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FUTURE DCS OBJECTIVES IN COMMUNICATION NETWORK TIMING AND SYNCHRONIZATION

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ABSTRACT

The Defense Communication System will be moving rapidly toward providing switched digital service to it's users within the next ten years. The principal driving force in the transition to a digital system is the requirement for high performance secure voice service. Additionally, the anticipated data requirements in this time frame can be handled most effectively by a digital network. The characteristics of a switched digital network which impose timing and synchronization requirements on the system design will be presented.

Several alternative approaches to implementing a timing subsystem suitable for a switched digital communications system have been considered. These include pulse stuffing, independent stable clocks, and clock correction techniques. The advantages and disadvantages of each approach will be discussed relative to both the strategic and tactical communication system requirements.

An inter-agency committee worked through mid-1973 to develop recommended parameters for interoperability between the various DoD communications systems, allied systems, and the commercial networks.

BACKGROUND

Synchronization in a communications system can be considered on at least three different levels—terminal-to-terminal, link, and network. Terminal-to-terminal synchronization is widely used today for digital communications between data terminals using modems connected by circuit-switched or dedicated analog channels. The terminal device, or the transmit portion of the modem, provides transmit clock. The receive modem develops timing from the incoming data stream (transmitted as quasi-analog signals through the analog channel), and detects and regenerates the digital data. Frame synchronization is developed by the terminal equipment as required. Thus the terminals, consisting of digital devices and modems, are designed to operate over half-duplex or full-duplex circuits, and develop timing and synchronization between the calling and called terminals independent of the network.

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Link synchronization is used in digital multiplexing, such as in the commercial T-type PCM carrier equipment. In the primary channel bank a group of analog channels (24) are digitized and combined into a single digital stream. Timing is supplied by a clock internal to the channel bank. The digital stream is either transmitted to the distant link terminal via cable or radio, or is combined with several other similar streams in a second level time division multiplexer (TDM). Since each channel bank has an independently derived time base, the TDM must asynchronously combine the various inputs to obtain a single higher rate output. The pulse-stuffing technique is used, whereby pulses are added to each input as needed, to bring all inputs to a single common higher rate. These added, or "stuff", bits are deleted at the receive terminal using information carried on a control channel associated with the second level multiplexer. In this case, as in the terminal-to-terminal case, timing and synchronization is provided between transmit and receive channel banks. The network has no synchronization requirements. The individual channels need not be synchronized with one another because the digitized multiplexed channels are returned to their analog form (which does not require timing) at each switch. A circuit may be digitized a second time at the output of a switch, but it will be to a new time base established by another PCM channel bank.

Network timing and synchronization must be considered when digital multiplexed channels are to be switched. This follows from the requirement for many different digital channels originating at various points in the network to be simultaneously passing through the switch with varying connectivity. If the switch uses time division switching, all these channels must be operating on the same time base as the switch. Even if a space division switch is used, where common timing is not required in the switch, common timing will nevertheless be required at the multiplexing point. That is, if the channel carrying digital signals from device "A" is to be multiplexed with the channel servicing device "B", these channels must be synchronous.

Precise network synchronization is fundamental to maintaining bit integrity in a digital switched system. Even when high error rates are experienced on the transmission media, or when the multiplex equipment loses framing and generates an error burst, if the time base is accurately established between the two nodes the system can maintain synchronization through the link interruption. This justifies a precise synchronization specification.

NETWORK SYNCHRONIZATION CONSIDERATIONS

There are two principal approaches to achieving network synchronism—(1) operate all terminals independently and use the pulse stuffing technique to align the channels at the switches and multiplex, and (2) develop a form of synchronous network such that all equipment is operating at a constant frequency or time base.

Although the channel pulse-stuffing technique is technically sound, and offers the possible advantage of avoiding network synchronization problems, the tremendous proliferation of stuff-destuff devices and attendant cost, reliability and maintenance problems, etc., act to negate this advantage. These devices would be required at every digital channel terminal, at every channel termination on a digital switch, and at every channel input to a multiplexer. No digital network now in the planning stages is known to be based on individual channel pluse-stuffing. Thus only the alternative of a synchronous network is considered further in this paper.

