Time Generation and Distribution

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Invited Paper

This paper presents a broad overview of time and frequency technology, particularly those trends relating to the generation and distribution of time and frequency signals. The characterization of components and systems is also addressed.

I. INTRODUCTION

Recent progress in time and frequency technology indicates that developments taking place today are more far reaching than any of those of the last two decades. The development of laser methods for manipulating the states and motions of atoms should provide dramatic advances in the performance of atomic standards. Advances in satellite time transfer now provide for transfer accuracy and stability well beyond the performance of most atomic frequency standards. Further progress in time transfer should support the application of even the most advanced frequency standards. In parallel with this activity, there is greatly renewed interest in substantially improving the synchronization of telecommunication networks, navigation networks, and electrical power networks. This paper provides a general look at these trends and, when practical, suggests where they are leading. We refer the reader to other papers, particularly to those in this issue, for greater detail.

For brevity, we will use the shorthand approach of simply referring to time measurement or time transfer to imply frequency measurement or frequency transfer as well. Similarly, we loosely use the term synchronization (same time) to imply syntonization (same frequency). Clearly, the requirements for each differ, and a distinction must be made when addressing a specific application.

II. BACKGROUND

A. Accuracy and Stability

We first emphasize the difference between accuracy and stability. Consider the performance of a cesium-beam frequency standard. The accuracy of the standard describes its ability to generate a frequency where the systematic uncertainties (frequency shifts) relative to the ideal (the model) are known. An accuracy statement involves an upper and lower limit for deviations of the standard from the model. In simple terms, the frequency stability of the standard is a measure of its ability to stay within specific frequency limits for some sampling time, τ. The evaluation of the accuracy of a standard is based on a physical model of the standard. The accuracy statement involves a proper combination of all of the errors derived from independent measurements and the theoretical predictions of the model. Such evaluations are inevitably checked through comparisons among the independently developed primary standards of the world. If a standard is highly accurate, it obviously has very good long-term stability. In the world's standards laboratories many take the unproven, but intuitively appealing, position that the best approach to long-term stability is to improve accuracy. The basis for this position is the idea that long-term variations in output are caused by variations in the systematic offsets. By reducing and controlling the offsets, we thus improve both accuracy and long-term stability. Clearly, the accuracy of a standard can be no better than its long-term stability.

Outside the standards laboratory, in practical situations, stability is often the key consideration. For example, if several nodes in a telecommunications system must be properly timed for synchronous communication, it matters little whether the time delivered to the nodes is accurate. All that really matters is that all nodes measure the same time. If, however, the network is very large (many nodes) and synchronization is acquired from several alternate sources, then it may be necessary to require accuracy as well.

Kartaschoff and Barnes [1], in the last special issue of this journal covering time and frequency, present a broader discussion of accuracy and stability. The measures of stability used in this field have matured to the point where they are now the subject of an IEEE standard [2], [3]. The precursor to this standard is a highly referenced paper by Barnes *et al.* [4]. In the historical development of these measures, time-domain methods have dominated. In this issue, two papers are devoted to the statistical characterization of frequency standards. Rutman and Walls [5] describe both measurement methods and the conceptual framework in which they are made. Percival [6] focusses on the characterization of frequency stability in the frequency domain.

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B. Frequency Standards

The major advances in timekeeping in this century have been the development of the quartz-crystal oscillator and the development of the atomic clock. Quartz oscillators are used in almost all timing systems. The number of quartz oscillators produced annually is measured in millions of units, far more than any other type of oscillator. Quartz-oscillator technology has been evolving steadily over a long period. The likelihood is the technology will continue this steady improvement as better crystals and clever compensation schemes are developed (see, for example, Vig [7]).

In order of increasing cost, the four main classes of currently used standards are quartz oscillators, rubidium frequency standards, cesium-beam frequency standards, and hydrogen masers. In general, this is the same as the ascending order of performance, except that the cesium standards provide the best accuracy and long-term stability while hydrogen masers provide the best short-term stability. The volume of atomic standards produced annually is measured in thousands of units.

