SUGGESTED ATTRIBUTES FOR TIMING IN A DIGITAL DCS

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ABSTRACT

Sometime in the future, the Defense Communications System (DCS) will predominately employ digital techniques. To be effective, such a system, which employs time division multiplexing of digital signals, must include a system timing capability. This follows because the time relationship of each particular pulse to the other pulses in the same sequential stream is fundamental to interpreting the information contained in each pulse. This time relationship determines the assignment of a particular bit to a particular use and a particular meaning. The loss of proper timing can cause all received information to be meaningless--a totally unacceptable condition. Thus, timing is a function of major importance in a digital military communications system (particularly if encrypted). Fortunately, correct timing is not difficult to achieve in a simple point-to-point digital communications system, and many approaches can provide at least a minimal timing capability in even the most complex digital communications systems. However, some of these approaches are unacceptable for the DCS, and the remaining ones have various degrees of acceptability.

To determine the value and effectiveness of the different approaches in satisfying the needs of the DCS, a set of desired attributes is needed against which they can be evaluated. This paper presents a set of suggested attributes for a timing capability for the DCS which must be capable of supporting full-scale warfare in addition to peacetime needs. Reasons for each attribute are given.

INTRODUCTION

Although this paper which is devoted to needed characteristics for a particular application of timing technology might seem a little out of place among the many technical papers presented here, this is a "Planning and Applications" meeting, and this paper is intended to call attention to some important applications considerations for timing* capability needed by a digital Defense Communications System (DCS). Requisites of a specific application are often equally as important as technical items and sometimes more so. For good planning, both technical factors and their specific application must be considered in determining a course of action. In previous annual meetings, technical possibilities for synchronizing a digital DCS have been discussed, so that it should be understood that providing the attributes suggested in this paper for timing in a digital DCS [1,2,3,4] is technically and economically practical. However, the requisites of the specific application probably have not been adequately considered in those previous papers. In particular, they did not demonstrate an adequate appreciation for the differences between the needs of peacetime civilian digital communications networks and worldwide military networks, such as the DCS, which are needed for support of any full-scale war. The suggested attributes presented here for timing in a digital DCS are offered for consideration as fundamental needs for such a system. It is believed that as new equipments are developed and procured, with proper planning these attributes can be provided quite economically and numerous problems avoided.

BACKGROUND

It is generally accepted that for the types of communications provided by the DCS, the advantages of digital systems over analog systems are almost overwhelming [5]. Therefore, it is expected that sometime in the future, the DCS will predominately employ digital techniques. Such a digital communications system requires a timing (synchronization) function in order to be effective. The time relationship of each particular pulse to other pulses in the same sequential stream is fundamental to interpreting the information contained in the pulses. If time division multiplexing is used, this time relationship determines to whom the information belongs and also what it means; i.e., particular time slots are assigned for particular purposes.

* Note: The word timing is used here in the general sense which includes synchronizing as a special case. It implies a wide variety of related meanings including: (a) scheduling; (b) making coincident in time or causing to occur in unison; (c) setting the tempo or regulating the speed; (d) ascertaining the length of time or period during which an action, process, condition or the like continues; (e) causing an action to occur at a desired instant relative to some other action or event; (f) producing a desired relative motion between objects; (g) causing to occur after a particular time delay; or (h) determining the moment of an event.

In analog communications systems, noise or small errors in either signal amplitude or frequency can cause undesirable but usually acceptable signal degradation, and the same can be said for isolated errors in a digital communications system. However, the loss of proper timing in a digital system can be catastrophic, causing all received information to be meaningless -- a totally unacceptable situation. This characteristic makes the timing/synchronization function one of the most important functions in a digital communications system. Fortunately, correct timing is not difficult to achieve in a simple point-to-point communications system, and there are many different approaches that can provide at least a minimal timing capability for even the most complex digital communications systems [1,2]. However, some of these approaches are unacceptable for application in the DCS and those remaining have various degrees of desirability. A set of desired attributes is needed against which the different approaches to timing can be evaluated. This paper offers a suggested set of such attributes and explains their importance to the DCS.

