Measurement of Maximum Time Interval Error for Telecommunications Clock Stability Characterization

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Abstract—**Maximum time-interval error (MTIE) is historically one of the main time-domain quantities considered for the specification of clock stability requirements in telecommunications standards. In this paper, MTIE is first introduced according to its formal definition. Then, the main issue of its experimental measurement is pointed out: the heavy computational effort in most cases of practical interest. Therefore, two suitable methods to face up to this issue are herein discussed, summarizing the state of the art of MTIE measurement techniques in telecommunications. A new effective technique is proposed, with the aim to provide an easy but accurate way to test the compliance of telecommunications clocks with MTIE standard masks. Several results, measuring clocks deployed in telecommunications networks, are provided.**

I. Introduction

NETWORK synchronization plays a central role in digital telecommunications networks [1], [2]. Indeed, while transmission equipment designed for the plesiochronous digital hierarchy (PDH) [3] does not need any network synchronization, since, through bit justification, the multiplexing technique adopted allows substantial frequency offsets between tributaries [4]. Digital switching equipment requires synchronization in order to avoid slips in the input elastic stores [5], [6]. While slips do not significantly affect normal phone conversations, they can even be catastrophic on some data services! The introduction of the circuit-switched data networks and of new advanced services such as those provided by the emerging ISDN, were the first to need more stringent synchronization requirements. As a matter of fact, the ongoing spread of synchronous digital-hierarchy (SDH) [7] technology in telecommunications networks has made synchronization a hot topic in standards bodies in the last few years; SDH heavily relies on network synchronization to meet all its performance objectives.

A major topic of discussion in standards bodies is clock stability characterization. Among the quantities presently considered for the specification of stability requirements [8]–[10], maximum time interval error (MTIE) has historically played a major role in characterizing time and frequency performance in telecommunications networks [11], [12]. Unlike other frequency stability measures [13]–[16] such as the Allan variance, all imply some kind of data averaging, MTIE is a rough measure of the *peak* time deviation of a clock with respect to a known reference. This involves some delicate issues in accomplishing practical measurements. Nevertheless, in relevant standards bodies, little effort has been made up to now to propose easy, suitable test procedures to check clock compliance with MTIE masks.

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II. What is MTIE?

A general expression describing a pseudo-periodic waveform which models the timing signal $s(t)$ at the output of clocks is given by [13], [14]

$$s(t) = A \sin \Phi(t) \tag{1}$$

where A is the peak amplitude, and $\Phi(t)$ is the *total instantaneous phase*, expressing the ideal linear phase increasing with t and any frequency drift or random phase fluctuation.

The general *time* function $\mathrm{T}(t)$ of a clock is defined, in terms of its total instantaneous phase, as

$$\mathrm{T}(t) = \frac{\Phi(t)}{2\pi\nu_{\mathrm{nom}}} \tag{2}$$

where ν_{nom} represents the oscillator nominal frequency. It is worthwhile noticing that for an ideal clock $\mathrm{T}_{\mathrm{id}}(t) = t$ holds, as expected. For a given clock, the *time error* function $\mathrm{TE}(t)$ (in standards also called $x(t)$) between its time $\mathrm{T}(t)$ and a reference time $\mathrm{T}_{\mathrm{ref}}(t)$ is defined as

$$x(t) \equiv \mathrm{TE}(t) = \mathrm{T}(t) - \mathrm{T}_{\mathrm{ref}}(t) \tag{3}$$

while the time error variation over an interval of duration τ

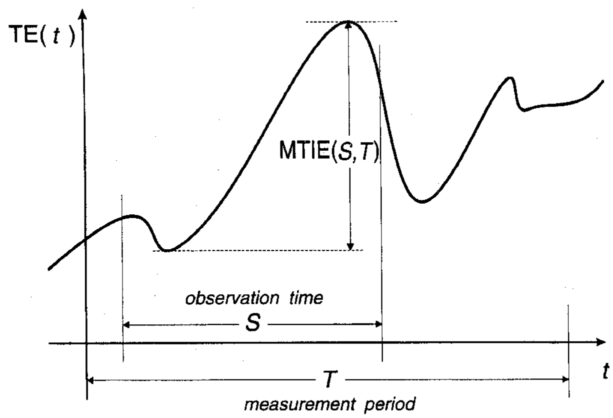

Fig. 1. Definition of MTIE(S, T).

