MASTER AND SECONDARY CLOCK IN TELECOMMUNICATIONS NETWORKS

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ABSTRACT

Telecommunication networks of time division switches, interconnected by digital transmission are being put into place. At each switch, each incoming bit stream is brought into its own buffer. Then the clock in the switch "reads" each buffer to re-establish phase. Care must be taken to keep frequency differences between various clocks from becoming too large, other-wise buffers will under/over flow at an unacceptably high rate. Based on empirically defined data transmission requirements, one major network has determined that fractional frequency inequality between switches should be no worse than $1.7X10^{-9}$.

A network needs near frequency equality between its own switches, and also between its switches and other networks with which it interfaces. Frequency accuracy - per se - is not required, but as a practical matter, the best way to achieve needed frequency equality is for each network to have master clock with an accuracy which is at least as good as $1X10^{-10}$. To be certain that this accuracy is achieved the master clock in each network should be based on a signal from a cesium source.

Cesium sources for the purpose of providing master clock, fall into two categories:

1) Cesium standard on site.
2) Cesium based signal distributed via some transmission medium.

Concerns of systems designers are that:

A) The master signal be tied to a properly functioning cesium standard.
B) If master signal is lost, the secondary clocks be of sufficiently low aging that they free-run at least a week before their accuracy degrades below $1X10^{-9}$.

The accuracy of a properly functioning <u>commercial</u> Cs beam standard is no worse than about $1X10^{-11}$. The master/secondary system must be designed such that the accuracy of the master can be verified.

The paper discusses the relationship between the master and the secondary clocks. The questions of master clock accuracy and precision and the free-running capability of the secondary clocks will be examined.

INTRODUCTION

Until recently, the time and frequency (T&F) requirement of the commercial communications industry was almost totally limited to quartz oscillators of low to medium quality. This situation is changing very rapidly. There now exists a significant need for atomic standards and high-quality quartz oscillators. There are two reasons for this:

1. Vital portions of most major networks are now, or soon will be, digital.

2. The breakup (divestiture) of the Bell System and associated changes in the industry.

The breakup of the Bell System is a major additional step in the Federal government's encouragement of competition in the telephone industry. This general encouragement plus one very specific aspect of the divestiture decision are of great importance in the industry's needs for T&F capability. Divestiture specifically requires "Equal Access." What this means is that, for any carrier, the cost of access to a long-haul (long distance) network and the quality of that access must be equal to that of any other carrier.

So competition and specifically, Equal Access, press for a widespread improvement in T&F capability and specific characteristics of digital communications define the quantitative requirement.

In most, if not all, existing and planned commercial networks, buffer interfaces are used on each incoming trunk of a digital switch. That is, it is not a totally synchronous network--phase is re-established at each switch. So even though the networks will be digital, the use of buffers at each switch means that it is only frequency equality (near equality) that is needed. (We think that this may not be true in the future because there are advantages to a totally synchronous system.) Since the network will be digital, the requirement is that, as they pass through the switches, the various bits must have a definite time (phase) relationship to one another. This is achieved at each switch by the local clock in the switch that sequentially "reads out" the buffers. If the rate of this local clock is not equal to that of the incoming bit stream, then the buffers will gradually under/over flow.

By empirical tests, the Bell System determined that data customers incurred unacceptable degradation if slip rates (buffer over/under flow rates) went beyond about one T-1 frame in 20 hours.[1] (A T-1 signal is communications traffic in a certain digital format whose rate is 1.544 Mb/s and whose frame length is 193 bits (125 microseconds) long.) This corresponds to an end-to-end fractional frequency difference of $1.7\text{X}10^{-9}$. Assuming that the frequencies of the nodal clocks are randomly distributed about some nominal value, the probable offset is about $1\text{X}10^{-9}$ to cause slippage at the level where corrective action needs to be taken.

Frequency accuracy, per se, is not required. But, as a practical matter, achieving frequency accuracy is the most cost-effective means of acheiving the needed frequency equality. If all users take this approach, which they seem to be doing, then each one will achieve both compatability and autonomy.