The atomic clocks of today share two common characteristics: 1) The atoms in all of them move at thermal velocities commensurate with room or higher temperatures. This means that Doppler shifts (and corrections for them) are extremely important. 2) The required difference in the population of atoms in the excited and ground states in clocks is achieved through a pumping or selection process which itself adds complications. For example, the Stern-Gerlach magnets used in cesium standards introduce a transverse velocity dispersion which, through the cavity phase shift, produces a frequency error. In another example, the discharge-lamp pumping of rubidium standards involves excess, broad-spectrum light which complicates the pumping process, and the aging of the discharge lamp contributes to drift and instability. The various types of standards are discussed in greater detail by Lewis [8] in this issue.

We are now on the threshold of a revolution in the design of atomic frequency standards. At the heart of this revolution lies laser control of the motions and atomic states of ions and atoms. Some very general aspects of this revolution are described in Section III.

C. Time Transfer Systems

Ten years ago, the methods for time comparison of widely separated clocks involved uncertainties which were greater than the performance of the best primary standards. In this environment, the development of better standards was largely an academic exercise. Signals could not be reliably transferred to other locations and accuracy claims could not be checked by comparison with other standards. The development of accurate satellite time transfer systems, which has taken place over the past two decades, has changed this. Common-view time transfer using the Global Positioning System (GPS) satellites, pioneered by NIST [9], has proven to be extremely accurate offering global coverage with an uncertainty on the order of 10 ns. The two-way method for time transfer [10], [11], which uses standard satellite communication channels, promises even higher performance. These systems put the accuracy and stability of time transfer (or time comparison) ahead of time generation. The development of better standards is thus no longer academic.

D. Network Synchronization

One of the key practical challenges to time and frequency technology is the synchronization of nodes in major networks such as computer networks, telecommunications networks, electrical power networks, and navigation networks. In the transfer of information in a communications system, synchronous operation provides for higher throughput. Synchronization in electrical power networks supports fault location, event recording, and control of system stability. Better synchronization in navigation networks obviously results in more accurate navigation. In this issue Kartaschoff *et al.* [12] address the synchronization of digital communications networks, Wilson [13] discusses timing for electrical power networks, and MacDoran and Born [14] deal with some aspects of ranging/navigation systems. There are a few general network synchronization issues which underlie all of these systems.

Systems for network synchronization can be divided into two broad categories: 1) peer organizations in which groups of nominally identical nodes exchange time data so as to establish a single self-consistent time scale, and 2) stratified, client-server arrangements in which the time of each node is obtained from a relatively small number of sources or possible a single primary source. By using time servers, the time distribution problem boils down to the determination of the errors introduced by the individual delays between the source and the network nodes. The success of the method will depend on how well these errors can be determined. Although groups of peers must also determine the delays between the nodes, the increased symmetry of this configuration may simplify the problem somewhat since the time of a single node is generally compared to the time of several other nodes connected by different paths with different delays. At least in principle, it is possible to perform a dynamic least-squares adjustment which minimizes the average errors over all the nodes. In either configuration, the reliability and short-term stability of the system is substantially improved if the central timing signal is used to steer a local clock at the node rather than being used to directly control the operations at the node. If the central synchronization signal is interrupted, the local clock can carry the system at that node for some period before synchronization is completely lost. Furthermore, the higher frequency noise inherent in time transfer systems substantially compromises the short-term stability of the received signal. Virtually all network synchronization relies on this approach (the control of a local clock by the synchronization signal). The quality of the local clock and the sophistication of the steering are choices dictated by the reliability required in the application.

Where reliability of synchronization is paramount, a second (or even third) independent distribution system (with or without a second independent reference clock) can be used. With two synchronization signals delivered to each node, the loss of one distribution system (or central clock) simply forces each node to rely on the alternate source.