One of the most fundamental changes that is going on in the DoD community is the change in perception of the DCS from that of a peacetime system to a communications system capable of supporting full-scale war [5]. In developing desired attributes for the timing/synchronization of a digital DCS, is is assumed that the DCS will not only transition from analog to digital, but also to a network capable of supporting full-scale war. The major difference between a communications system designed for peacetime and one designed for wartime is the need for survivability of sufficient communications capability to make our military forces effective. Survival of the timing function in a digital communications network is essential to survival of the communications function. It can also be highly desirable to have an acceptable timing capability available even when the communications function is not available. One reason is that the timing function can be useful for establishing or reestablishing the communications function. For example, the length of time required to acquire synchronization of a spread spectrum signal that is being jammed, depends on the size of the search window. An acquisition search window of a few milliseconds might require a thousand times longer to acquire synchronization than a window of only a few microseconds. This capability (accuracy of a few microseconds) is already used in the DSCS to permit the acquisition of spread spectrum signals within a reasonable period of time in a jamming environment.

In the past, problems have occurred in the timing relationship between different digital communications networks that were not originally engineered to communicate with one another. In some cases, these problems were overcome by the addition of variable storage buffers and adequate clocks to control them, while in other cases modification of equipments might also be required. Even after these corrective measures, it might sometimes be necessary to interrupt traffic to reset the variable storage buffers. It is not always possible, at the time of equipment development, to predict just what system interfaces will be required during the lifetime of an equipment. Therefore, design of the equipment to meet a minimum timing compatibility standard is highly desirable for avoiding future problems. Such a timing compatibility standard should be developed to follow a well-developed DCS timing plan. This DCS timing plan should satisfy a set of desired DCS timing system attributes such as those presented and discussed in this paper.

DESIRED TIMING SYSTEM ATTRIBUTES

In this section, a set of suggested timing system attributes for a digital DCS are presented, following which the importance of each attribute is discussed. Parts of the discussion of some of the attributes presented early on will also apply to attributes that follow. This is particularly true of the discussion of the first attribute.

Time and frequency reference information utilized in applicable Federal Government telecommunications facilities and systems shall be referenced to (known in terms of) the existing standards of time and frequency maintained by the U.S. Naval Observatory, UTC (USNO), or the National Bureau of Standards, UTC (NBS).

Discussion: This is a direct quote from FED-STD-1002, and it is DoD policy to comply with Federal Standards. However, different people have chosen to interpret this standard in different ways. The following discussion will illustrate the need for using a standard timing reference and should help to bring out a desirable interpretation of the first attribute as applied to a digital DCS.

Can you imagine trying to make connection at a busy airport, such as Chicago's O'Hare, if each airline used only its own clocks, and clock time for each airline was different from that of the other airlines? At the least, it would cause considerable unnecessary inconvenience. A century ago, that was the situation that existed in some large railroad stations. You could set your pocket watch to any one of a number of clocks on the station wall, each indicating the official time for its associated railroad line. Problems with this are obvious, but the railroads were heavily criticized when they adopted a standard railroad time in 1883. Standard time slowly gained popularity, and in 1918 congress passed the Standard Time Act. The advantage of standard time for planning interconnecting flights when using modern air travel is quite obvious. Crossing time zones can cause problems to travelers in keeping track of which time zone applies to their present location. These time zone problems are sometimes alleviated for both travelers and long distance electromagnetic communications by using a worldwide time standard such as coordinated universal time (UTC).

The problems of scheduling the transfer of bits of information from one transmission link to another, where each bit must be made to coincide with its assigned time slot, are somewhat similar to those of transferring passengers from one airline to another. Each is made simpler by well planned and well maintained traffic schedules. However, a major node of the digital communications network will typically handle many millions of bits each second, and the bits travel between nodes at speeds up to 186,000 miles per second (3 x10 Exp 8 m/s). As with the passenger trains, although it is not necessary that all clocks read the same (bits can be stored in buffers just as passengers can be stored in depots), it is obviously highly desirable; and whereas tolerances of a few minutes were acceptable for the railroads, tolerances of a few microseconds are desirable for a high capacity digital communications network. Corrective action for an information bit that misses its assigned time slot might be even more difficult than corrective action for a passenger who misses an assigned aircraft flight. Unlike the airline passenger, a single communications bit that misses its time slot assignment is likely to cause those that follow to miss theirs also.