If compatability is to be achieved, every node (switch) in a given network which is to interface with a node in another network must have fractional frequency accuracy of at least $1X10^{-9}$. From a metrology viewpoint, one would like to have a reference whose accuracy is of the order of ten times better than those devices which are to be controlled/measured, i.e., about $1X10^{-10}$.

FURTHER CONSIDERATIONS ON NETWORK FREQUENCY REQUIREMENTS

For most users of T&F equipment, their major business is something else, e.g., telephony--and they want to keep it that way. This means that ideally, all equipment should arrive from the manufacturer on frequency, and it should stay within one part in 10^9 for many months. When recalibration is required, it should be performed at low cost by people who have no particular expertise with T&F technology.

The reality of the situation is that a quartz oscillator whose aging rate is about $1X10^{-10}$/day will be out of frequency tolerance in a few weeks if left to free-run. Such an oscillator (known in the telephone industry as a Stratum 2 oscillator) is near the top of the line in commercially available quartz oscillators. As a pratical matter, this means that in any major network, there must be a minimum of at least one atomic frequency standard. We believe that these sources should be based on cesium. That is, it should be a cesium standard on site, a GPS (Global Positioning System) receiver, or a Loran-C receiver. With one such cesium master clock and suitable transmission lines to the other nodes that interface with the outside networks, an autonomous network of minimal frequency capability can be assembled. The remainder of this paper is a discussion of what is meant by "suitable transmission lines" and "minimal frequency capability." What we will sketch out is that the design of an optimum T&F network, based on the criterion of overall communications network profitability, is a rather general systems problem. One significant factor in the analysis is to try to account for the general unease of the telephony industry at having to deal with sophisticated T&F considerations.

Figure 1 is intended to make three points:

1. In a big network (e.g., a network covering most of the U.S.) some switches can be adequately slaved off a given master, but not all. In the figure, the solid lines joining nodes/ switches are short-haul (local distribution) paths that typically are less than 100 miles long. The broken paths are long-haul, for example, a satellite path. Whether a path is suitable to transfer master clock depends on four things--the

quality of the slave oscillator; the instability that the path adds to the transmitted signal; the cost of using a portion of the bandwidth of that path for sending the T&F signal; and the realibility of the path. It is not our purpose to discuss these things in detail, both because of lack of space and because it could only be hypothetical since the optimum solution for each link of a given network depends on the present and future competitive situation for that network. It is useful, however, to give an example: Assume that the link between two nodes say, switches 1 and 2 of Network B, is a satellite path. If "clock" is to be passed from switch 2 to switch 1, then the slave clock at switch 1 must have a sufficiently low aging rate to average out the doppler shift due to satellite motion. The motion is approximately periodic with a period of one day. If the goal is that the clock at switch 1 never be more that $1X10^{-10}$ away from the master then its aging rate will have to be better than $1X10^{-10}$/day. The reason is that the lock-loop time constant cannot be shorter than one day.

In summary, one of the major considerations in deciding whether to slave a clock located at the end of a given transmission path is to examine the trade-off between slave-clock quality/cost and stability/reliability of the path.

2. The figure is drawn to indicate that it is unadvisable for one major network to take its master clock from another major network. For example, with the connections as shown, consider what would happen if Network A took its clock from either Network B or C. If the signal goes away (for whatever reason) Network A will not be able to serve its own internal needs or have a connection of adequate quality to the still-functioning "other" network. We believe that every major long-haul network should have its own (autonomous) cesium-based master clock at at least one node.

3. We believe it will be very common for a switch of a large private network to be interconnected with two or more long-haul carriers. (See "Customer 4" in the figure). Such a customer may or may not wish to take clock from one of these commercial carriers. In any event, it again points up the need for good frequency equality between all parties--private as well as commercial.

What about the quality of the slave clocks? In the commercial networks, any digital switch site that directly interfaces with (no intervening switch) a digital switch of a competing carrier should have a clock that ages no worse than $1X10^{-10}$/day, that is, a Stratum 2 clock. With a slave of this quality, if the master is lost, frequency accuracy at least as good as $1X10^{-9}$ will be maintained for at least one week. This will probably be sufficient time to restore the master.