III. TIME GENERATION

Current studies at a number of laboratories are demonstrating principles which, when applied to standards and oscillators, will certainly result in improved performance. For example, Doppler shifts can now be minimized by reducing velocities of beams of atoms and the thermal motions of trapped ions. Newer methods for optical state selection and detection eliminate some of the negative side effects of current methods. In this issue, Ramsey [15] presents a brief history of the development of atomic standards and projects the future development of these standards. Also in this issue, Itano [16] and Rolston and Phillips [17] describe progress toward cooled-ion and cooled-atom standards. In the following sections, we present brief discussions of the various types of clocks and oscillators, indicating the status and directions of work. Finally, Lewis [8], in this issue presents a comprehensive description of the various types of atomic standards and their characteristics.

A. *Cesium-Beam Standards*

Primary cesium-beam standards are approaching certain practical limitations. For example, in a typical primary standard the correction for the second-order Doppler shift is about 2×10^{-13}. For a system with a design accuracy of 1×10^{-13}, this correction is not too difficult to make, but at a level of 1×10^{-14} it becomes a substantial problem. The narrowest linewidths for the cesium clock transition ($\sim$ 9.2 GHz) are typically tens of hertz, so at an accuracy of 1×10^{-14} the clock servo system must find line center with an accuracy approaching 1×10^{-6}. These are but a few of the reasons we cannot expect to see the performance of these standards go much beyond 1×10^{-14}. Drullinger [18], [19], Ohshima *et al.* [20], and de Clerq *et al.* [21] are building thermal beam systems which use optical state selection and detection rather than the conventional magnet selection. This approach, as well as other variations on the conventional technology, should allow achievement of the 10^{-14} accuracy, but they do not really avoid the problems noted previously.

The real solution to these limitations lies in slowing the atoms so that the Doppler shift is reduced and longer observation times can yield narrower resonance linewidths. Itano [16], in this issue, describes a most direct solution, the trapping and cooling of positive ions. This concept has matured to the point where high-performance prototype standards have been demonstrated. Phillips [17], also in this issue, discusses an approach involving the slowing of neutral atoms. The lack of a suitable trap for neutral atoms limits the achievable linewidth. One proposal for a cooled-atom standard involves a fountain where slowed atoms are lofted vertically and interrogated as they rise and then fall under the influence of gravity. With slowed neutral-atom standards the potential signal-to-noise ratio is better than with trapped ions. Furthermore, the definition of the second is now based on neutral cesium, so primary standards based on slowed cesium atoms would continue to be favored unless other standards prove to be greatly superior.

The two areas in which new concepts will likely affect practical cesium standards (field standards) in the next ten years involve optical state selection/detection and closed-cell standards in which cesium atoms are cooled sufficiently to reduce transition linewidth and Doppler shift. A key advantage of optical state selection and detection is that it can support the use of all atoms in the atomic beam. In conventional magnetic selection, 15/16 of the beam is in the wrong atomic state and has to be discarded. The more efficient use of the beam atoms means that signal-to-noise ratio can be greatly increased (at the same beam flux), or the lifetime of the standard can be increased by operating at lower oven flux (while maintaining respectable signal-to-noise performance). The cesium-cell concept developed by Monroe *et al.* [22] uses slowed cesium atoms contained in a closed envelope similar to that used in rubidium standards (see the discussion of rubidium standards by Lewis [8] in this issue). The cell approach is likely to result in a simpler overall system (once the laser diodes are sufficiently simplified) of very good medium-term stability.

B. *Stored Ion Standards*

The most readily understood advantages of using trapped ions as frequency standards are that 1) the first-order Doppler shift is eliminated because the ions remain fixed in position and 2) the transition linewidth is dramatically reduced by long observation times. Furthermore, trapped ions can be readily laser cooled minimizing the effect of the second-order Doppler shift. The use of radiation pressure to cool trapped ions was first demonstrated in 1978 by Wineland *et al.* [23] and Neuhauser *et al.* [24]. The cooling of neutral atoms, first demonstrated in 1981 [25], [26], also uses radiation pressure. In these ion and neutral-atom experiments, the fundamental cooling concept is the same, but the implementations are quite different. The ion-storage technology is clearly more mature, and demonstrations of high accuracy and high stability performance already push the performance of conventional cesium standards.