Whenever a new communications system is planned, the system planners seem to quickly arrive at the conclusion that it is only important to provide synchronism within their own system -- that they don't have to worry about other systems that are being planned. Doesn't that sound like those old railroads where each had its own time? Like the railroads, each can be made to work, but also like the railroads, taken together they present problems that can easily be avoided by using a standard time system.

In the past, this country's largest telephone company has provided for its own digital synchronization needs as it saw those needs, and interfacing companies had to accept timing from that company. Although that policy has not changed, present planning is to eventually reference that company's atomic clocks to the National Bureau of Standards. What is wrong with an approach where one telephone company provides a timing reference for all of the others? First, there are two U.S. Government organizations charged with keeping standards of time and frequency - the National Bureau of Standards and the Naval Observatory. Master clock time at each of these organizations is in close agreement with Coordinated Universal

Time as determined by the Bureau International de l'Heure, to which both of these U.S. Government organizations contribute timing information. Second, although smaller U.S. telephone companies might be willing to accept their timing reference from the largest U.S. telephone company, the likelihood of this occurring internationally is much smaller -- an international time standard should be used. Third, as now being implemented by the telephone company, their synchronization system permits time delays to accumulate as the timing information is passed through the system, and in some cases individual local clock errors also can accumulate through long tandem connections. This means that clocks in different parts of the network have somewhat different time (or phase), although clocks at adjacent nodes are within acceptable (bufferable) tolerances. Although this is quite satisfactory for civilian digital communications, it is quite likely that it could not be tolerated by some future military systems. The functional division between digital communications and computation by digital computer is becoming less distinct, as well as that between communications and navigation or position location. For these relationships to be mutually beneficial, all should be based on common time standards. From a wide variety of viewpoints, the digital networks of the DCS should fully comply with a restrictive interpretation of FED-STD-1002.

<u>Timing tolerances (clock errors) at major nodes of digital DCS networks should be specified in time or continuous phase (not modulo 360 degrees) rather than frequency.</u>

Discussion: Relating this to the previous example of making connections between flights at busy airports, it is not enough to have the clocks for all airlines running at the same rate, but they should also indicate nearly the same time. In digital communications, the timing/synchronization system is used for assigning individual communications pulses to specific time slots. For this to be effective, tolerances should be established on the location (in time or phase) of the time slot and also on the arrival time (or phase) of the assigned pulse. Received bits should be retimed by temporarily storing them in variable storage buffers from which they are removed at the proper time as determined by the local clock. If the local clock pulse is not at exactly the right time, it will be either early or late by a certain phase angle at the pulse repetition rate; or, alternatively, early or late by a certain amount of time (in microseconds). A timing tolerance stated in microseconds is normalized, which makes it convenient to apply to any of a large number of data rates likely to be encountered throughout the communications system. The size of the variable storage buffer determines the ability to accommodate early or late arrival of pulses relative to the local clock. The phase (or time) tolerances of the local clocks and the bit rate of the communications stream along with expected variations in signal path delays determine the necessary size of the buffers.

There is no simple way that these timing errors (the ones of basic significance to the digital communications timing system) can be stated as frequency errors (Hertz) or fractional frequency errors. However, because of the relationship between phase angle and frequency (frequency is the time derivitive of phase angle), the phase angle error at any time can be determined from an initial phase angle error plus the time integral of the frequency error from the time of the initial phase error to the time of the measurement of interest. In order for the phase angle (or time) error to be bounded, the average frequency error must be zero. Any nonzero average frequency error will eventually result in an unacceptable phase error; i.e., it will eventually require interruption of the communications traffic to reset the variable storage buffers to prevent them from either emptying or overflowing. If the allowable phase (or time) tolerance has been specified, average frequency errors that will permit that tolerance to be maintained for a specific time can be determined. In general, relatively high errors can be accepted in the pulse rate for a short period of time. As an example, assume that the pulse frequency in a system which initially has no phase error, is 1 percent low over a period of five pulses, and then is 1 percent high for the following five pulses. After the first five pulses, there will be a phase (or time) error equal to 5 percent of the pulse period -- a normally acceptable value -- and after the second five pulses (a total of ten pulses) the error will be zero again. Now as a further example, assume that the frequency had been high for five billion pulses instead of only five pulses and then low for another five billion pulses. Then, if the maximum phase (or time) error were not to exceed 5 percent of the pulse period, the frequency error could only be one billionth of 1 percent. In both examples, the phase (or time) error is the item of predominant interest, and the frequency error is of interest only because of its relationship to the phase (or time) error.