We turn now to the idea of "minimal frequency capability" raised earlier. We said there that a single source of "cesium" at just one site was minimal. Later we indicated that, in a very large network, several sites would probably need their own master clock. We also think that, for at least one site in each of these networks, it will prove very valuable to have a dual "cesium" source.
The need for dual cesium is based on the idea that the master clock needs to be indisputably accurate. If Master clocks of any two switches, of different networks, are interconnected with one another, accuracy probably will be in question.

There are four major types of master clocks that are likely to be found. They are:

- Cesium Standard(s) on site
- The ubiquitous 1.544 Mb/s digital signal in the format known as DS1
- GPS receiver
- Loran-C reciver

The DS1, GPS, and Loran options are all, of course, based on cesium standards but the users' site is typically very remote from the source. Also, the signal arrives in a form (a format) which requires processing in order to extract the frequency of the cesium standards that lie behind them. (The T&F signal broadcast by Station WWVB of the National Bureau of Standards is also used in some cases. But, due to the nature of the signal, the averaging time needed to acheive the required precision will be longer than is convenient for most users.)

But, for a while at least, the means of obtaining master clock will probably divide into two major categories:

1. The Bell System Reference Frequency Network (BSRFN) and

2. Other, where "other" consists of on-site cesium, or GPS, or Loran, or some combination of these three.

The BSRFN, which is owned and operated by AT&T Communications, has been discussed in detail in other places.[1,2] It is important, however, to summarize its essential characteristics: It is based on a triad of cesium standards located in a single geographical location. The signal is transported in sinusoidal form to approximately 100 sites throughout the U. S., where it is terminated.

These sites are locations of #4ESS switches (the very large digital toll switches of the AT&T long-haul system). This signal becomes the master clock for each switch and, as such, its frequency is embedded in the DS1 traffic streams that emerge from these switches. Finally, some of these DS1 streams terminate in other digital switches which are part of the conventional telephone operating companies (These companies include the Bell Operating Companies (BOC's) and what, prior to divestiture, were known as the "Independents.") The 8 kHz Fourier component of these streams becomes the master clock for these switches.

So now we have the situation of a great many BSRFN-derived master clocks interconnecting with each other and the "other" based clocks in neighboring networks, such as MCI and Sprint.

There have been and will be cases where there is--or appears to be--an out of tolerance frequency difference between switch pairs. It will not be easy to determine which, if either, of the switch clocks is in error. This is because the measurement needs to be made to an accuracy of at least $1X10^{-10}$ (and $1X10^{-11}$ at international gateway sites).
And it is because each and everyone of these master clocks will have been transformed at least once in its pathway from its originating cesium standard. (Almost without exception it will only be via an incoming DS1 traffic stream that a switch will be able to access the frequency of its neighbor.) The noise which accompanies these transformations, and the associated transmission processes, will require appropriate averaging times--typically from one to eight hours--to achieve a precision of $1X10^{-11}$.
We contend that, for at least one node in each major network, it will prove very cost effective to have a means of easily--unambiguously--determining the accuracy of your own and your neighbor's clock. The way to do this is with dual cesium capability of either the Cs/GPS or the Cs/Loran variety, and a DS1 interface that extracts the clock from the incoming traffic stream.

If the intercomparison of such a dual cesium system shows a fractional frequency difference not much larger than $1X10^{-11}$ then, to a very high probability, both sources are accurate approximately $1X10^{-11}$.
A check of the incoming clock against one of the members of the duo will then complete the tests. All-in-all, the resources spent to create a high-quality frequency reference system for a communications network will, in the long run, prove to be very cost effective.