starting at t_0 is called time interval error $\text{TIE}_{t_0}(\tau)$ and is defined as

$$\text{TIE}_{t_0}(\tau) = \text{TE}(t_0 + \tau) - \text{TE}(t_0). \quad (4)$$

Finally, the maximum time interval error function $\text{MTIE}_{t_0}(\tau)$ is defined as

$$\text{MTIE}_{t_0}(\tau) = \max_{t_0 \le t \le t_0+\tau} [\text{TE}(t)] - \min_{t_0 \le t \le t_0+\tau} [\text{TE}(t)] \quad (5)$$

and represents the maximum error committed by the clock under test in measuring a time interval over the whole interval $[t_0, t_0 + \tau]$.

Historically, the ITU-T and ANSI standards bodies [11], [12] have adopted the stability quantity MTIE(S, T), i.e., the maximum peak-to-peak deviation of TE in all the possible observation intervals S (denoted above as τ) within a measurement period T (see Fig. 1), defined as

$$\text{MTIE}(S, T) = \max_{0 \le t_0 \le T-S} [\text{MTIE}_{t_0}(S)]. \quad (6)$$

The dependence of MTIE(S, T) behavior on both the parameters S and T was discussed in [17]. The latest ETSI standard [9] stays aligned with this definition, denoting the observation interval as τ. It should be noted, however, that these standards specify the MTIE limits simply as a function of S (or τ), thus implicitly assuming

$$\text{MTIE}(S) = \lim_{T \to \infty} \text{MTIE}(S, T). \quad (7)$$

In other words, rigorously to assert the MTIE compliance of a clock with standard specifications, one should verify that, for every S, MTIE(S) stays below the allowed limits *for all of the device life*. As an extreme case, if after *years* of regular operation a clock should exhibit a fortuitous over-mask phase hit, this event would cancel all the past (honest) history in the resulting MTIE curve.

In order to cope with this issue, recently ITU-T [8] redefined MTIE(τ, T) as a specified percentile β of the random variable (cf., (6))

$$X = \max_{0 \le t_0 \le T-\tau} [\text{MTIE}_{t_0}(\tau)]. \quad (8)$$

A point estimate of the random variable X (i.e., of the classical MTIE(S, T) (6)) can be obtained by accomplishing an $x(t)$ measurement over a single measurement period T and then evaluating (8). Interval estimates of MTIE (for specified τ, T and β), with their respective degrees of statistical confidence, may be obtained from measured data if measurements are made over multiple measurement periods. Based on such a definition, an MTIE percentile mask should be interpreted as the limit not to be exceeded in more than, e.g., 99% of measurements.

Now, it should be pointed out that for other statistical quantities (such as the Allan variance) it is well known how different noise spectra impact on the trends of the stability quantities [13]–[16] (cf., the relationship between the power-law spectrum slope in the frequency domain and the variance slope in the τ domain). MTIE in its original definition (6), owing to its peculiar nature of rough peak measure, cannot be mathematically bound in a similar way to any other statistical quantity such as power spectra. The noise statistics model can impact only on the *probability* that a given limit is exceeded by a measured MTIE curve. With the redefinition of MTIE as a percentile quantity, it is then possible to bind the trend of a percentile MTIE(τ) curve (not exceeded in more than a given percentage of measurements) to the noise power spectrum via an integral relationship [16], as proportional to TIErms(τ).

