems are the basic method employed in the Dataroute system to utilize these microwave facilities. These modems, used over the analog system, provide a 56 kb/s channel which is the basic trunk for the digital system. The modem typically interfaces with group level equipment in a FDM carrier system.

An alternate way of providing 56 kb/s trunks for Dataroute is by use of a Time Slot Access Unit on T1 facilities. This equipment converts the 56 kb/s signal to a 64 kb/s data stream suitable for insertion directly into a PCM voice channel. This type trunking is used in

Dataroute where T1 facilities are available.

Channelizing for Dataroute is provided by a two-level time division multiplex system. The highest level multiplexer is bit interleaved and synchronous on both the input and output. It provides channels for all circuits of 2400 b/s or greater speeds. It can be programmed for any combination of input channel speeds which are multiples of 200 b/s. The multiplexer in conjunction with the T/S subsystem minimizes delay through the network by time aligning all transmit and receive frames at a node. This capability to align the transmit and receive frames allows channels to contain submultiplexed channels which need not be demultiplexed as the composite channel is patched through a node on a drop-and-insert basis. This is achieved without adding framing overhead to multiplex the subchannels. This time alignment also allows patching data signals only (no clock) between multiplexers.

The second level multiplexer is normally programmed to accept both a bit clock and a frame clock from an external source (the T/S system). This configuration is used at nodes where a station clock is used - normally wherever two or more links come together. However, at terminal sites which connect to a single other location, the multiplexer can be programmed to slave to a bit clock and frame clock derived directly from the incoming line.

The lower or first level multiplexers used in Dataroute are character interleaved machines which provide asynchronous low speed channels. The high speed sides of these multiplexers are operated synchronously and feed into the low speed ports of the synchronous second level multiplexers described above.

From the beginning of the TCTS data communications network, the T/S system has evolved through three stages. Originally, a very simple master-slave system was used with a rubidium master located in Toronto. The next stage, and that which is primarily in operation now is a master-slave augmented with extra capabilities. This T/S system has been in operation since early 1974 in conjunction with the subsystems previously described and today forms the heart of the Dataroute. Dataroute people refer to the augmented master-slave system as Hierarchical Master Slave (HMS).

Plans are presently underway in the CCG to add a third level of multiplex to the Dataroute and with it to overlay a higher level T/S subsystem. This "new" T/S network will again be essentially a pure master-slave type which will obtain its reference from the same basic source as the present HMS system. A new third level multiplexer and the new T/S system will operate at 1.544 Mb/s and will provide channels for the existing 56 kb/s Dataroute. The two timing systems (new MS and old HMS) will organize and run independently except for the common master reference.

The new higher level MUX and T/S equipments are presently in the early field trial and deployment stages and are not discussed further in this report.

The HMS system is discussed in what follows and is referred to simply as the Dataroute T/S system.

The Dataroute T/S system is implemented by a master-slave system in which double endedness and self-organization are incorporated. (Directed control is of course used as it is inherent in master-slave.)

The HMS system is like a conventional master-slave system in that network timing emanates from a stable master source located somewhere near the geographical center of the network (Toronto in this case). This timing is fed down the network in tree-like fashion. Self-organization is accomplished in a hierarchical fashion hence the HMS name. Accompanying the timing signal is a ranking, or figure of merit signature whose value at any location is generally dependent on how remote the location is from the master source. This signature is carried on a 400 b/s overhead channel. The signature is carried as a three digit number where digit one designates the node from which the clock first originates. Digit two signifies the number of links that have been traversed from the node having the original (master) clock, and the third digit carries the value of the immediately prior node. As the timing reaches each node and is passed on, the last two digits are updated. At every node in the network each incoming 56 kb/s stream carries such a signature. At a node with several incoming channels, the stream with the lowest valued signature is chosen as the one from which to derive timing reference. Continued monitoring will permit the network to automatically reconfigure in event of loss of master or a link failure; timing loops will not be set up in the reconfiguration. Automatic reconfiguration without setting up unstable timing loops was the primary reason for using the HMS system as opposed to a straight MS system.

Another system feature incorporated in Dataroute is called Master Frame (MF). This concept is basically the dissemination of a framing epoch marker by the timing supply at each node in addition to a bit epoch marker. In the 56 kb/s system, the basic frame is 280 bits long, and the frame epoch occurs at a 200 Hz rate. Thus the nodal timing supply, or station clock, delivers to each multiplexer both a bit clock at 56KHz and a frame clock at 200 Hz. This delivered frame clock is the Master Frame. This common frame marker is obviously time aligned at all multiplexers in a given station and is useful in minimizing delay through the network for a channel patched through a station. This minimization comes about because the low speed input buffer requirements are minimized on each multiplexer. The Master Frame concept also allows drop and insert of submultiplexed channels without requiring overhead framing bits for the submultiplexing.

Another feature called Universal Time Frame is implemented in the Dataroute T/S system. Universal Time Frame (UTF) is an embodiment of double endedness. This embodiment actually involves an interfunctioning of the T/S subsystem with the second level multiplexers (56 kb/s). The designers of Dataroute included UTF to further minimize network user delays. They recognized that this feature would also allow precise time dissemination; however, it is not exploited in the system.