<u>The timing/synchronization function in the DCS should not be solely dependent on the continued operation of any particular network node, transmission link, or facility external to the network.</u>

Discussion: Since nodes of the DCS and the transmission links interconnecting them are subject to enemy destruction or electromagnetic jamming attack, it is obviously desirable to construct the timing system to minimize the impact that the loss of any link or node, or any combination of links and nodes, would have on the timing function for the surviving portions of the network. No specific nodes or links in the network should have such individual importance to the network timing function that a successful enemy attack on them would seriously degrade the network timing. No specific parts of the timing system either within or external to the communications network should appear to be particularly attractive targets to an enemy. This implies that control of the timing system should be distributed rather than centralized.

Following the loss of any node or transmission link of significance to the timing function, either through failure or enemy action, the timing system for the DCS should automatically reorganize itself.

Discussion: For any communications network timing approach, there is either some optimum hierarchy of the links and nodes, or some optimum set of parameters for providing a stable system, or both. When links or nodes of the network are lost, adjustments to the networks (which might include partitioning or reconfiguration) should be made to assure that degradation of the timing function is acceptably minimized. In civilian peacetime systems, where the need for such adjustments only results from occasional equipment failures or rare acts of nature, it is acceptable to manually make the necessary adjustments, and necessary repairs to the failed equipment could be expected to be made promptly. However, in a wartime situation, extensive damage to the military communications system due to enemy action might simultaneously occur in many widely separated areas. The maintenance and repair function might be intentionally or unintentionally impeded by enemy action. Access to areas where repairs are needed might be severely restricted, and required skilled personnel might not be available when needed. Therefore, the timing/synchronization system for a military communications system should be highly automated. In particular, the reorganization of the timing system following the loss of any link or node of the communications system should be totally automatic; and by attribute number 3, it should also be distributed rather than centralized.

So long as any communication link to a node survives, it should be capable of supporting the timing function.

Discussion: Unlike a civilian communications system where failures in the timing system can be expected to be random and infrequent, sudden massive destruction of many parts of the wartime military communications system can be expected over a short period of time. Whereas a couple of backup paths would be quite adequate to assure timing at a particular node in the peacetime civilian system, it might not be unusual to lose all but one communications link to a major node (or even several nodes) in a wartime military system. Since it is not possible to assure which link might remain intact following such an attack, every link must be capable of supporting the timing function.

A node temporarily disconnected from the network should have the timing capability to rapidly reenter the network -- including capability for rapid synchronization of spread spectrum signals in a jamming environment.

Discussion: Under jamming conditions, the length of time required to test a given timing relationship to determine whether or not it is in synchronization is greatly increased. If 1 second of sampling time is required to make a decision between being in synchronization or out of synchronization for each 10 nanoseconds change in timing, an uncertainty window of 10 microseconds could require a total of 1000 seconds to search. If correct synchronization were not found the first time through, the window would have to be searched again. Obviously, the amount of search time required depends upon the design of the system and the environment in which it must function, but it is desirable to maintain a small search window for acquiring or reacquiring synchronization in a military communications system which is subject to enemy jamming. In addition to speeding up the synchronization process for spread spectrum equipment, good system timing can also be used to speed the synchronization of multiplexing and cryptographic equipment. This reduces the amount of time the equipment is out of synchronization following signal outages, thereby minimizing the loss of communications traffic.

To the extent practicable, disturbances in the clocks at individual nodes of the network should be prevented from propagating to other nodes of the network.

Discussion: Errors in local clocks as a result of disturbances at remote clocks propagating to the local clocks use up a portion of the available phase tolerance at the local node and make it more susceptable to loss of synchronization from other causes. This includes an overall reduction in the stability of the timing system making it less capable of accommodating signal fades and other transmission disturbances. This attribute is particularly important if the disturbances occurs just prior to the time a node enters a backup free-running mode of operation where an induced frequency error will be integrated over a long period of time producing a very large phase error. This attribute provides increased resistance to enemy attack and perturbations.