The MTIE can be measured both in the *independent clock configuration* and in the *synchronized clock configuration* [8], [9], [16], [18]. In the former case, the reference time $\text{T}_{\text{ref}}(t)$ of (3) is the time generated by a second independent clock, usually a highly accurate and stable one as an atomic frequency standard; in the latter, $\text{T}_{\text{ref}}(t)$ is the input to a slave clock, while T(t) is its output. This paper, for the sake of simplicity, is focused on MTIE measured in the synchronized clock configuration, but most considerations also apply to the former case.

III. Measuring MTIE

MTIE measurement is usually based on the time-domain measurement of the TE process $x(t)$ between—as far as the synchronized clock configuration is concerned—the output of a slave clock-under-test (CUT) and its input reference (see Fig. 2). Sequences of TE samples $\{x_i\}$, defined as

$$x_i = x(t_0 + (i-1)\tau_0) \qquad i = 1, 2, 3, \cdots \quad (9)$$

where t_0 is the initial observation time and τ_0 is the sampling period, are measured using digital counters and stored for numerical post-processing over a total measurement period T. The samples x_i are typically measured between two corresponding zero-crossings of the timing signals at the input and the output of the CUT, as shown in Fig. 2.

A. Direct Approach: Crude Computation

Starting from the TE measured sequence $\{x_i\}$, the most straightforward way to compute MTIE(S, T) is to apply directly the formula (6). Letting $N_T = T/\tau_0 + 1$ be the total number of available samples and $N_S = S/\tau_0 + 1$ be the number of samples available in the window of span S, to obtain a

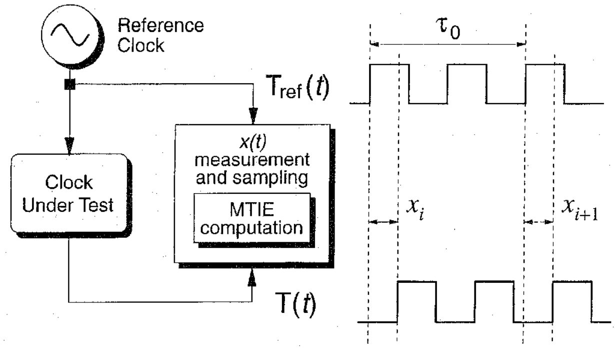

Fig. 2. TE measurement between the input and the output of a slave clock and MTIE computation.

single value MTIE(S, T), the following expression has to be computed

$$\mathrm{MTIE}(S, T) = \max_{j=1}^{N_T-N_S+1}\left[\max_{i=j}^{N_S+j-1}(x_i) - \min_{i=j}^{N_S+j-1}(x_i)\right]. \tag{10}$$

MTIE masks currently specified in standards [9], [10], still under discussion, span over a wide range of S: four decades, namely, from 10^{-1} s up to 10^3 s. For a long time, this range was even wider, from a few milliseconds up to 10^5 s. Moreover, many researchers do agree not to limit MTIE as a simple measure of wander, i.e., oriented just to point out slow phase changes (historically, this was stated first by ANSI [12]). Rather, MTIE, too, has proved very useful for characterizing clocks focusing on high-frequency noise. In this case, it should be computed from data collected at the highest possible rate in order to capture the fastest phase fluctuations.

In our opinion, typical values of interest in characterizing a clock, beyond mere conformance testing, are S from 1 ms to 10^4 s (or even 10^5 s) and T in the order of at least a few hours, while the target sampling period can be as short as $\tau_0 = 488$ ns for a 2.048 MHz timing signal. Hence, it obviously appears that the direct computation of the estimator (10) quickly tends to be unmanageable as the number of samples to store and process becomes huge.

B. Suitable Approaches to Practical Measurement

Different approaches can be envisaged to face up to the issue of storing and processing this huge amount of data, and therefore to accomplish the practical measurement of MTIE without making use of a supercomputer.