Bollinger *et al.* [27] demonstrated the first high-accuracy prototype ion standard using Be^+ ions. The accuracy was equal to that of NBS-6, the present U.S. primary standard. Cutler *et al.* [28] have demonstrated a very high stability ion standard (not laser cooled) which outperforms cesium in the medium term. Prestage *et al.* [29] have further developed this type of standard. But the real promise for ion standards still lies in the future. The NIST group [30] in studies of an optical-frequency transition in single trapped Hg^+ ions anticipate that systematic frequency shifts can be determined to 1×10^{-18}. The linewidth of this optical transition is 2 Hz providing an inherent Q factor of 10^{15}. Bergquist *et al.* [31] have locked a laser to this transition and achieved a linewidth of 80 Hz limited by the linewidth of the laser. This represents the narrowest laser linewidth and the highest-Q atomic or molecular transition ever observed. Optical transitions are appealing for frequency standards because they offer the highest Q factors, but there is a fundamental problem in working in the optical region. This is the difficulty of precisely relating the output frequency to a frequency in the microwave frequency region where the performance can be applied to practical electronic metrology. Frequency synthesis (or division) between the microwave and optical regions is extremely difficult. It must be dramatically simplified before optical frequency standards are widely accepted. The Hg^+ ion also has a clock transition at 40.5 GHz. This can be used in standards that do not look too different (electronically) from conventional rubidium standards. Using laser cooling to narrow the linewidth, a clock based on this transition should achieve an accuracy of better than 1×10^{-15}.

One disadvantage of ion standards is that the highest-accuracy, single-ion systems exhibit rather poor signal-to-noise ratios. Prestage *et al.* [29] have shown that a modification of the usual trap to one of linear geometry allows trapping of a larger number of ions without a substantial decrease in the potential accuracy. The larger number of ions provides for a higher output signal and a better signal-to-noise ratio. Preliminary experiments suggest that ion standards based on a linear trap might even challenge active hydrogen masers (see the following) in short term stability.

C. Other Atomic Standards

Two other classes of atomic standards, hydrogen masers and rubidium standards, play a significant role in science and technology. Hydrogen masers are the common choice where very high short-term stability is required, and rubidium standards now provide a cost-effective performance which is better than that of quartz oscillators, although below that of cesium. (Superconducting-cavity-stabilized oscillators [32] actually show the best short-term stability, but they are not yet in common use.)

There are two types of hydrogen masers. Active hydrogen masers are distinguished by the fact that they oscillate spontaneously. Passive masers use an external oscillator to probe the hydrogen resonance. Active masers are critical to very long-baseline interferometry (VLBI), where observations of radio-emitting stars must be time tagged with very high short-term stability. Passive hydrogen masers developed during the last decade are smaller (comparable to the size of a cesium standard) and less expensive than active masers. Their niche is intermediate-term stability, which is generally better than that of cesium standards.

Much of the research surrounding present maser development involves the wall coatings of the bulbs which contain the hydrogen within the microwave cavity. A key characteristic of masers is the very long interrogation time of the hydrogen transition which results from the fact that individual hydrogen atoms can suffer many collisions with the walls in the bulb without disturbing the atomic state in a major way. There is, nevertheless, an energy (frequency) shift associated with the wall interaction. The stability of this shift has long been a source of study and discussion. Wall coating, often more an art than a science, has played a key role in maser performance, and future improvement in maser performance is critically dependent upon it. Masers developed recently in the Soviet Union [33] have performances which suggest a substantial improvement in wall coating. Another approach to the wall problem has been the development of masers which use liquid ^3He as the wall coating [34], [35]. Preliminary experiments with these cryogenic masers look promising. Yet the technology is still very difficult, and it will probably be many years before such masers are ready for practical applications.