A normally operating timing system should not require interruption of traffic solely for resetting variable storage buffers to accommodate errors in uncoordinated system clocks.

Discussion: Planners of several civilian digital communications systems in North America considered the use of accurate free-running clocks with provision for occasional interruption of traffic to reset variable storage buffers [6]. All of these system planners rejected this appooach because they felt that it would be unacceptable to their customers. It is even less desirable in a military system where there are additional functions, such as encryption and spread spectrum transmisssion, which require synchronization. The worldwide nature of a military network prevents use of a low traffic night time period for such interruptions because the sun never sets on such a worldwide network.

<u>Capabiliy to reset variable storage buffers with minimum interruption of traffic should be provided in order to permit continued communications by operating in a free-running mode whenever means for clock coordination is not available.</u>

Discussion: This is a last ditch backup mode of operation to permit continued communications (although degraded because of required interruptions) if all means of clock coordination should be lost while at least one communications link is otherwise intact. In a well designed system, it should be a very rare occasion when this mode of operation would be required, but it would be shortsighted not to provide this capability. The timing system should not be permitted to be the sole reason for communications not being available. This attribute could be very important for the very rare occasions when it is needed, because this could be a period of time when continued communications is of utmost importance.

<u>Systematic self-monitoring of the timing function should be provided.</u>

The timing function in a digital DCS is expected to be very reliable. Under normal operating conditions, undisturbed by hostilities, failures will occur very rarely. Under these conditions, it will be very difficult to maintain well trained, experienced personnel for servicing failures to the timing system. Because of this, it is important that the timing system provide automatic self-monitoring and fault diagnosis. It is desirable that such monitoring include the monitoring of the actual timing function in addition to normal power-supply voltage measurements and signal level measurements. Many types of failures that can affect the operation of a timing system can only be detected by monitoring the actual timing function. It is also important to detect pending timing failures long before any interruptions to communications traffic occur. Trend information and automatic statistical evaluation of systematic self-monitoring of the timing function can be used to automatically provide early detection of problems and self-diagnosis of their causes. This information can then be used to automatically indicate the needed corrective action.

<u>Options with potential importance for satisfying future timing</u>

requirements should not be precluded without good reason.

It is a common occurrence that inadequate planning for future needs finally results in a situation requiring either (1) a very large expenditure of funds or (2) forgoing the service. When it arises, this situation always seems to be unexpected because it was not included in the original planning. Sometimes the capability could have been provided at no extra cost at the time of original equipment development, and nearly always at a small fraction of the cost for retrofit after the equipment is fielded. It is difficult to predict at the time of equipment development all of its applications during its lifetime. Therefore, it is very desirable to leave open all options that might make it possible to satisfy those unpredicted applications as they arise, unless this results in some significant penalty, e.g., significant additional costs.

SUMMARY

A set of desirable attributes for timing in the digital DCS has been suggested. The suggested attributes provide for keeping the major nodes of the DCS within acceptable phase tolerances of one another by coordinating all of their phases with the standard provided by the U.S. Naval Observatory (UTC (USNO)) or the National Bureau of Standards (UTC (NBS)) whenever either is available. If UTC is not available, a particular clock within the network is automatically selected as a reference for the rest of the network. Survivability of the network is further enhanced by: (1) assuring that it is not dependent on any one point of centralized or concentrated vulnerability to enemy action, (2) providing adequate automation to accomplish most corrective actions (other than equipment repair or replacement) without manual intervention, (3) assuring that timing coordination is available at any node so long as there remains one functioning communications link to that node, and (4) providing a backup mode for degraded operation of any node that finds its ability to coordinate its clock has been lost for any reason. Any improvement in stability and accuracy through improved clock disciplining procedures will further enhance a system's capability to provide all of these attributes under all conditions likely to occur in a full-scale war.

References:

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QUESTIONS AND ANSWERS

MR. CHI:

I would like to make a comment. Particularly I like your example of the illustration of comparison between people and bits, that is in terms of the requirements between the railroad for the timing and digital communications. I think it was very well illustrated. We talk about the requirements for time, but the fact that you have illustrated it and gave us a very simple example in such a way that most people can understand what it is. Thank you.