1) Contriving a suitable efficient alternative algorithm to the crude computation of (10). Any computational trick (except real-time data processing), however, would not let us avoid storing all those data.
2) Drastically reducing (trivial but effective!) the number N_T of samples x_i to process. This is achievable through shortening the measurement period T and/or lengthening the sampling period τ_0 (which is equivalent to sample decimation).
3) Following an alternative approach, such as the one outlined in Section III-D.

At present, the most widely adopted techniques for MTIE measurement in telecommunications consist of combining the first two approaches (*techniques based on estimator computation*). The technique outlined in Section III-D (*measurement using disjointed intervals*), on the other hand, follows a completely different approach; it was conceived with the aim of providing an easy but accurate way to test the compliance of telecommunications clocks with MTIE standard masks, exploiting the maximum TE sampling rate made available by instrumentation.

C. Techniques Based on Estimator Computation

The evaluation of MTIE curves through plain implementation of estimator (10) is feasible only on sequences of a *few* samples, acquired over a short measurement period T and/or over a long sampling period τ_0. This approach is equivalent to performing a drastic sample decimation. As an example, it is worthwhile noticing that achieving N_T of the order of 10^5 is possible by letting, e.g., $T = 50$ ms, $\tau_0 = 488$ ns (if aiming at exploiting the maximum sampling rate) or $T = 24$ h, $\tau_0 = 860$ ms (if aiming at observing the clock over a longer measurement period). In other words, in characterizing a clock over one day, we must give up observing high-frequency phase noise components.

Plain evaluation of estimator (10) is inadvisable, owing to the large number of operations nested in loops (for $N_T = 10^5$, there are from $2 \cdot 10^5$ to $5 \cdot 10^9$ comparisons, for every value of MTIE(S, T)). Some more effective algorithms can be derived, which cut down the computational effort.

D. Measurements Using Disjointed Intervals

The underlying idea is not to consider *all* the sliding windows of width S over the measurement period, but to perform a sequence of M consecutive independent measurements of MTIE(S), as shown in Fig. 3, each one taking into account disjointed sets of samples x_i collected at the maximum rate allowed by the measurement instrument. Each MTIE(S) measurement is done by letting $T = S$ in (10). Thus

$$\mathrm{MTIE}(S) = \max_{i=1}^{N_S}(x_i) - \min_{i=1}^{N_S}(x_i). \tag{11}$$

In Fig. 3, the measurement period was marked with T^*, since it has nothing to do with T of Fig. 1 and (10); here it is simply the period during which the clock is under test including dead time between measurements. Moreover, M different measurements of MTIE(S) can be accomplished in sequence by varying S step by step from a minimum value S_{MIN} up to a maximum S_{MAX} as a geometric progression of ratio

$$\rho = \sqrt[M-1]{\frac{S_{\mathrm{MAX}}}{S_{\mathrm{MIN}}}}. \tag{12}$$

The idea is to collect M snapshots of the clock peak-to-peak noise, by evenly sweeping the interval of interest [S_{MIN}, S_{MAX}]. Since the expression (11) is very simple, it can be evaluated in real time (e.g., in hardware) with virtually no limits on the number of samples x_i to process, thus allowing

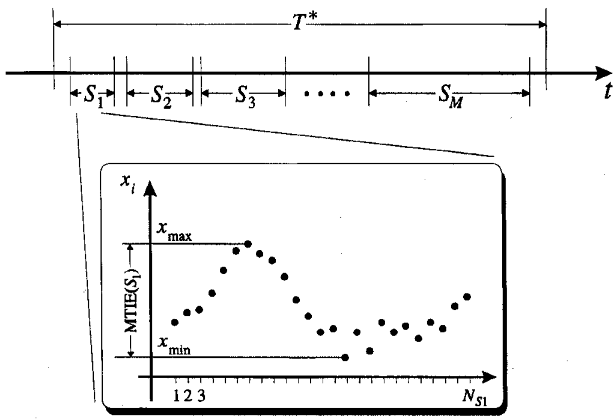

Fig. 3. MTIE(S) measurement technique using disjointed intervals.