Conventional rubidium standards, optically pumped by special discharge lamps, use a passive buffer gas to slow the diffusion of rubidium atoms. This increases the lifetime of the atomic states in the interrogation region resulting in a narrower linewidth. Because these standards perform better than quartz oscillators and sell for only a fraction of the price of cesium standards, they fill an important gap in the technology. However, they do suffer aging effects which give rise to substantial drift, and the excess spectrum of light from the pump lamp adversely affects the signal-to-noise ratio.

Recent research [36], [37] suggests that some of these problems might be overcome through replacement of the discharge lamp with a suitably controlled diode laser operating at the rubidium transition frequency. This appears to minimize (or even eliminate) both the lamp-aging problem and the excess light which affects the signal-to-noise ratio. Some people suggest that the rubidium standard might some day achieve a short term performance challenging that of today's active hydrogen masers.

D. Quartz Oscillators

The state of development of quartz-crystal oscillators is reviewed by Vig [7]. Steady improvements over many years have involved improvement in the quality of materials, introduction of different cuts of crystals, better mounting and packaging, and improvements in temperature control and vibration isolation. Clever schemes for temperature compensation have given rise to the Temperature-Compensated Crystal Oscillator (TCXO), an advance which significantly reduces drift. More recently, microprocessors have been combined with quartz oscillators to yield the Microcomputer-Compensated Crystal Oscillator (MCXO). The microprocessor in this device stores the frequency-versus-temperature characteristics of the crystal, and, using a second mode of the crystal as a thermometer, makes temperature measurements to arrive at more accurate compensation.

Considering the present state of development of quartz oscillators, there is no reason to expect anything other than steady, small improvements in performance. Unlike the atomic standards, there are no new physical principles offering promise of order-of-magnitude advances.

IV. Time Distribution

The transfer medium plays a critical role in time distribution. For example, short wave (HF) distribution of time signals is very cost effective, but with the unpredictable bouncing of the signals between the earth and ionosphere, it is an inappropriate method for high accuracy dissemination. In another example, the transmission delay for satellite distributed time signals is strongly dependent on the carrier frequency. Ionospheric variations in delay can be tens of nanoseconds at the 1 GHz GPS frequencies. These variations are lower by a factor of 100 in the 12–14 GHz band. Clearly, the selection of the linking medium is an important consideration in network synchronization.

A. General Concepts

The general concepts for time transfer are easily sorted into three categories, one-way, common-view, and two-way time transfer. These are shown schematically in Fig. 1. The problem in every case is how to best deal with the delay introduced by the transmission medium, be it a radio-wave path, an optical fiber, or a coaxial cable.

The one-way delivery of a time signal from a source to a user (Fig. 1(a)) is typified by shortwave radio broadcasts such as those emanating from WWV in Colorado. The delays in such broadcasts, which can be tens of milliseconds, are highly variable because the transmission path often involves multiple reflections between the ionosphere and the surface of the earth. The accuracy of one-way transfer can be improved by characterizing the delay of the medium, but in the case of shortwave broadcasts, this characterization involves a large uncertainty. On the other hand, one-way signal delivery through a coaxial cable or from a satellite involves a much more predictable path, and delay corrections can be quite stable. Cable delays are affected, for example, by temperature and stress on the cable, while satellite delays are affected by dispersion in the ionosphere and troposphere and, of course, changes in position of the satellite. In general, one-way systems are limited by the difficulty in obtaining a complete characterization of delay variations.

The common-view method of time transfer (see Fig. 1(b)) can be used to advantage where the path from some reference source to each of two receivers involves a path delay with common characteristics. For nearly simultaneous observations of the common source, the two sites record time differences which are $A-(R+\tau_{ra})$ and $B-(R+\tau_{rb})$, where A, B, and R are the readings of clocks at site A, site B, and the Reference. τ_{ra} and τ_{rb} are the respective delays between the Reference and sites A and B. If the two sites then share their readings and take the difference between them, the difference, $A - B - (\tau_{ra} - \tau_{rb})$, does not contain the common reference, but leaves only the differential delay, $(\tau_{ra} - \tau_{rb})$, as a correction. Clearly, the more common the characteristics of the path, the better will be the time transfer. Furthermore, the accuracy of the time transfer does not depend (to first order) on the quality of performance of the common reference clock. Allan *et al.* [38] have used this technique with the GPS satellite clocks as references. While time directly received from these space-borne clocks is accurate to no better than about 200 ns, they achieve a time transfer accuracy on the order of ±10 ns. Careful error correction and averaging of at least a day's observations are needed to achieve this performance.