Universal Time Frame operates as follows. Consider the case where one of two communicating nodes is slaved to the other for timing dissemination purposes. The two multiplexers when initially put into service, will be programmed such that each transmitted frame is advanced in time (relative to local master frame) by an amount which slightly exceeds the propagation delay. This delay is known from theoretical or empirical (or both) considerations. Because the frames are advanced at the transmitter, they arrive at the far end of the link (nearly) in phase with master frame. The receiving multiplexer at the master station of the communicating pair measures the time alignment of the received frame by measuring the operating position of its high speed input buffer. This buffer position is then communicated to the slaved node via the overhead channel previously mentioned (with regard to the HMS signature information). At the slaved node, this information is used to generate an error signal to the local station clock. This signal causes the clock to adjust its frequency so as to advance or retard the time alignment of the frame marker. Correcting the slaved clock obviously adjusts its master frame epoch relative to the master station. This continuing, dynamic correction of the slaved station's master frame obviously serves to keep the slaved frame marker time aligned with the master station marker, and the alignment passes down through the network.

The transmittal of buffer position information to the other node constitutes a form of double endedness.

Specific answers to the set of questions follow:

A. Fundamental Reasons for Choosing Dataroute T/S System as Implemented

Efficiency (ratio of data bits to data-plus-overhead bits), ease of submultiplexing many different rates of user channels, and system simplicity were the chief reasons for choosing a synchronous digital network. The criteria for choice of which type synchronizing system were largely based on the Canadian network topology. It was envisioned that a long thin network would initially be deployed but that a highly interconnected topology would evolve. Flexibility to accommodate relatively unpredictable growth was also considered essential.

The Dataroute T/S system is master-slave augmented by double endedness and self-organization. A straight master-slave system as well as a mutual synchronization system were also considered. The choice was made on grounds of enhanced security, ease of network expansion, and relative insensitivity to link failures. The choice was also tempered by a desire to retain simplicity to the extent possible. Thus performance was directly factored into the choice; costs and O/M influences were indirectly factored in.

Referencing the system directly to UTC or to a national standard was not considered as needed for Dataroute, but it was recognized that the Universal Time Frame feature allows distribution of (relatively) precise time. CCG did not foresee a need or market for this service to the extent that the additional hardware would have been cost justified. On the other hand, compatibility with other systems was felt to be a future need worthy of factoring into the choice of T/S system. It was expected that interfacing with other synchronous digital networks would be needed and it was recognized that a master-slave type system allows this simply by using a common reference as the primary master source.

B. Theoretical Design of Chosen Dataroute T/S System

After the choice was made as to the type of T/S system, a number of factors constrained the design of the hardware. This basic trunking medium was primarily to be over existing 4 GHz microwave systems and the design had to account for the characteristics of this transmission channel. The rate of delay variations due to the transmission media, the induced jitter on the timing signals, the probability of outages and link failures, and the probability/frequency of re-routing of transmission channels were among the factors considered.

Other factors which led to specifications on the T/S hardware included: the desired time to loss of bit count integrity in case of failures in the timing dissemination chain, the reliability budget for the overall system, and cost goals throughout the system.

C. Practical Design/Engineering Considerations for Dataroute

No significant obstacles were encountered in the design/development of the Dataroute T/S system hardware. Each node in the system contains two station clocks. Basically these clocks are made up of a highly stable VCXO configured in a phase-locked loop. The loop is designed with a very narrow bandwidth (nominally specified in microhertz) and with variable slew-rate control. Each clock also contains the logic circuitry to accept and compare up to 32 incoming reference signals plus signatures and the logic circuitry to compute its own outgoing signature. Additionally of course, there is digital frequency synthesizer circuitry for deriving the various clock and frame rate signals.

None of the above circuitry presented inordinarily difficult design problems. The logic speeds involved were not extreme and the usual precautions in board layout, wiring procedures, etc., were sufficient to ensure good performance.

D. Initial Field Deployment, Testing, O&M

Specific, identifiable installation problems were not encountered in the early field installation of Dataroute. As is described later, some difficulties were met that can generally be traced partially to the complexity of the method of implementing the double ended T/S system concept. These are discussed more fully below under Systems Operations Experience.

Because the deployment of Dataroute was planned to be carried out as a field trial, engineering-level personnel from both CCG and hardware contractor organizations were used extensively. The fact that the field craftsmen from the constitutent TCTS organizations were mostly experienced in FDM-FM analog technology influenced the decision to rely heavily on engineers for initial deployment.

No specialized or otherwise non-routine test equipments were required in the early field deployment of Dataroute. As with most digital systems, the indispensable tool utilized was an oscilloscope that could be externally synchronized. A logic analyzer type instrument designed to interface with the multiplexers, was used and is of course a specialized item. This however, was not necessarily required, i.e., the system could have been put into service without its use. More importantly, the use of this instrument was not influenced by the type of T/S system in use. The utility would have been the same with independent clocks, mutual synchronization, or whatever at the T/S method.

E. Systems Operation Experience

The Dataroute T/S system has operated as expected. Basic specifications have been met and no problems directly related to concepts or theory have been encountered. However, two issues have arisen. One of these relates to a practical problem on clock distribution in the terminal. The other relates more to system design philosophy.