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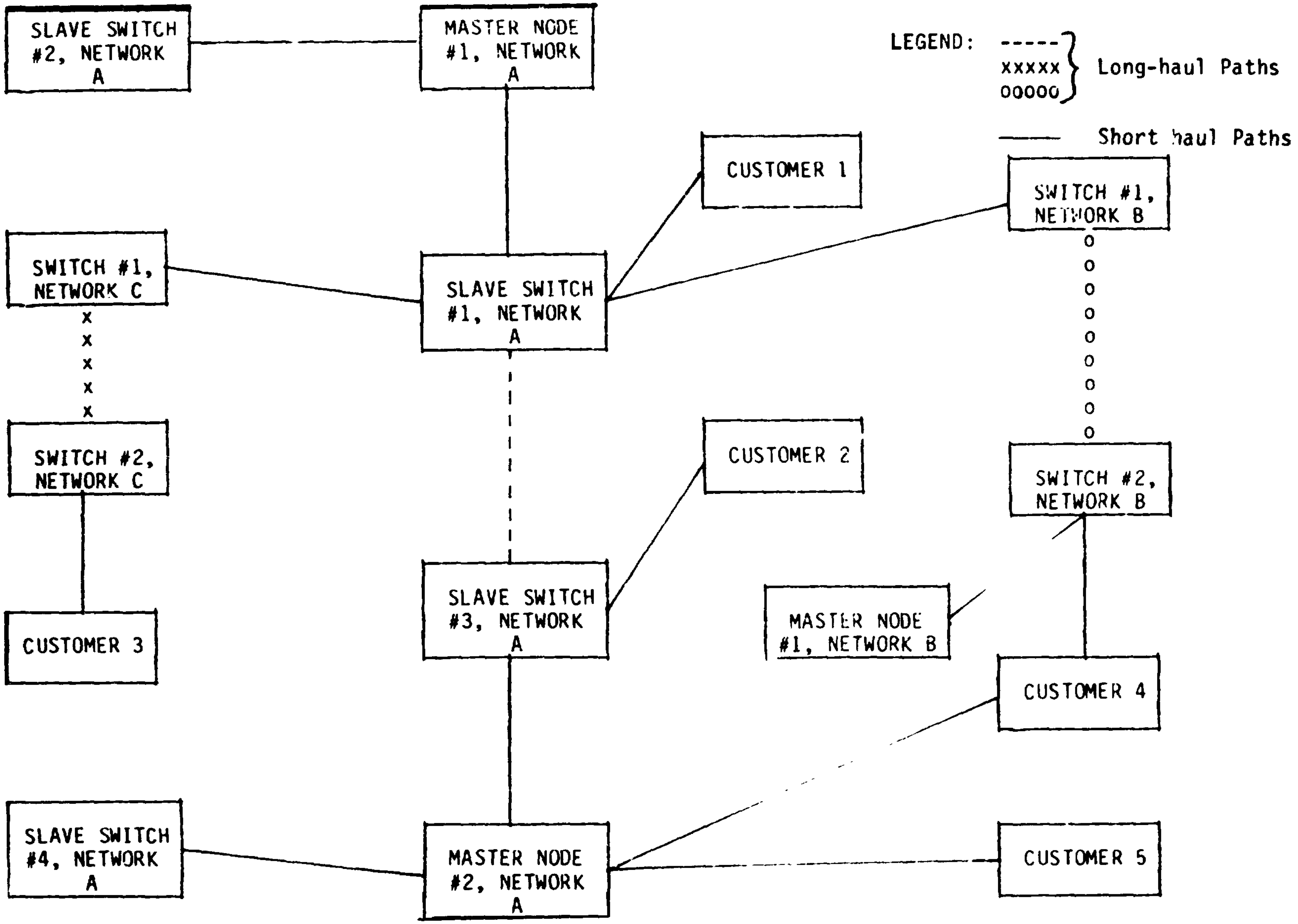
SLAVE SWITCH #2, NETWORK A
MASTER NODE #1, NETWORK A
LEGEND:
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xxxxx
ooooo
Long-haul Paths
Short haul Paths
CUSTOMER 1
SWITCH #1, NETWORK B
SWITCH #1, NETWORK C
SLAVE SWITCH #1, NETWORK A
SWITCH #2, NETWORK C
CUSTOMER 2
SWITCH #2, NETWORK B
SLAVE SWITCH #3, NETWORK A
MASTER NODE #1, NETWORK B
CUSTOMER 3
CUSTOMER 4
SLAVE SWITCH #4, NETWORK A
MASTER NODE #2, NETWORK A
CUSTOMER 5