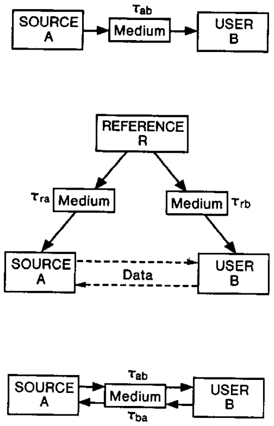

Fig 1. Three general categories for time transfer. (a) ONE-WAY. In the one-way system the timing signal delivered from the source A to the user B is delayedτ_{ab} by the medium. An estimate of this delay can be applied to correct the user clock. (b) COMMON-VIEW. If the source A and the user B make simultaneous observations of the time of a common reference relative to that of their own clocks, then, in subsequently exchanging observations, taking the difference between the two differences removes the reference leaving only the differential delay,$\tau_{ra} - \tau_{rb}$, as the error. Where the two paths share common properties, the differential delay can be substantially smaller than either individual delay. (c) TWO-WAY. In a simultaneous exchange of signals, the source A and user B obtain data which, when compared, yield the difference in readings between the clocks at the two sites plus the difference between the two delays, τ_{ab} and τ_{ba}. If the medium through which the exchange takes place is common, τ_{ab} can almost exactly equal τ_{ba} thus canceling the delay term. This amounts to an accurate calibration of the delay between the two sites.

The common-view method can be extended to the case of more than two receivers, and there may be advantages to such an arrangement. The data from each receiver can be combined with many others to yield simultaneous common-view estimates of the time differences of all of the members of the ensemble, and a least-squares adjustment can then be performed to minimize the error at each node. The power of this procedure will depend on the correlations among the various differential delays.

The two-way method for time transfer (see Fig. 1(c)) provides the best opportunity to accurately determine the transmission delay between separated clocks. When sites A and B simultaneously exchange time signals through the same medium and compare their received readings with their own clocks, they each record the respective differences, $A - (B + \tau_{ba})$ and $B - (A + \tau_{ab})$, where τ_{ba} is the transmission delay from B to A and τ_{ab} is the reverse delay. Taking the difference between these two sets of readings we obtain $2(A - B) - (\tau_{ba} - \tau_{ab})$. Now, if the transmission path is fully reciprocal, that is, if $\tau_{ba} = \tau_{ab}$, then the difference, $A-B$, is known perfectly and the value of the transmission delay is also determined. The two-way method should provide for near-real-time synchronization of clocks at nanosecond or greater accuracy.

The common-view and two-way methods impose different requirements on the transmission medium. The common-view method depends on the relatively high correlation between the paths from the transmitter to the two receivers. The paths may include arbitrary delays and need not be reciprocal. The two-way method, on the other hand, places a premium on reciprocity and does not depend on the correlation between the delays in different portions of the path. Although there are areas of overlap, each technique also has a domain in which it can provide better performance. The common-view method, for example, is likely to be more robust in computer networks, which have large transmission delays and poor reciprocity. The two-way method is probably the method to choose when signals follow cable or line-of-sight paths.

B. Applications of the Time Transfer Concepts

In the discussion above we used several examples to illustrate the different time transfer methods. But the concepts are general, and each can be applied to a variety of transmission schemes. The discussion in this section is not meant to be comprehensive, but rather to indicate a few of the real and potential applications of the concepts.