The clock (and frame) signals in a Dataroute node are distributed from the station clock equipment rack to each rack of multiplexing equipment by means of a redundant bussing scheme. Two busses, one from each of the (redundant) station clocks, distribute signals to each rack of multiplex equipment. This distribution is accomplished via distribution modules mounted on the top of each bay (rack) of multiplex equipment. Several problems have arisen with this. It was found that although up to six multiplexers could be driven in tandem, this was insufficient in some nodes and further expansion was not easily implemented. The lesson in this is to plan that the clock distribution system be easily expanded and that ideally, the expansion capability be unlimited in size.

Initially the clock signal was a current source-to-ground format. This contributed to the limitations on the number of multiplexers to be driven. It also gave rise to interference problems through noise pick-up, and common mode coupling. This problem was eliminated by redesigning with a format using a transformer-coupled, bipolar, balanced signal of several volts.

The second (philosophical) issue relates to the capability of the T/S system. As has been described, the Dataroute T/S system is basically a master-slave with three complementing features.

1. Hierarchial Master-Slave (self-organizing)
2. Master Frame clock along with bit clock
3. Universal Time Frame - a form of double endedness

In Dataroute, the reason for using Hierarchial Master Slave was to allow automatic reconfiguring of the network, without setting up unstable closed timing paths, in the event of link or master clock failures. However, experience has shown that network reconfigurations are so rare that the utility of HMS is questionable. In other words, the self-organizing feature is so seldom used that a cost/benefit analysis based on this experience would likely dictate not incorporating it in the design if the choice were to be made again for Dataroute.

Note: The rarity of failures has other implications for military systems. Because of the rarity, it is possible, even probable that personnel may be so "out-of-practice" that they cannot diagnose and correct T/S system problems in a timely manner and may actually compound the problem through incorrect activities. This of course could be disastrous in a wartime situation. Thus automatic self-correction may be much more desirable.

The second feature, Master Frame, was implemented to allow cross patching between multiplexers without the need for (low speed channel) input buffers. In retrospect, the Dataroute operators now question whether or not the ability to dispense with the low speed buffers is a significant advantage. With LSI and VLSI usage growing exponentially, the cost of adding buffering to channel cards is not large. The simplicity of channel cards is a positive feature however, and the ability to patch channels with only signal leads (i.e., without separate clock signals) is a positive feature. This reduces the problems that arise when large numbers of channels in a single rack make physical room for the signal and clock cables scarce and the opportunity for wiring errors are compounded.

The third significant feature in the Dataroute T/S system is Universal Time Frame (UTF). The original reason for UTF was to minimize user delay through the network; UTF does this by assuring that the high speed frame alignment buffers in the synchronous multiplexers remain, on average and in absence of propagation delay variations, at their center or null positions. However, with the hindsight that has accrued through several years of operating experience, it is now felt by the Dataroute operators that user delay through the network is not critically important. This is increasingly true as data users begin to move away from protocols that employ acknowledgement type transmissions (such as Binary Synchronous protocol). Delay considerations are also less critical to users who continue to employ acknowledgement protocols but who take advantage of the better channels (lower error rates) increasingly available. Longer data block sizes are feasible (to a point) on the better channels and with the longer blocks/fewer errors, turnaround time, or delay, is less degrading to overall throughout.

The reliability of the T/S system on Dataroute has proven to be degraded by the complexity of the station clock. The HMS function plus UTF are implemented at the cost of increased complexity. This increased complexity serves to cause increased hardware failures plus contributes to maintainability problems as discussed below.

The maintainability of the T/S system on Dataroute has proven to be significantly more of a problem than anticipated. This is partially due to the complexity of the double ended, self-organizing system and partially due to the method of implementation. The system has been in operation over 5 years now and maintenance craftsmen do not yet totally comprehend the synchronizing hardware. Engineering level personnel are heavily involved in T/S system maintenance and operation. Even people with this level of training/competence lack in understanding the system. This complexity and the attendant lack of familiarity by the field people serves to reinforce the skeptical attitudes as to the cost benefits of UTF and HMS. Considerable effort has been expended to write and rewrite equipment manuals and to upgrade training, but as a practical matter, the maintenance people continue to regard the T/S equipment with considerable confusion. Much of these comprehension difficulties can be attributed to the specific method of implementing the double endedness. If, for example, the information passed from one end of the link to the other were available to maintenance/operation personnel in familiar units of time (seconds or microseconds), much of the difficulty would probably be overcome, (Note that the information is presented as a dimmensionless number referred to as "Diff" in the present implementation).

The flexibility of the Dataroute T/S system is judged to be acceptable. No restrictions on growth or change to the network are imposed by the synchronizing system. It is notable however that in the planning for the 1.544 Mb/s network, which is a growth step for Dataroute, a straight master-slave technique for T/S is planned. Future requirements appear to be for a longer, less interconnected network - one wherein closed loops are less probable.

Advice to be offered to U.S. Government/DoD in planning for T/S of the future DCS was succinct: simplicity should be watchword. To the extent that survivability, security, and other specialized military considerations allow, the simpler the T/S system, the better will be the performance. Maintainability will be a strong function of simplicity and reliability/availability will probably re related to maintainability more than any other system parameter.

DATRAN DIGITAL SYSTEM

Data Transmission Company (Datran) was a specialized common carrier company formed in the late 60's to design, build, and operate a nationwide network for data communications.