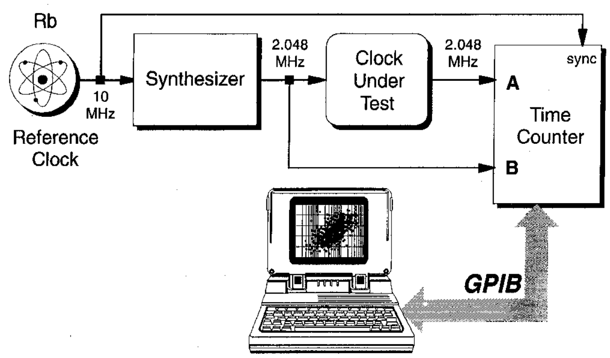

Fig. 4. MTIE measurement test bench.

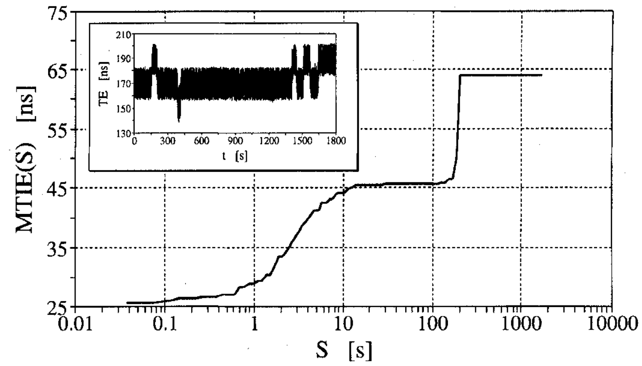

Fig. 5. TE and MTIE measured on the SEC of the ADM-1 A (estimator computation technique, $\tau_0 = 37.5$ ms, $N = 47450$).

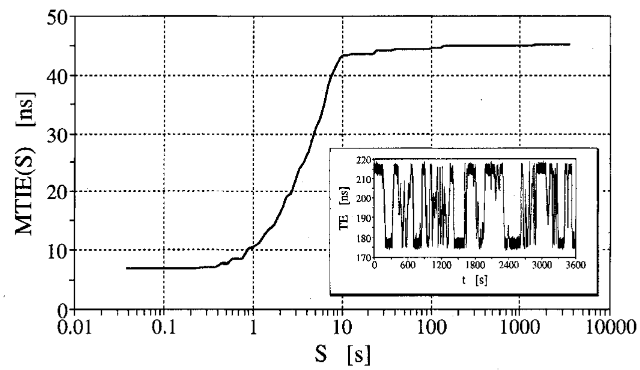

Fig. 6. TE and MTIE measured on the SEC of the ADM-4 A (estimator computation technique, $\tau_0 = 37.5$ ms, $N = 96750$).

achievement of the maximum sampling rate without worrying about data storage and, what's more, the time needed to compute (10).

The output of this test procedure is a scatter diagram typically showing a cloud of points (measurement results) of coordinates S, MTIE(S), which represent the CUT behavior during the whole measurement period T^*. A *necessary condition* for the clock compliance with standards is that *all* the measured points be below the specified mask, if adopting the classical definition of MTIE(S, T) (6). Obviously, the test becomes stricter as the number M of successive MTIE measurements becomes larger.

IV. Measurement Results

Both the techniques outlined have been extensively applied throughout the last three years in testing several timing devices, for conformance testing and for research purposes. The MTIE measurement test bench, according to the schematic diagram in Fig. 2, is outlined in Fig. 4. A high-performance time counter, with a resolution of 200 ps, measures the TE between the output timing signal of the CUT and its input reference (both 2.048 MHz G.703/10 [4] signals). The latter is synthesized from a rubidium frequency standard which also supplies the time base to the time counter. The time counter is driven via a GPIB IEEE488.2 interface by a laptop computer which manages data acquisition, processing and visualization.