Jackson and Douglas [39] and Levine *et al.* [40] describe two-way methods for synchronizing remote clocks through the telephone system. They both use the following variation of the two-way idea. Rather than accomplish the two-way exchange through simultaneous transmissions, these systems send a time signal from site A to site B where it is echoed (reflected) back to site A. Site A then has a measurement of the round-trip delay which, assuming reciprocity in the lines (an assumption good to better than 1 ms for many systems), is divided by 2 in order to provide a direct measure of the delay. The main difference between the methods described in the two publications above is that one takes care of the correction at each receiver and the other makes the corrections at the transmitting end.

Using a similar scheme in cable-connected systems, two-way time transfer can push the stability and accuracy of synchronization into the picosecond regime, even for systems with very long cables. Where the demand for accuracy/stability of distribution of time are high, the use of this method along with optical fiber connections [41] is especially appealing since the fiber transmission provides excellent immunity to noise introduced by ground-isolation problems.

Navigation or ranging systems which are based upon time of flight of radio or optical signals can often be used for time transfer. For ranging applications these systems assume that the time references are known and solve for relative positions of base stations. For time transfer, the known locations of the base stations are given and the relative time at the stations is then determined. This is the basis for the GPS Common-View Method of time transfer described earlier [38]. The common-view technique of VLBI, used to obtain high-resolution images of distant radio stars or relative positions of observation sites, provides another means for highly stable time transfer [42]. In this technique, signals received at two sites from a set of common radio stars are cross correlated (in a computer) in the same fashion that optical signals are combined in an optical interferometer. A key product of this computation is a very precise measure of the relative phase of arrival of signals at the two sites. This can be used to provide an extremely stable measure of the relative stability of clocks operating at the two sites. With the very high cost of radio telescopes and peripheral equipment and the need for extensive computer processing of data, this is an extremely expensive approach, and it is generally used only as a research tool. MacDoran *et al.* [43] have developed a short-baseline interferometer which relies on the same concept. Their scheme uses common-view observations of signals from GPS satellites. Receiver costs are reasonable, but, as with the VLBI technique, this interferometric method still involves substantial computation.

For satellite time transfer, the one-way method remains attractive because of the simplicity of equipment at the receiving site [44]. Two-way time transfer requires broadcasting to a satellite from each station, a process which requires more equipment and special government licensing. The common-view methods call for exchange of information between sites as well as substantial averaging to obtain good accuracy and stability. A one-way satellite dissemination system which promises very good performance has been proposed by Hanson and Howe [45]. They suggest use of commercial communication satellites in the 12–14 GHz region. At these frequencies the ionospheric variation in delay is only a few nanoseconds. The technology for these geostationary satellites has been widely developed for direct-broadcast television, so receivers should be particularly simple and inexpensive. A key facet of their proposal involves the tracking of the satellite (geostationary satellites do move about somewhat) from three sites using the two-way time transfer method. The two-way exchange of signals between all three stations provides ranging information which can establish the position of the satellite. This position is then broadcast with the time signal so that the receiver can correct for variations in the path between the receiver and the satellite. The accuracy of such time transfer should be better than 100 ns and the stability might well be better than 10 ns.

C. Practical Synchronization Limits

Given adequate clocks, the synchronization of two nodes or a network is likely to be limited by the transmission medium and/or the time-transfer method. In many cases it is possible to gain auxiliary information which might allow for a refinement of the estimate of time delay. For example, knowledge of the temperature of a coaxial cable along with an understanding of the delay-temperature relationship can provide for an improvement in one-way synchronization through coaxial cables. In another example, a model of ionospheric delays is currently used to improve upon GPS common-view time transfer. Furthermore, if variations in delay have suitable statistical properties, these can be used to place a confidence on a particular measurement or, with a proper time constant, to better steer a remote clock to a central standard.