The definition of "synchronous network" can become highly complex and unenlightening. From a practical viewpoint, the principal parameter is the period of time over which synchronism is maintained. For example, a pair of interconnected Teletype machines are synchronous for the period of one character. Similarly, an independent clock technique is described later which provides network synchronism for periods on the order of one day. The objective for the Defense Communications System (DCS) is network synchronism for an unbounded period of time, which requires the same average frequency at all nodes of the network over some specified period of time or equivalently, the maintenance of a time coherence with some fixed, specified tolerance between all nodes of the network.

In addition to the network timing system which provides the time and/or frequency base throughout the system, "elastic" buffers are required at the termination of each transmission link at a network node. The purpose of this buffer is twofold: (1) to provide a reservoir of bits to adjust for instantaneous differences in the transmitting and receiving rates at the two ends of the link, and (2) to adjust for variations in the absolute time delay through the link. The size of the buffer will depend on the magnitude of these two factors, and on the digital rate of the link. Thus clock tolerance and buffer size, adjusted by path delay variations, can be traded to obtain the most effective system design.

A number of network synchronization techniques are capable of satisfying the basic communications requirement for keeping bits in the proper sequence at time division multiplexers and/or switches. These include such concepts as: (1) timing derived from external sources such as the Loran-C navigation system, (2) an independent clock system in which precise clocks are placed at each node, (3) discrete control correction (a form of frequency averaging) in which a weighted average of the contents of the storage buffers at each node are used to correct the frequency of the nodal clock at discrete intervals of time to prevent buffer overflow, and (4) time reference distribution in which time reference information is distributed over every transmission link of the network to assure that all nodal clocks of the network have the same time.

One presently planned communication system (TRI-TAC) will use the independent clock system with a tolerance on frequency rather than time. The principal advantage of this technique is that the timing of each node is self sufficient and independent of the rest of the network, which is a highly desirable property for a tactical, mobile system. Atomic standards will be employed at each node to provide a frequency accuracy on the order of one part in 10^{11}. This accuracy permits the use of reasonable size buffers to equalize the frequency difference between nodes for periods up to 24 hours. The buffers are reset, with attended link interruption, when required. The impact of link interruption for buffer reset is considered undesirable, and it is not acceptable for a strategic world-wide communication system.

A different technique, which avoids the buffer reset requirement, obtains the time reference for the nodal clocks from a source external to the communications system. Several sources could be used such as Loran or navigation/timing satellites. The use of Loran-C to provide the reference imposes the least technical risk of all the different techniques. It can be made compatible with other systems if satisfactory standards and buffers are provided. Its accurate time can be used for the resynchronization of switches, multiplex, and cryptographic equipment. It is an existing technique for which considerable experience has been accumulated. It could be implemented with a high degree of confidence. However, the survivability of a communication system based on an external reference system must be considered, since the required use of an external reference system for the DCS would make that timing system a "desired" target. Also Loran-C presently does not provide world-wide availability, thereby limiting its application.

The discrete control correction system uses the weighted average of the contents of all of the buffers at each node to make frequency corrections to that nodal clock at discrete instants of time. The timing at the nodes is independent except at these discrete correction times. Studies have shown that this technique provides a stable network and frequency base, and that its frequency can be locked to that of an external network by selecting the proper weighting factors. Its major advantages are simplicity of implementation and the lack of any requirement for resetting of the data storage buffers.

The time reference distribution system might be considered to be an upgrading of the TRI-TAC independent clock technique, wherein the clock time at each node is corrected instead of resetting the buffers. In this concept the communications path is used for the distribution of a time reference. This reference is based on the master clock in the system; e.g., the Naval Observatory. All nodes have their time traceable back to this master. If the master is lost, provision is made to pass this function to another "qualified" node in the system. When considered from an overall system point of view, including system monitoring, maintenance, trouble shooting, and the application of future technology, it has many advantages. Since a time reference is available from every incoming link at a node, each node will always have a time reference if it is connected to the network. Thus the technique is highly survivable. Its major disadvantage is that it is somewhat more complex than other alternatives and has not been proven in practice. However, its concepts are closely enough related to systems which have been or are being implemented so that it can be approached on an evolutionary basis with a high degree of confidence. Refer to "A Time Reference Distribution Concept for a Time Division Communication Network" for a more detailed discussion of this technique.