A. Estimator Computation Technique

Two excellent examples of MTIE curves, measured according to the estimator computation technique, are reported in Figs. 5 and 6. These results were measured on the clocks of two pieces of SDH equipment (supplier A), namely, add-drop multiplexers STM-1 (ADM-1) and STM-4 (ADM-4). With standard terminology, we refer to SDH equipment clocks as *synchronous equipment clocks* (SEC's).

Two sequences of N TE samples were acquired, with sampling period $\tau_0 = 37.5$ ms, respectively over a measurement period $T \cong 1800$ s ($N = 47450$) and $T \cong 3600$ s ($N = 96750$). The smaller inner graphs in Figs. 5 and 6 plot these sequences decimated to about 8000 samples in order to show the TE trend. The MTIE curves (outer graphs), on the other hand, were computed in up to 24 points per decade according to (10).

B. Measurement Using Disjointed Intervals

This technique allows exploiting the maximum TE sampling rate achievable by the time counter. A special hardware function of the time counter allows real-time evaluation of (11) on up to $2 \cdot 10^9$ TE samples x_i measured on *every* edge of the 2.048 MHz timing signals ($\tau_0 = 488$ ns).

The measurement results provided (see Figs. 7–12) were obtained by testing the clock of a PSTN world-wide deployed digital switching exchange (supplier B), the clocks of four

TABLE I
ACTUAL MEASUREMENT PARAMETERS FOR THE RESULTS SHOWN IN FIGS. 7–12 (MEASUREMENT USING DISJOINTED INTERVALS)

Fig.	CUT Type	S_{MIN}	S_{MAX}	M	T^*
7	PSTN digital switch B clock (OCXO[1])	1 ms	500 s	200	~2.5 h
8	ADM-1 SEC A (TCXO[2])	1 ms	500 s	300	~3.5 h
9	ADM-4 SEC A (TCXO[2])	1 ms	1000 s	500	~10.5 h
10	ADM-1 SEC C (TCXO[2])	1 ms	1000 s	100	~2.5 h
11	DXC 4/3/1 SEC D (TCXO[2])	1 ms	1000 s	500	~10.5 h
12	SASE E (OCXO[1])	1 ms	1000 s	1000	~21 h

[1] *Oven Controlled Crystal Oscillator (quartz)*
[2] *Temperature Compensated Crystal Oscillator (quartz)*

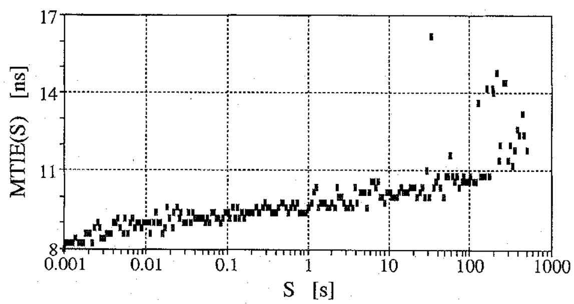

Fig. 7. MTIE values measured on the clock of the PSTN digital switch B (measurement using disjointed intervals).

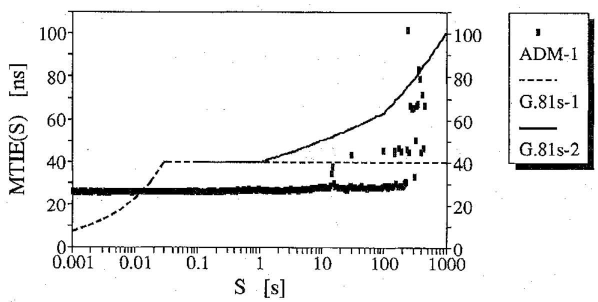

Fig. 8. MTIE values measured on the SEC of the ADM-1 A versus ITU-T G.81s mask (measurement using disjointed intervals).