The system designed and built by Datran is distinct from the others surveyed in this report because the total network was newly conceived, designed, and built as a digital system. There were no constraints of having to utilize existing plant or equipment; nor was the design forced into compromise in order to have a voice channel or other analog transmission capability. It was therefore feasible to consider techniques, including the T/S system, which perhaps were not feasible as candidates for the other systems surveyed.

The radio equipment in the Datran network is a digitally modulated, line-of-sight microwave system which uses 8-level PSK modulation. Fully loaded, it accepts two, phase-synchronous 21.504 Mb/s data signals as well as a coherent 21.504 MHz clock signal.

The timing signal is recovered and the data regenerated at every repeater in the Datran system. Timing recovery is accomplished in 14.7456 MHz phase-locked loops. The loop bandwidth (3 dB) is 1 KHz in the radio system. The free running stability of the oscillators in the timing recovery loops is $1{:}10^{-6}$ (short term).

A three level multiplexing system is used in the Datran network. All three Datran multiplexers are synchronous machines. Each utilizes bit interleaving to combine parallel low rate channels to a higher speed serial bit stream. Every multiplexer features buffers on both the high and low speed input ports for jitter reduction and to accomodate propagation delay variations.

The system which provides timing and synchronization for the Datran network is a straightforward application of master-slave techniques. The T/S hardware is primarily made up of an equipment called the Datran Station Clock (DSC) which supplied bit rate clock to all levels of multiplexers. However, the overall network timing subsystem is composed of functions in the multiplexers, the DSC's, the microwave radios (as a timing dissemination channel), and one or more rubidium standards which provide the basic reference signal (master source).

The DSC basically is a highly stable, highly reliable disciplined oscillator with the ability to "remember" an input reference frequency after loss of the reference. It includes a frequency synthesizer for deriving various system clock rate signals from the basic oscillator frequency and line drivers for distributing these clock rate signals. It also includes logic hardware for interfacing with the multiplexers on a systems basis and for controlling its own functioning. The DSC provides clock signals at 21.504 MHz, 2.688 MHz, and 168 KHz.

The heart of the DSC is a triplicated set of modules called Timing Generators. These are highly stable 's, each in a phase-locked loop configuration where the loop error voltage is simultaneously fed to the VCXO and also digitized, filtered to an effective 0.04 Hz bandwidth, and stored in memory. The digitizing is done to a 12-bit accuracy which translates to a frequency accuracy at the VCXO of a 5×10^{-11}. This stored error voltage is applied to the VCXO in instances when the station clock transitions from slave operation to master. Because of the narrow bandwidth of the digitized error feedback loop, input jitter with frequency content down to much less than 1 Hz is filtered. By virtue of this jitter reduction, when the clock becomes a local master, frequency differences between it and the normal master will remain sufficiently small to maintain bit count integrity for more than 30 minutes (based on the buffers used in the C-MUX's). This is in the presence of up to 5 percent rms jitter with a bandwidth from 0.1 to 1000 Hz.

The bandwidth of the (undigitized) error voltage in the phase locked loop is 4 Hz. This translates to a capture, or pull in range for the Slave Node of $\pm 1 \times 10^{-7}$.

In the following, answers are given to the set of questions as they pertain to the Datran System.

A. Fundamental Reasons for Choosing Datran T/S System as Implemented

The criteria used for choosing the T/S method for the network were principally performance, cost, and state of the art (practical state as opposed to theoretical) prevailing at the time of system design. Methods other than master-slave were considered. Nonsynchronous operation using independent clocks and various types of pulse stuffing were evaluated as possible candidates. Synchronous techniques considered majority voting logic for controlling the triplicated functions in the DSC required close attention to signal delays, board layouts, etc. Adherence to good engineering practices common to nanoseconds speed logic design ensured a minimum of problems in this area.

One problem was encountered in a systems level test of the T/S equipments. The problem related to the ability of the DSC to properly hold the system frequency when a jitter corrupted reference signal was lost. It was found that the frequency spectrum of the jitter on the reference was of critical importance in how well the system frequency was maintained. The overall specification required that when using 32 bit buffers, bit count integrity would be assured for at least 30 minutes when a reference with 10 percent rms jitter, with a frequency spectrum between 0.1 and 1000 Hz, was lost. Recall that the bandwidth of the loop in the DSC which held the error voltage, or "remembered" the system frequency, is 0.04 Hz. However, it was found that if the jitter spectrum was concentrated near the lower end of the specified bandwidth, the loss of reference would sometimes leave the remembered frequency deflected enough to cause buffer overflow in less than 30 minutes. If the jitter spectrum were spread uniformly over the 0.1 to 1000 Hz band, or concentrated near the high end however, the specification was easily met.

This problem of maintaining bit count integrity in the presence of low frequency jitter was never manifested in actual field operation but only in lab tests where jittered references were synthesized.

With the exception of the above described phenomenon, all specifications on the T/S system were met or exceeded by the completed design. For example, a jitter reduction ratio of greater than 20 to 1 was measured in the field for the DSC whereas the specification was 6 to 1. A mean time between maintenance repairs of greater than 22,000 hours was also measured in the field on the T/S equipment. This compares to a design calculation of 6700 hours. As for mean time to catastrophic failure, no such failures had been encountered at last check so that a meaningful quantitative statement cannot be made.

