Active Measurement and Time-Domain Characterization of IP Packet Jitter

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***Abstract* — Synchronization over packet-switched networks has been attracting increasing attention lately, e.g. due to migration to IP transport in GSM networks. Timing is distributed by sending packet flows with constant rate. At the receiver, timing is recovered mostly based on PLL schemes that equalize packet random delay. The performance of these schemes depends significantly on the statistics of packet jitter, thus yielding a growing interest for real data measurement. We developed an experimental setup to measure IP packet jitter by active probing, aiming at statistical characterization of packet jitter in real heterogeneous networks. We present some experimental results, measured in networks including bridges and routers. Contrary to previous studies in literature, we emphasize data analysis by means of Modified Allan Variance (MAVAR) and Maximum Time Interval Error (MTIE), two well-known time-domain quantities widely used for synchronization interface specification in international standards. Although our setup is simple, the noise floor is negligible, compared to the network jitter under measurement.**

***Index Terms* — Communication system traffic, Internet, jitter, traffic measurement (communication).**

I. Introduction

Several fixed and mobile operators are migrating to an IP packet-switched network (PSN) infrastructure. This trend is driven by prospected lower operative costs and the convergence between fixed and mobile services. However, migrating trunk lines to IP transport poses thorny problems, in particular for circuit emulation and synchronization of network elements.

Packet jitter is defined as the random variation of packet transport delay. It may be caused by network queuing, congestion, route changes and other phenomena [1]—[3]. It impairs all synchronous services over PSN.

Synchronization of network elements may be based on transmitting packet flows with constant rate from the master and then on local clock recovery or buffer reading [4]—[7]. In fact, PSNs do not carry synchronous signals natively, since packet jitter may be high. The remarkable growing interest for this emerging topic (a.k.a. *synch-over-packet*) has also led to proposing new standards [8][9], still under development.

Various algorithms were conceived to recover the packet clock rate. Their performance clearly depends on various factors (e.g., traffic load, mix, policy, shaping and priority), as well as on the statistics of packet jitter. Thus, there is also a renewed interest for experimental characterization of packet jitter in real networks, possibly by fine analysis methods defined in standards for synchronization signals [10].

We developed an experimental setup to measure IP packet jitter by active probing. The main goal is the statistical characterization of packet jitter in real heterogeneous networks. In this paper, we outline the measurement setup and present some experimental results, measured in networks across switches and routers. Unlike previous studies in literature, we emphasize data analysis by means of Modified Allan Variance (MAVAR) and Maximum Time Interval Error (MTIE), two well-known time-domain quantities widely used for frequency stability characterization and network synchronization specification in international standards.

II. Packet Jitter Measurement and Statistical Analysis

Packet jitter is defined as the random variation of packet transport delay across the network. It can be measured by a *passive* or an *active* measurement system.

In passive measurements, aggregate traffic streams are sniffed and analyzed, to individuate a single packet flow transmitted with constant rate (e.g., VoIP packets). Practical realization of this method is thus not simple.

In active measurements, probing traffic is transmitted and observed at the receiver to measure the quantity of interest (e.g., packet jitter). This method may be more accurate, because packet transmission can be controlled (inter-packet intervals must be as much even as possible). It is also possible to move the receiver around the network. The drawback of this method is that it may slightly perturb real network traffic.

A. Methodology for Measurement of Packet Jitter

We adopted the active approach, based on sending a constant-rate flow of packets with timestamp (time instant at the transmitting network element). By difference with a local receiver timestamp, the jitter introduced by the carrier network can be estimated. The measurement scheme is shown in Fig. 1.

We transmit a sequence of N UDP packets. Within every UDP payload, we write the transmission time based on the transmitter clock (T_k). At the receiver PC, the network card receives the UDP packet, records the time instant of reception (R_k) based on the receiver clock and extracts the UDP payload.