DR. STOVER:

The railroads had a hard time, you know, getting standard time across. We are having that same kind of a problem.

DR. WINKLER:

Maybe I should say a few things, particularly about your items 7 and 11, which struck me as very important and very general. Seven has been, if I remember correctly, that means should be provided to prevent the disturbances of a single clock to propagate throughout the system. Now that is something which is, of course, important, not only for your particular application, it is essential to all timekeeping. And what does one do in order to prevent that?

And now, it appears to me that the approach which is usually taken is to just straight average and this is something which has been criticized by several people, the last one, which impressed me most, was an article which I read two years ago in "Die Klein-Hallbacher Berichte", the German URSI reports about the falacies of using the mean as the best estimator in cases of disturbances which are not at all Gaussian and may not be right in time correlation. And in that article, the great advantage of using the median was discussed, that in fact the median, the central point of all incoming time reports which a model point would get from its surrounding points would be a completely insensitive estimator to any individual disturbance. A clock could go any arbitrary amount off and by taking the median instead of the mean, you are safe. It would not be affected at all and I wanted to point that out, that in filtering, in selecting routines to reject such outlyers, the assumption of the normal distribution is an incorrect one because as we deal with digital systems, digital systems are usually outrageously wrong and not Gaussian distributed.

And 11, the importance of satisfying future requirements. That strikes me as something of even greater generality.

DR. STOVER:

It is even harder to get examples of.

DR. WINKLER:

That we so often find the role of management defined as -- These people must think that management must have something to do with monocles to restrict people's choices in the future, while in fact good management ought to enlarge the choices which the future generations have. And I think excellent technical management would be one which keeps wide open all these future choices instead of restricting them in too short-sighted a view. And that, again, is an overriding generality.

QUESTION:

I too have had access to some of the German publications and especially when you are talking about different types of weapons which may be releasing electromagnetic radiation which could affect large numbers of clocks in an area, but the aspect of going to the median also bothers me because there may not be a discrete median. There is a range for which there is a set of values can be the median, so how do you try to solve this problem of large-scale, propagation disturbances with large numbers of clocks being simultaneously disturbed with the ionosphere being disturbed and which all would masquerade and it is the same. I think that is a very major problem in tying everything together.

DR. STOVER:

Well, one of the things that I had in mind at the time that I wrote that was one of the systems that has been very highly discussed in the communications literature for timing for digital communications systems is the so-called "mutual system", in which all the clocks in the whole communications network effect each other, so that the whole system can float around, so to speak, with bulges here and bulges there as far as the error is concerned and everything effects each other. And one flaw in one clock will effect all the other clocks. That was the thing I was really trying to rule out when I wrote that statement. And my preference is to tie everything to UTC, as was stated in the very first one which is a Federal Standard. But as you read that Federal

Standard, different people can interpret it differently, when it says it is traceable to the Naval Observatory, some people will say that it has some frequency that is traceable to the Naval Observatory, while I would like to say time or phase which is stated in one of the later ones. And some people will say that the accuracy with which that frequency needs to be traced to the Observatory is not really very great. Now I disagree with both of those statements as you can tell, and think that we should accurately, in phase, in time, clock the DCS, because it is a wartime system.

DR. WINKLER:

I agree very much and I think that agrees with general principles which have been mentioned recently by Professor Becker. Is he here? Would he like to say something about that?

DR. BECKER:

I will address it in my paper later.

DR. KAHAN:

Have these attributes that you have listed been accepted and implemented within the DCS system?

DR. STOVER:

No. This is the first time that they have been presented as a group, as a desirable. We have to get them accepted. You know how the military works. When you tell somebody you have a requirement, they want to know which directive from the Joint Chiefs state it as being a requirement. So you have to beat on these things a long time before they can be stated as being requirements. So that is why we are calling them "desirable attributes".

QUESTION:

You mentioned item 7 here as non-propagation of errors. Do either one of you have any suggestions as how one might implement the desirable attributes?

DR. STOVER:

Well, the thing I had in mind, of course, was the types of things that I have presented at previous meetings here. I am biased there, of course, and so if you would read the proceedings from the year before last you would get an excellent idea of what I would consider an outline of how to do that.