DOD INTEROPERABILITY COMMITTEE RECOMMENDATIONS

Interoperability among the DCS, tactical systems, foreign allies, and domestic and foreign commercial systems is deemed an essential requirement in the design of future systems. Common, or interoperable timing and synchronization between these systems is a basic parameter in achieving this requirement. To address this, and the many other parameters involved in interoperability, a joint committee was formed operating under the co-chairmanship of DCA, TRI-TAC, and NSA. Also participating were the representatives of the military services and the OJCS. The report of this committee, "Final Report of Committee on Interoperability of DoD Telecommunications", dated 20 September 1973, contains recommendations for common or compatible values, methods, and procedures for the system parameters considered to have an impact on the ability to provide end-to-end encryption of DoD telecommunications systems. Specific recommendations are made for network timing and synchronization.

Several forcing factors drive the selection of the time/frequency nodal tolerances for the DoD communications systems. These include the considerations for tactical applications, performance suitable for the long-haul DCS, and the need to maintain bit-count integrity for satisfactory overall digital system performance. Tactical applications involve optimizing parameters for simplicity, survivability, flexibility, ease of movement, and reconstitution of network operations. In the light of these requirements, an independent clock system with frequency tolerances was specified as best meeting these tactical requirements. However, buffers must be reset on occasion, causing traffic interruptions. Since interruptions to the DCS carry a much greater impact, such a system in unacceptable for the DCS unless other approaches cannot be proven or are substantially more costly.

Recognizing the near-term need for digital systems, the committee recommended that equipment under current development continue to utilize the independent clock approach designed to meet the specification tolerances of TRI-TAC (Table 1). This frequency tolerance (one part in 10^{11} per day), combined with properly sized buffers, will limit buffer reset to at most once per day when frequency standards

Table 1

TRI-TAC Timing Specifications

	Frequency Tolerances	
Primary STD	**Secondary STD**	**Backup**
1×10^{-11} /day	1×10^{-11}/day	1×10^{-9} /day
1×10^{-11}/6 mos.	1×10^{-10} /6 mos.	
Setting Accuracy		**Repeatibility**
Primary STD	**Secondary STD**	**Secondary STD**
1×10^{-11}	1×10^{-11}	3×10^{-11}

at adjacent nodes are far from their nominal values in opposite directions. Such current development must not preclude the future inclusion of some form of network clock correction technique to provide the future capability for long-term network synchronization, fail-safe operation in the equipment failure mode (that is, utilization of the independent clock system in a fall-back mode), and avoidance of the need to reset buffers.

As an objective for the ultimate DoD, a time tolerance of ±2 microseconds between any two major nodes was recommended. Minor nodes, such as PABX's, could be slaved to major nodes and must provide independent timing to their subscribers whenever such minor nodes become isolated from the network.

The TRI-TAC timing requirements will be met through the use of atomic frequency standards. Tactical atomic frequency standards are proven and their costs, including the required buffers, are a small fraction of the nodal costs. Their performance is two orders of magnitude better than currently planned commercial standards. Therefore, no difficulty with commercial interfaces is expected in this respect. As techniques are proven and implemented to attain the ±2 microsecond time tolerance objective for the ultimate system, both frequency standard and the time standard can coexist in the network without difficulty or constraint.

CONCLUSIONS

The adoption of the recommended frequency standard for the implementation of near-term DoD systems will result in garbling a relatively small amount of traffic when buffers are reset. While this standard is in use, care should be taken in network operation to minimize this effect. Such care includes: resetting whenever traffic is interrupted for other purposes such as crypto key change on the link; preplanned resetting at low traffic periods; and off-loading of switched traffic prior to resetting.

The recommended objective for future DoD systems requires time coherence to a specified tolerance throughout the network. Although time coordination among the many nodes of a large communications network has not been accomplished, the basic concepts involved have been exercised in the coordination of such Navigation networks as Omega and Loran-C, and through the DSCS time transfer program. Thus, it is believed that a long-term coherence between nodes of a network is a feasible and useful objective for communications purposes, and will provide a precise source of time to other users as well.