Therefore, at the receiver PC, we process two time sequences $\{R_k\}$ and $\{T_k\}$ to estimate jitter. In summary:

- N: total number of packets transmitted.
- T_k: timestamp generated by the clock of the transmitter PC, expressed as μs count from 1st Jan. 1970 with $1 \le k \le N$. Ideally, packets are equally spaced by ΔT, inverse of the packet generation rate.
- R_k: timestamp generated by the clock of receiver PC, expressed as μs count from 1st Jan. 1970 with $1 \le k \le N$.

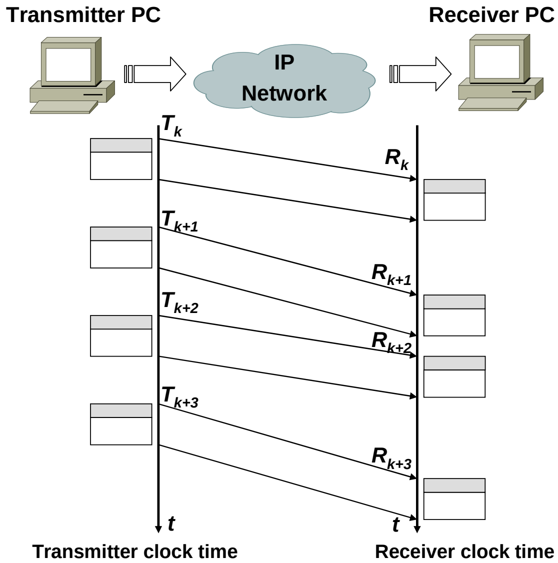

Fig. 1: Testbed model and representation of packet times.

$d_k = (R_k\text{-}T_k)$: difference of receiver and transmitter timestamps.

Since PC clocks are not synchronized, the two sequences $\{R_k\}$ and $\{T_k\}$ exhibit time and frequency offset and even drift, which have to be properly subtracted from jitter results.

B. Jitter Model

We assume that jitter is simply modeled as

$$\mathbf{d} = \mathbf{X}\begin{bmatrix} T_{\text{off}} \\ \alpha \end{bmatrix} + \mathbf{j} \tag{1}$$

where:

$\mathbf{d} = \{d_k\}$ $(1 \le k \le N)$, sequence of timestamp differences;

$$\mathbf{X} = \begin{bmatrix} 1 & 1 & 1 & \dots & 1 \\ \Delta T & 2\Delta T & 3\Delta T & \dots & N\Delta T \end{bmatrix}^T ;$$

T_{off} = initial time offset between the two clocks;

α = fractional frequency offset between the two clocks;

$\mathbf{j} = \{j_k\}$ $(1 \le k \le N)$, sequence of measured jitter samples.

Note that frequency drifts, of any order ≥1, have been assumed negligible, at least over measurement intervals of interest.

To measure jitter, first we estimate $\hat{T}_{\text{off}}$ and $\hat{\alpha}$ by Least Squares (LS) estimation, since no *a priori* knowledge of the $\{j_k\}$ process is available. The LS estimator is defined as

$$\begin{bmatrix} \hat{T}_{\text{off}} \\ \hat{\alpha} \end{bmatrix} = (\mathbf{X}^T\mathbf{X})^{-1}\mathbf{X}^T\mathbf{d} \tag{2}$$

Now we can obtain a measure of packet jitter, simply by difference between $\mathbf{d}$ and the regression line, as

$$\mathbf{j} = \mathbf{d} - \mathbf{X}\begin{bmatrix} \hat{T}_{\text{off}} \\ \hat{\alpha} \end{bmatrix} \tag{3}$$

Measured jitter data $\{j_k\}$ were analyzed, unlike previous studies, by the Modified Allan Variance (MAVAR) and the Maximum Time Interval Error (MTIE). MAVAR and MTIE are two well-known time-domain quantities, widely used for frequency stability characterization and network synchronization interface specification in international standards [10].

C. Modified Allan Variance (MAVAR)

MAVAR is a well-known time-domain quantity, conceived in 1981 for frequency stability characterization of precision oscillators [11]—[15] by modifying the definition of the Allan Variance. MAVAR has been demonstrated to feature superior spectral sensitivity and accuracy in fractional-noise parameter estimation, coupled with excellent robustness against nonstationarities in data analyzed (e.g., drift and steps) [16]—[18].