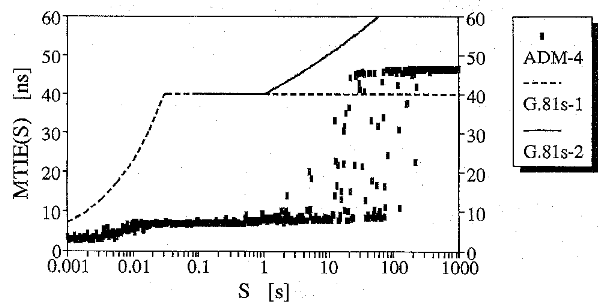

Fig. 9. MTIE values measured on the SEC of the ADM-4 A versus ITU-T G.81s mask (measurement using disjointed intervals).

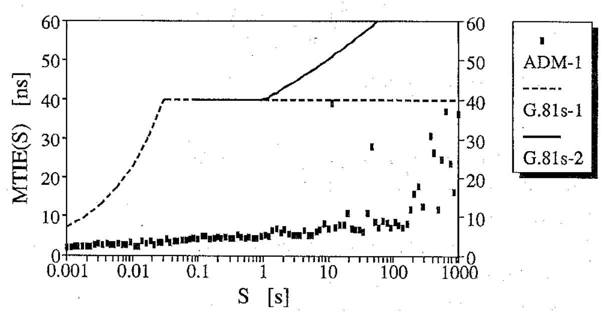

Fig. 10. MTIE values measured on the SEC of the ADM-1 C versus ITU-T G.81s mask (measurement using disjointed intervals).

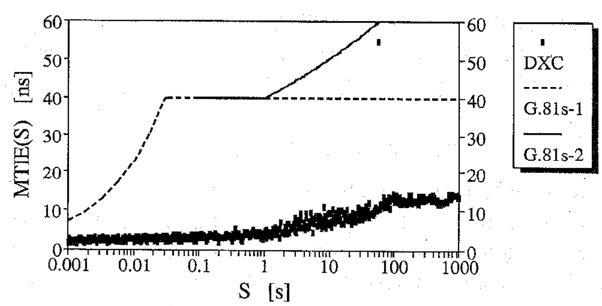

Fig. 11. MTIE values measured on the SEC of the DXC 4/3/1 A versus ITU-T G.81s mask (measurement using disjointed intervals).

pieces of SDH equipment—namely, two ADM-1s (suppliers A and C), one ADM-4 and one digital cross-connect (DXC) 4/3/1 (both of supplier A)—and one state-of-the-art stand-alone slave clock for synchronization networks (supplier D). With standard terminology, we refer to the stand-alone slave clock as *stand-alone synchronization equipment* (SASE). For easier understanding, the actual values of the parameters S_{MIN}, S_{MAX}, M and T^* for each test—together with the CUT type—are summarized in Table I, since tests were not executed in the same run.

MTIE graphs regarding SEC's (Figs. 8–11) depict also the limits specified in relevant standards; the MTIE mask specified in the latest version of G.81s [10] and of ETS DE/TM-3017 [9] (part 5) is the solid line G.81s-2, while the old mask, in force for a very long time, specified in previous versions is the dashed line G.81s-1. As shown by the graphs provided, some SECs exhibit higher noise than other CUT's, as they are implemented with lower cost oscillators. The SEC of ADM-1 A in Fig. 8, in particular, is not compliant with the original mask G.81s-1, since it exhibits a 26 ns noise floor for $S \leq 13$ ms, and some measured MTIE values are above the