D. Datran Initial Field Deployment, Testing, O&M

In the initial deployment and operation of the Datran network, all field personnel were given comprehensive, but extremely time-compressed training on all equipments. By and large, the personnel were experienced in FDM-FM analog systems as opposed to digital systems; thus many of them encountered and progressed through a distinct learning period on the entire network. While the T/S subsystem presented no more problems during this learning period than did the other equipments, nevertheless the nonfamiliarity was of significance. The triple redundancy of the Station Clock added to the nonfamiliarity problems to such an extent that it considerably complicated the understanding of the equipment. It also greatly added to the difficulty of troubleshooting equipment malfunctions.

Datran procured several items of test equipment related to the T/S system that were nonroutine. Among these were portable rubidium standards, frequency synthesizers, and phase jitter meters. In retrospect, it is apparent that these equipments were not necessary for operating and maintaining the network. They were useful in monitoring the network performance from the point-of-view of an extended field trial where continued engineering data was desirable. However, from a standpoint of routine, day-in, day-out system operation and preventive maintenance, an oscilloscope in conjunction with built-in test functions on the DSC is adequate.

No significant changes in system design are obvious in retrospect that would enhance or otherwise favorably influence field deployment and testing.

E. Datran Systems Operating Experience

The T/S subsystem in the Datran network has operated substantially as expected. No significant problems have been encountered that would give reason to reevaluate the basic concepts or upgrade the system. However, it is probable that a simpler, less complex system would be designed if the task were to be done again. Some reasons for this are noted below.

The fully triplicated, highly reliable (and relatively expensive) DSC was deployed by Datran at every three-way junction station and at every terminal. In retrospect, such reliability and expense is probably only justified at remote three way stations. Even there, the need for triplication is questionable. The DSC's provide quite long mean-time between maintenance repairs; and the nature of failures encountered to date indicate that double redundancy (and the simplified control hardware inherent in this) would have sufficed.

Likewise, experience gained in actual operations of the system tended to indicate that early concerns over jitter on the recovered timing signals was not warranted. In the actually deployed Datran network, the longest span between DSC's was eleven microwave hops. Had the system been deployed to the west coast as planned, spans of over thirty hops would have been encountered. Nevertheless, experience with the eleven hop system indicated that jitter buildup was much less than expected. The worst measurement for the eleven hop system was jitter of less than 4 percent rms which would extrapolate to much less than 10 percent jitter on a 30 (+) hop span.

The Datran network actually deployed was a topologically thin, long line network with no closed circuit configurations. Thus no opportunity ever arose to evaluate bit count integrity type questions on loss of continuity of the timing dissemination chain.

Performance of the Datran T/S system was judged adequate, and reliability was more than acceptable and perhaps over designed in some applications.

The maintainability of the T/S system probably should be judged acceptable to slightly marginal. The only questionable area would be in the use of triplicated functions as noted above. This tended to obscure craftsman understanding of the equipment and to render trouble shooting more difficult. It was certainly not a severe problem particularly for the better qualified, more industrious field people who would put forth the effort to understand the hardware.

The flexibility for growth/change of the Datran Station Clock is judged acceptable. It was found that in one instance, added driver ports were needed to enable clocking additional multiplex bays in a station. Careful, tedious work was necessary to add the capability to an on-line DSC without disturbing customer traffic, but it was accomplished. Should a redesign ever occur, it would be desirable to provide for easier (physical) expansion of the drive capability; this was not a major problem, however.

F. Any Other Information Useful to U.S. Government DoD in Planning Defense Communications System

The same advice regarding simplicity of equipments as offered by Canadian Dataroute operators would be evidenced by the Datran experience. The less complex the system, the better will be the reliability and maintainability. And, in the absence of major design errors, maintainability will probably impact performance more than any other single factor.

One other comment is pertinent. Compared to the late sixties/early seventies when the Datran network was designed, there is a plethora of data on digital systems available now. Each succeeding conference or symposium on broadband communications provides additional experience documentation (as well as theoretical work). Notable useful examples are LOS microwave delay data and multipath fading degradation experience. Obviously, all these sources should be used in planning the future DSC timing and synchronization systems.

TIMING/SYNCHRONIZATION PLANNING FOR NO. 4ESS

As noted in the introduction, original plans were to include information on the implementation and operational experiences of Bell System's Digital Data System in this report. (This system is a private line synchronous network put into operation in the U.S. in 1974). Unfortunately, this information is not available; Bell officials decline to provide such data due to the extensive pending litigation revolving around the Digital Data System (DDS). These officials were, however, willing to provide information on the current planning and engineering efforts related to synchronization of a network of large digital switches presently being implemented throughout the U.S. This information was provided by way of interview with several engineers currently involved in the engineering and planning efforts. In this section, this information is described.

The No. 4ESS is an electronic, software-controlled toll switching center designed to tie local facilities to the nationwide long distance network. The switching center is basically a digital machine which interfaces both digital and analog trunks. At the inception of No. 4ESS deployment, and at the present time, analog trunks predominate in number. As digital trunks become increasingly available however, (a trend that is growing rapidly), the interconnected No. 4ESS systems take on more and more attributes of large integrated digital networks. As this happens, the advantages of reliably synchronizing the whole network are obvious. This is recognized by Bell and considerable effort has been expended to plan for this synchronization. Much of this planning is inextricably interwoven with planning and analysis that has been going on at Bell Labs since the early sixties. This early planning was the initiation point in the discussions with Bell engineers.