For the one-way method, practical limitations simply involve the variations in path delay and methods used to estimate them. Practical limitations of the two-way method are also readily understood. These limitations relate primarily to the assumption of reciprocity of the signal path through the medium and the transmitting and receiving equipment as well as the simultaneity of the exchange. The current approach to two-way time transfer through communication satellites involves different frequencies for the up links and down links with the satellite. Since the delay is frequency dependent, the path is not fully reciprocal, although the errors introduced appear to be very small [46]. A general analysis of the limitations of common-view time transfer is more difficult for a number of reasons. The common-view cancellation of delay error is usually only partial, and a variety of additional methods are used to reduce the uncertainty in the determination of the remaining differential delay. These methods include straightforward averaging over many observations, cross correlation of the data obtained in observing a number of independent reference sources, and modeling or independent characterization of the transmission medium. Because of this complexity, the limitations of this transfer method involve more detailed consideration.

The synchronization limits imposed by the time transfer process are, in a certain sense, very general limits on time and frequency technology. The development of atomic clocks with performances beyond the time transfer limits makes sense only if such clocks are to be used in isolation. Applications for such isolated clocks are fewer, probably involving only scientific studies.

V. CHARACTERIZATION OF COMPONENTS AND SYSTEMS

The wide acceptance of a standard approach (IEEE standard 1139-1988 [2], [3]) to characterization of clocks and oscillators provides the designer with a consistent means for projecting system performance and specifying certain components. A recent edited volume from NIST [47] includes description of the performance definitions along with a collection of papers devoted to measurement methods supporting the definitions.

Unfortunately, there are no consistent standards for characterization of the time transfer links. This is a key problem which will plague systems engineers until it is resolved. Consider the simple hierarchical synchronization shown in Fig. 2. If the four nodes at the bottom represent nodes in a synchronous communications network, then it is the relative times at these four nodes which is important to the system designer. The performance of the individual clocks at each level can be readily characterized, but the links between them have only been treated in isolated ways. Abate *et al.* [48] describe their approach to synchronization of a real telecommunications network. Characterization of the links connecting system clocks is an important implicit consideration in their system. In another paper, Allan [49] has done a preliminary analysis of the properties of GPS common-view links. Clearly these efforts represent only a beginning. We really need to see a conceptually broader approach to this problem. In the long term the technology will require standard definitions and measures of performance which can be easily combined with the measures of clock performance to arrive at an overall estimate of system performance.

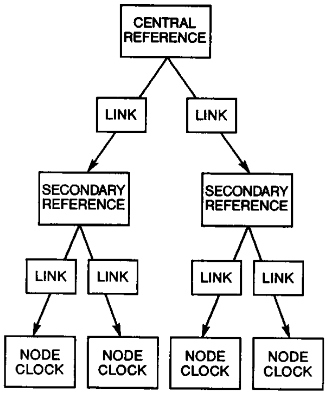

Fig. 2. A simple hierarchical scheme for synchronizing four clocks at four network nodes. The synchronization of such a network is clearly limited by the links between the clocks.

VI. DISCUSSION/CONCLUSIONS

A. Clocks and Oscillators

The development of methods for manipulating the states and motions of atoms and ions will certainly result in substantially improved atomic clocks. Since there do not appear to be any new principles to apply to quartz oscillators, we should expect performance improvement to be much less dramatic. There is a strong motivation for improving the performance of clocks only as long as time transfer techniques lead the performance of the clocks. Should clock development outpace transfer systems, then such high performance will be available only in the laboratory. Accuracy which cannot be transferred to another site is probably important only in specialized applications in science (for example, tests of relativity).

B. Time Transfer

The one-way, common-view, and two-way time transfer concepts have been around for many years. The dramatic improvements which we are seeing in time transfer are more closely related to general technological developments which make the implementation of some of these concepts economically feasible. The areas of development which have had impact on time transfer include those in satellite communications, computers and microprocessors, and optical fibers. The focal problem in time transfer continues to be the characterization of the delay through the time transfer medium.

C. Characterization of Components

Because of the importance to network synchronization, we can expect to see efforts directed toward the development of consistent methods for describing the performance of time transfer links. Without standard means for characterization of these links, network synchronization will have to rely on excessive engineering margins, and synchronization levels will remain below the potential of the technology.

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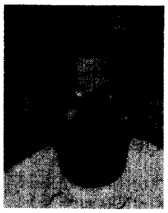

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