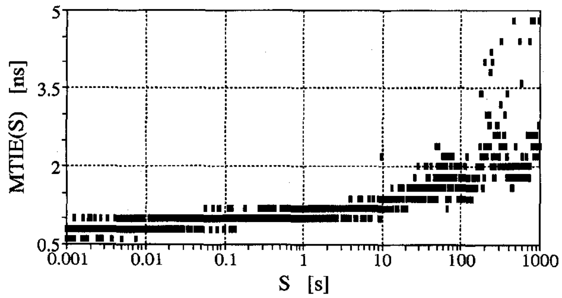

Fig. 12. MTIE values measured on the SASE D (measurement using disjointed intervals).

limits in the range 10 s $\leq S \leq$ 1000 s. The new mask G.81s-2, on the contrary, is much more permissive, so that almost all the measured values are below those limits. Analogous considerations apply to the ADM-4 SEC of the same supplier in Fig. 9; while the measured values for $S > 10$ s are well over the original mask G.81s-1, the new mask G.81s-2 has granted "amnesty" by also allowing the 46 ns values under the limits. Finally, not surprisingly, the clock featuring the best performance is the SASE (Fig. 12), designed to distribute timing to the synchronization network and therefore offering the highest stability.

V. Comparison between the Estimator Computation Technique and the Measurement using Disjointed Intervals

While any technique based on the estimator computation is more in line with the formal definition of MTIE (cf., Section II) than the measurement using disjointed intervals, it implies the issue of its computational effort exploding with the number of TE samples stored. This generally forces the experimenter greatly to undersample the TE(t) process in order to apply the estimator on a reasonable number of samples. However, the estimator computation technique is mandatory when analyzing transients, such as phase hits.

The method of measurement using disjointed intervals, on the other hand, distinguishes itself by its ability in capturing the fastest phase fluctuations, thus allowing very small values of S in characterizing clocks with MTIE. Moreover, scatter diagrams are very useful in rendering the statistics of measured values—clouds thicken where values are more likely—and thus help in checking percentile masks at a glance.

We want to point out, moreover, the excellent agreement between the results measured with the two techniques on the SEC's of the ADM-1 A (compare graphs of Figs. 5 and 8) and the ADM-4 A (graphs of Figs. 6 and 9). Although measurements were accomplished in very different times, in both cases the MTIE curves evaluated through estimator computation do match with measurements using disjointed intervals, thus confirming, on the one hand, the validity of the latter method, on the other, that those graphs really show the typical behavior of CUT's and not fortuitous misbehaviors.

Finally, measurements using disjointed intervals appear to be stricter conformance tests, as they yield slightly worse results (i.e., higher MTIE(S) values with equal S), compared with those obtained through computation of the estimator *(10)* on *short* sequences $\{x_i\}$ sampled at a much lower rate. This is quite natural, since the peak-to-peak deviation of a set of N_S TE samples, spanning an observation interval S, is greater for larger N_S (keeping constant S, i.e., by decreasing the sampling period τ_0). Comparing to a Gaussian noise model, collecting more samples causes the histogram tails to stretch out! We remark, once again, that in the graphs shown MTIE($S = 1000$ s) measurements are based on $2\cdot10^9$ samples.

For the sake of precision, this is especially true if, in the timing signal under test, a broadband noise such as white phase noise [13], [14], [16] dominates. Other low-frequency noises, viz., flicker frequency or random walk frequency noise, yield slower TE changes, and thus the impact of shortening the sampling period τ_0 on the peak-to-peak deviation is reduced.

VI. Conclusions

In this paper, suitable approaches to practical measurement of MTIE were discussed, summarizing the state-of-the-art of MTIE measurement techniques in telecommunications. A new effective technique was outlined, with the aim to provide an easy but accurate way to test the compliance of telecommunications clocks with MTIE standard masks. Moreover, several measurement results were provided. The results shown were chosen from among those obtained throughout the last three years by testing clocks of widely deployed digital switching exchanges, clocks of SDH equipment and SASE's. The proposed technique has proved effective and very useful, both for plain conformance testing of clocks and for gaining more insight into the actual performance of commercial timing equipment in terms of peak-to-peak phase noise.

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