In the early sixties, various users of the Bell Telephone System began to implement digital networks. At first, relatively elaborate word stuffing was used to provide a synchronizing mechanism for the networks. The cost (at that time) of shift registers caused a change to bit-by-bit pulse stuffing techniques and eventually to consideration and analysis of other synchronizing methods. Considerable attention was focused on the concept of mutual synchronization. Many investigators, both inside Bell Labs and elsewhere, studied and published papers on the technique. One of the advantages ascribed to mutual synchronization was that it was "administration free". However, it was decided by the No. 4ESS network planners that this is not, in reality, the case. As an example, it was noted that up to 20,000 DS-1 (1:544 Mbps) trunks can converge on a No. 4ESS. To choose which of these would provide the timing reference paths for a mutually synchronized system is a considerable problem. This is especially true when the dynamic nature of the topology of these trunks is considered.

Another aspect of mutual synchronization noted as significant was the dumbell effect. This situation arises when two separate, relatively complex, interconnected areas are connected by a thin trunk structure. In this case, the input to the T/S systems in each of the ends of the dumbell must carry heavily weighted importance. This tends to distort the survivability of the mutual sync network and to compound administration problems, particularly when the exact composition of the "thin" trunking is dynamic.

Mutual synchronization was eventually discarded as a candidate synchronizing method for three significant reasons. As indicated, it was determined that its main attribute, i.e., administration-free operation, was not a practical reality. This was the primary reason for rejecting the technique. Also, evolution in crystal oscillator technology in the late 60's was a factor in moving away from mutual synchronization. Double oven crystal oscillators with millidegree temperature stabilities became economic realities. The resulting frequency stabilities added to the case for master-slave techniques. Additionally, digital phase-locked loop (DPLL) technology progressed to the point that economic practicality was achieved. The significance in this was that DPLL's with "automatic" integral-plus-proportional feedback was then achievable. Note that integral plus proportional feedback had long been used, but the integral feedback had been a mechanical screwdriver adjustment (to oscillator free-running frequency). "Feedback" of course was a technician periodically nulling loop stress voltages. Digital implementation of this function meant greater automatic long-term stability in the oscillators since drift due to crystal aging could be compensated.

Another influencing factor on synchronization planning was that the DDS network began to be engineered. At first, the objective was to build a totally slip free network for DDS. However, the No. 4ESS planners took the position that a totally slip free DDS was not practically achievable. As an example of the several reasons, most of which are of an administration/operation origin, it was pointed out that there are some 60,000 separate group channel trunks in the Bell System. Of these, an average of 20,000 yearly are dynamic in the sense that they are removed and subsequently returned to service for one reason or another. Since these trunk assets were to provide the transmission channels for DDS, it was felt that such a dynamic makeup would prohibit practical operation of a slip free network.

For the DDS, it was eventually agreed that three system impairments would be foremost. These were i) bit errors; ii) misframing where multiplexers lose frame synchronization and iii) slips where single eight-bit bytes are lost/gained. Additionally of course, timing jitter due to accumulation on the transmission lines and due to pulse stuffing/destuffing is encountered. Of these impairments, the most significant in terms of timing and synchronization is slip and the byte interval defining slip. Of course, the longer the byte interval, the less the frequency accuracy requirements on a timing source for given slip rate. An upper limit is placed on byte length in the Bell System because the byte buffers give rise to cross-office delay in patching channels. At a point, this excessive delay begins to cause echo suppressors in the circuits to hang. This led to the 8-bit byte which is 125 microseconds in a 64 kb/s channel.

After the byte length was determined, an acceptable slip rate was evaluated. A number of factors were considered by Bell in determining a slip rate specification. In voice channels slips are trivial. However, for voice band data channels, slips can result in modems retraining which results in outages of up to several seconds. Slips also can have a severe impact when Common Channel Interoffice Signalling is carried over a slipping channel. The effect of slips of digital data varies depending on the application. It was noted by Bell that commercial applications of secure voice are foreseen over data channels in the future and slips could result in cryptographic sync problems.

The above and other considerations led to the Bell System eventually settling on a specification of one slip per 5 hours for an end-to-end reference circuit. This translates to a relative clock frequency difference specification of 1.7×10^{-9}. Because the possibility of longer frames becoming desirable in the future however, a tighter stability specification of 1×10^{-10}/day was agreed upon.

At the present time, the working specifications of the timing and synchronization subsystems for the No. 4ESS network are:

1. Clock frequency inaccuracies of less than 1×10^{-10}/day.

2. Synchronizing unit at each switch will phase lock to an external reference. This reference will be either a DS-1 signal at 1.544 MHz or the standard Bell System Reference Frequency (BSRF) 2.048 MHz. Note that this latter reference is presently distributed throughout the network.

3. The synchronizing system will be arranged in a hierarchical structure with frequency (not timing) information emanating from an atomic standard at Hillsboro, Missouri.

4. The timing system will have a highly structured maintenance plan administered out of a centralized location.

Note that specifications 2 and 3 define a master-slave system when the DS-1 reference is disseminated throughout the network. When the BSRF is used, an independent master system is being implemented.