QUESTION AND ANSWER PERIOD

DR. REDER:

Did I understand you right that you said the TRITAC committee recommended the use of the atomic standards with the provisions that they are not supposed to be reset to the standard in frequency more often than once a month—once in six months?

MR. MENSCH:

As I understand it, if rubidium standards were used, they would have to be reset in frequency occasionally. If they were used—there is a contractor option. The contractor chose to go cesium, there is no reset requirement in that type of clock, as I understand it.

DR. REDER:

This is my question. Is there no requirement? I think there is. If you do not allow for resetting the crystal, for instance, in the 5061, you may be in trouble, if the requirement is 1 part in 10 to the 11th.

MR. MENSCH:

Will that cesium clock stay within absolute center accuracy, to within 1 part in 10 to the 11th?

DR. REDER:

I have my doubts.

DR. WINKLER:

I think there is a misunderstanding here.

So far as I understand your requirements, Mr. Mensch, the emphasis is on external reference. In other words, this, what you are referring to, would have to be incorporated in the maintenance instructions for that cesium standard. It is true that the cesium standard if left all by itself for one-half year would not necessarily stay within 1 part in 10 to the 11th, but that can be taken care of following the instruction manuals in reference to the cesium standard itself.

That is, in my opinion, fundamentally different from the situation with the rubidium standard where you will have to make even larger adjustments, with respect to an external reference.

MR. MENSCH:

This is my understanding also, Dr. Winkler, that in the case of rubidium, something, like the traveling clock, or some external means would have to be brought in to that terminal in order to bring that within the tolerance window that would be allowed.

DR. REDER:

Apparently I took too literally what you said. If you permit maintenance, which means you watch the meter, and if the error meter shows a deviation more than a certain amount, that you are permitted to reset it, fine.

I thought maybe there was somebody standing with a fly swatter and you know, knock you on the hand or something if you touch it.

(Laughter.)

DR. KARTASCHOFF:

May I perhaps add to this discussion by saying that the current view is in my country now, my own and some of my colleagues, about the use of rubidium versus cesium? We intend to use rubidium on the relatively low level, low rank exchange—not the lowest, but low rank exchanges, and we will slave them to cesium standards in the country.

You just have to look at the results in the U. S. Naval Observatory—they kept a part in 10 to the 12th over six months.

MR. MENSCH:

This would be in more of a synchronized network. Now, in the TRITAC thing I am referring to, let's assume that they implement the equipment that is used at a node with a rubidium standard. These would be sprinkled throughout a network. There would be no synchronization or adjustments between them. There would just be buffers between them, and those buffers are large enough to soak up that frequency difference over some period of time, like 24 hours.

If that buffer fills in that period of time, you then push the button, throw some bits away, and start over. They will also automatically push that button if the link fails between them, if you have a fade. There is another aspect of this, that this link will be incrypted, and periodically we have to come in and change the variable in that crypto equipment, at which time again we drop sync.

So, it is not just due to frequency errors. Will we have an opportunity to, lets say, not just to buffer fill or empty, will we have a situation where we have a loss of sync and get to reset the buffer.

But the point is that each of these nodes in the network is free-running, but they are synchronous for a finite period of time.

Now, we in the long haul business, let's say, of the Defense Communications System, do not want to design a system that requires us to drop sync on purpose, so we are staying on top of that now, let us correct those clocks by some means, either through external timing system, or by distributing time through our network, and as long as we keep those clocks corrected everybody is happy. If we do lose that system, we will then fall back in a fail safe mode to running independently over a short period of time, as short as 24 hours.

Now, the interesting aspect, if we look at the impact of the satellite systems in such a communications network, since satellites will be—are becoming, if we ever get some satellites up that work, a very important mode of communications. The potential variation in that path, depending on the stability of the orbit itself, but we could end up with hundreds of thousands of bit buffers to soak up the absolute path delay variations of a satellite link, if we are working on the order of, let's say, a megabit or two, of our communications link. And we do have some orbital perturbations in that bird.

We are talking about fairly sizeable buffers, and are accepting the fact that in a synchronous network this must be. Now that will be a special box in the satellite link, as opposed to the land situation.