It was noted by the Bell engineers that the fourth entry in the above specification list is extremely important as contrasted to its innocuous appearance. It has historically been found that maintenance activities are always reflected negatively in reliability performance figures for communications networks. Significant percentages of outages are traceable to maintenance personnel activities. Since the timing sources for digital networks are so central in the operation, and outages are potentially so catastrophic, it is felt that the structured maintenance philosophy is critical. In general, alarming and alarm reaction plans for the timing and synchronization hardware on No. 4ESS will have long time constants. A loss of reference alarm will, for example, be considered only a minor alarm for up to several minutes. Other reaction times numbered in hours are planned. The central administrator with network-wide status visibility will be consulted closely on all alarm responses and maintenance activities.

The phase-locked loop in the TSU incorporates integral-plus-proportional feedback. The integrated component of the loop feedback has a time constant of approximately 2 days. The time constant of the proportional factor is approximately 2 hours. Additionally, a manually activated Fast Start mode allows rapid acquisition when the TSU is first put into operation or following a major reconfiguration or outage. Automatic phase buildout is also designed into the TSU hardware.

The above briefly describes many of the factors which have entered in the planning for No. 4ESS timing and synchronization. The Bell engineers emphasized that many of the choices and trade-offs made were dominated by network administration considerations. This of course reflects the culmination of many years experience in operating the largest common user communications network in the world. Little or no consideration has been given to some factors important to military strategic communications systems. Survivability in the presence of hostile activities is an important consideration in evaluating timing and synchronization techniques for the DCS. Understandably, this has had little or no influence on the Bell designs. Likewise, interoperability with tactical systems is a consideration for the DCS not dealt with by Bell.

A last topic discussed with the Bell engineers during the interview concerned the distribution of precise time. The T/S system being engineered for the No. 4ESS network does not incorporate double endedness and thus does not readily admit of precise time dissemination. However, consideration has been given to this by Bell engineers. In general, the same concern for network administration considerations influences time dissemination that influenced T/S system design. In fact, the Bell engineers expressed the opinion that administration problems would so adversely effect time distribution as to make it impractical in the Bell System. Two examples noted were network topology dynamics and emergency restoration. The statistic previously described wherein 20,000 of the 60,000 group trunks in the system are taken out of service and restored each year was pointed to as an example of the dynamics.

Emergency restoration, and the tempo of activities that exist during outages was mentioned as the other prominent example of administrative problem in time dissemination. During outages, especially those that effect large cross-section trunks, intense effort is involved. Customers and management are usually demanding quick restoral and little acceptance of procedures which would inhibit or delay restoration would be anticipated. Coordination of clocks, and of new trunk path delays, etc. is seen by Bell engineers as just such a procedure. It was noted however, that automation of such procedures by use of microprocessors might become economically feasible in the future.

SUMMARY OF SURVEY

Each of the systems surveyd is a synchronous network, and each uses a T/S technique that is essentially of the basic master-slave category. The Datran network T/S system and the planned No. 4ESS netowrk T/S are straightforward applications of master-slave. The Western Union network and particularly the Canadian Dataroute network T/S are master-slave with added features.

Retention of bit-count-integrity, i.e., the avoidance of slips was the foremost criteria in the design of the networks. Flexibility and adjudged practical state of the art in T/S technology also weighed heavily in the initial system designs - particularly in the case of the Western Union and Datran networks. Minimization of user delays over the network was a strong factor in the Dataroute system design; recognition of network administration problems strongly influenced Bell System plans and choices.

Only the Canadian Dataroute system provides for automatic network reconfiguration (and automatic network initialization) following failure or other perturbations. Related to this is the fact that among the four systems surveyed, only the Dataroute requires an overhead channel.

Each of the system designers recognized the crucial importance of realibility in the T/S hardware/subsystem. Outages due to lack of timing supply are potentially catastrophic and could disrupt very large numbers of users. Thus, considerable effort and dollars were expended to build high availability into the T/S equipment. Western Union and Canadian Dataroute system architects accomplished this by using double redundancy with automatic switchover. The Datran system utilized triple redundancy in the station clock with all three portions contributing in the unfailed, or normal, operating mode. Majority voting logic in effect switches out the failed circuitry when problems arise.

The field deployment experiences of the organizations surveyed were remarkably similar. Each of the Western Union, Dataroute, and Datran initial deployment efforts were reasonably straightforward, but extensive use was made of engineering-level personnel (as opposed to technicians or craftsmen). The lack of a ready supply of digitally oriented field personnel was noted. In each case, however, the T/S system type or its features had little or no influence on deployment difficulties or lack thereof.

In the area of operations experience, only Datran and Dataroute were able to contribute information., The Western Union network never went operational and the Bell System's deployment of No. 4ESS is only now underway. The Dataroute operational experience has been adversely effected to some extent by the conceptual (and hardware) complexity of the T/S system and to implementation procedures. To date, field personnel are not totally comfortable with their knowledge and understanding of the method of timing and synchronizing the system with the extra features of the master-slave system. Notably, the next evolution of the Dataroute system is planned to be an unadorned master slave.

In the case of Datran operational experience, no significant problems arose which were attributable to the T/S concept. However, the triple redundancy in the hardware did complicate craftsman understanding and troubleshooting. Failure rates were so low as to call into question the need for triple as opposed to double redundancy.

The above briefly summarizes the information gained in the survey of commercial digital networks. It should be noted that several key criteria which greatly influence the design and (satisfactory) operation of a strategic military network such as the Defense Communication System are absent from the list of commercial network criteria examined. Among these are:

1. Survivability
2. Compliance with Federal Standard 1002
3. Intersystem Operability
4. Self-reorganization
5. Precise Time Availability

In the above list, survivability is the most significant entry; the fact that a network plays a central role in national defense means that survivability must be as pivotal in design trade-offs as are any other parameters. This, of course, can completely alter the conclusions of a cost-effectiveness study.

Precise time availability is another feature that might be of considerable value in a defense communications scenario but of lesser importance in the commercial world. Covert communications requirements lead to spread spectrum and cryptographic system use. Precise knowledge of a coordinated time standard, or course, greatly facilitates the synchronization of such systems by reducing acquisition search windows. Likewise, a knowledge of relatively precise time facilitates navigation and position fixing - another distinct advantage in a military environment but of lesser importance for commercial applications. (Although the commercial need for precision navigation aids should not be minimized.)

The commercial networks surveyed have made no attempt to use their T/S systems in any manner to augment or form a basis for network monitoring and evaluation. This is of course an area where the benefits could be of importance to a commercial system even though it doesn't have the special requirements of a military system. Such a use of the T/S system would generally require preplanning and engineering of the monitoring and evaluation capability into the hardware during initial design, something obviously not included in the systems surveyed. Recognition of the benefits to be obtained through monitoring and evaluation could influence the type of T/S system chosen. Some T/S methods are more compatible and synergistic with monitoring and evaluation than others.

A concluding comment is in order. Simplicity and administration related issues were mentioned over and over by the systems operators. It was emphasized that these aspects should be central in the design of any T/S system. The reasoning behind these statements is not presently debatable, especially among experienced systems operators. However, the potential influence that microprocessor evolution is having and will continue to have on this aspect should not be overlooked. Increasingly, it is feasible to automate activities heretofore constrained to be manually accomplished. With automation, or machine driven activity, the rationale behind simplicity arguments should be reexamined. Without the factor of human error, much in the way of automatic corrective routines are feasible. And much in the way of system features now considered very useful, but too complex to be practical, become realistic. This can and certainly should be factored into any current T/S systems design.

QUESTIONS AND ANSWERS

MR. THEODORE FRENSCH, Hewlett-Packard:

Can you elaborate on the double or triple redundancy? I can see for catastrophic failures that double redundancy works where, simply, there is no output. But what is the practicability for frequency shifts in double redundancy?

MR. MITCHELL:

That consideration is one of the things that led to triple redundancy choice in DATRAN, the idea being that for amplitude failures, certainly double redundancy allows you to decide which one has failed and which one is operating normally so you can switch appropriately. But for phase-type changes, if you have a phase shift in one of two sources, it is difficult if not impossible to determine which one is right and which one is wrong. Whereas, if you have three, you can do majority voting.

That is well and good. Our experience, again from a practical point of view, was the clock as it was built. Admittedly, we spent an appreciable sum to make it reliable. But it was so reliable that that came into play so infrequently, never in my experience with DATRAN, that that almost fell into the realm of an academic consideration. Does that answer your question or address what you are driving at?

MR. FRENSCH:

Are you saying, then, you actually don't need any redundancy or are you saying that catastrophic failures were more common than frequency shifts?

MR. MITCHELL:

Yes, in our case we didn't have either. When you have a network that potentially has 8,000 channels on it, you can't afford to have no redundancy, even if it only happens once every 30 years. First of all, if you had to get out and try to market the network and somebody started asking questions about the market service on the network, it would cause you problems.

In fact, some of our station clocks in the three-way repeaters were 60 miles from the maintenance center. So you are talking about hours before the service could be restored if you didn't have some kind of backup there and the clock did fail. So I think you can't afford to go with no redundancy just from a practical point of view.

But as far as going to the expense, and I would guess that the expense of the DATRAN clocks went up 50% due to the triple redundancy, and certainly the development problems were increased by at least 50%; you know, the design problems for the people that provided it. Had they not had the triple redundancy to contend with, the design would have gone a lot more smoothly; not to say that it didn't go relatively smoothly anyway. Yes, sir?

DR. C. C. COSTAIN, National Research Council:

Data Route has installed a terminal in our laboratory and we continuously monitor their frequencies. We are, in fact, going to feed back to them digitally on the network their offset, which they can use as they wish operationally. But I just wanted to mention that after we were monitoring, there was a catastrophic failure of their master in Toronto, or their sync channel, whatever, or something in the loop. Montreal took over and they were rather pleased they had it because it was a holiday weekend with, of course, the least experienced, most junior engineer in charge. The system did exactly what it was supposed to do in case of a failure of equipment. We monitored it beautifully and we were rather pleased to have the experiment, which you wouldn't create normally.

MR. MITCHELL:

Very good. You touched upon a point I neglected to mention that did come out in the survey. The fact that these timing and synchronization systems seldom fail can be important, particularly in a military-type environment, because it means that the people who have the responsibility for maintaining them when they do fail, have forgotten what to do because it's been so long since they had a similar problem. So if you have a network that automatically heals itself in some sense, that is an advantage. It is probably even more so an advantage in a military network or critical network than it would be in a commercial network.