DR. WINKLER:

May I make another comment here, not a question but a comment.

It is in regard to the frequent reference to a master reference standard—presumably they use the U.S. Naval Observatory's master clock.

In view, however, of any of these systems really being totally worldwide, the question of possible interface with NATO or other allies inevitably arises. And here, I would like to inform you that, for those who do not follow the time scale bulletins regularly, that we have demonstrated the capability during the last seven months or so, to stay within one-tenth of a microsecond of the international time reference.

It is our belief that even with very small variations in IAT, the international reference time, that we can sufficiently well in advance predict these changes to stay safely within one microsecond. Actually, we have done ten times better.

So, giving you a number of two microseconds, to which you want to keep all these clocks, I think that you have already a system available in which you have access to any of the national references in the international system, and for which corrections to 0.1 microseconds are known.

MR. MENSCH:

You are saying you are demonstrating the feasibility of being able to achieve this.

DR. WINKLER:

Yes, These numbers are published in advance, in fact. We extrapolate the difference between the master clock and the international BIH time, and if you look at the BIH bulletin Series D, which we distribute upon request, if you look through these you will find that we only have random fluctuations around zero, minus one-tenth, plus one-tenth around zero. It can be done. I am quite confident that we will continue to do so in the future.

MR. MENSCH:

Dr. Winkler, you made one point that I had a note that I didn't mention, and it comes up this way, that we will also have a requirement to interface our digital network with commercial people.

We are encouraging, and plead with anybody that is here, that the commercial systems also consider operating off the same master clock, for international time, to ease the problem of when we hook our channels to them, if they are running on a separate time base, we are going to have to have an awfully big buffer, or reset, and this becomes a problem, because the majority of the Defense Communications Systems is leased channels to the common carriers. We do not own the majority of our circuits.

We are hoping these common carriers, such as the Bell Digital Data system, DATRAC, NCI, et cetera, will go toward not only having master slaves, but that their master clock becomes time coherent with that of our master reference.

DR. WINKLER:

Yes. There is yet another problem which has to be addressed, or not forgotten, and that is the establishment of a well-defined hierarchy in the interest of survivability.

MR. MENSCH:

This is a point that I think was made in Stover's paper. These rules provide exactly this, that there is built into that type of a system, or a master slave system, a procedure that if you lose your master clock, you have a graceful passing down of the master responsibility.

DR. WINKLER:

And that is exactly why we want to use precision clocks, and that is where the difference between a synchronized system and a coordinated system is most striking.

A synchronized system does not operate with any inertia. However, a coordinated system, once you have all your clocks in operation for a couple of weeks, you can actually completely cut your communications, as we have done in other systems already, and you will still stay within a microsecond for a considerable period of time.

MR. EASTON:

We have time for one more question?

MR. CHI:

In view of your stated requirement of a part in the 11th per day, and plus or minus two microseconds, and especially if you use a hierarchy does it not mean also that almost any kind of standard with reasonable stability, such as a crystal, should also be considered. It is just a matter of tradeoff, with the frequency of correction as well as the costs.

MR. MENSCH:

And the size of the buffers that are to be used. It is a tradeoff.

So, the tactical people are going to this atomic clock version such that they can have their little node, or their communications node, and put them and move them several times a day, and not have the network synchronization problem. They just turn it on and they are all set.

This is the tactical doctrine.

In the DCS, where we do not have the mobility requirement, we can see a sprinkling of precise clocks, be they atomic or disciplined, or however we achieve it. But that it is coordinated, as Dr. Winkler says, that they may very well be. The majority of our nodes may be disciplined quartz oscillators, for example, from the cost effective standpoint. Certainly with seven hundred nodes scattered around the world we do not want to have triple redundancy cesium beam standards every place, just from a maintenance standpoint.

But certainly at our major switching nodes it would be a good idea, since these would be the next step in the evolution of hierarchy.

So, the big cost gain is yet to be done. We have not done this, although this then is going to be part of the choosing of what concept is used to arrive at this time coordination, and this is our next step of study to select and recommend the appropriate concept for a future system.

MR. EASTON:

Thank you very much, Mr. Mensch.