Given a finite set of N samples $\{x_k\}$ of a signal $x(t)$, evenly spaced by sampling period τ_0, MAVAR can be estimated using the ITU-T standard estimator [11]

$$\text{Mod}\,\sigma_y^2(\tau) = \frac{\displaystyle\sum_{j=1}^{N-3n+1}\left[\sum_{i=j}^{n+j-1}\left(x_{i+2n} - 2x_{i+n} + x_i\right)\right]^2}{2n^4\tau_0^2\left(N-3n+1\right)} \tag{4}$$

where the observation interval is $\tau = n\tau_0$ and $n = 1, 2, \ldots, \lfloor N/3 \rfloor$.

The MAVAR is a kind of variance of the second difference of input data, including an internal average over n adjacent samples. A recursive algorithm for fast computation of this estimator exists [11], which cuts down the number of operations needed for *all values* of n to $O(N^2)$ instead of $O(N^3)$.

It should be noted that the point estimate (4) is a random variable itself. Along a plot of MAVAR(τ), confidence intervals are negligible for short τ and widen moving to longer τ, where fewer terms are averaged [19]—[21].

D. Maximum Time Interval Error (MTIE)

The Time Error TE(t) is the difference between the time T(t) generated by a clock under test and a reference clock [11][22]. Then, the Maximum Time Interval Error (MTIE) is defined as the maximum peak-to-peak variation of TE in all possible observation intervals τ within a measurement period T, i.e. [23]

$$\text{MTIE}(\tau, \text{T}) = \max_{0 \le t_0 \le T-\tau}\left\{\max_{t_0 \le t \le t_0+\tau}\left[TE(t)\right] - \min_{t_0 \le t \le t_0+\tau}\left[TE(t)\right]\right\} \tag{5}$$

MTIE has played historically a major role for characterizing time and frequency performance in digital telecommunications networks [10][11][22][23]. In particular, MTIE specifications are well suited for the design of equipment buffer size.

A binary-decomposition algorithm for MTIE fast computation exists, which cuts down the number of operations to $O(N \log N)$ instead of $O(N^2)$ for any value of MTIE(τ) [24].

III. Experimental Setup

We used two Linux PCs as traffic transmitter and receiver hosts. We chose RUDE/CRUDE (Real-time UDP Data Emitter /Collector for RUDE) [25] as traffic generator program. This UDP packet emitter features good precision in setting the inter-packet interval, because it uses a round-robin-real-time process scheduler with high priority, although it runs in the user space and not in the kernel space as other programs.

As probing traffic, we transmit a stream of UDP packets with payload 50 bytes and rate 50 packets/s. Thus, the stream consists of Ethernet frames with length 96 bytes (50 payload UDP + 8 UDP + 20 IP + 18 Ethernet) with overall bit rate

38400 bit/s. The measurement interval is $T = 657$ s, including 32850 generated packets. Packet timestamps, expressed as microsecond count, are obtained by the *gettimeofday()* library function. A microsecond resolution is adequate for packet jitter measurement, because in real networks packet jitter is expected to be typically on the order of milliseconds and above.

Anyway, before measuring real packet jitter, we measured the background noise jitter of the experimental setup (*resolution* and actual *accuracy* of measurement do not coincide). Among possible causes of this noise floor, we mention that:

- it is very difficult to generate a sequence of packets with perfectly equal inter-packet intervals using a standard PC;
- the time-stamping process at the receiver is software-based and may be thus the greatest source of noise jitter; this effect can be reduced, e.g. by granting highest priority to the receiver process, but it cannot be eliminated;
- the two PC clocks are not synchronized; what's more, they are cheap quartz oscillators with poor frequency stability.

In spite of all this, the set-up noise floor resulted much lower than the measured network jitter.

IV. Measurement Results

We carried out four series of measurements of packet jitter between two PCs, connected in the following configurations:

- back-to-back by a short cross Ethernet cable (measurement of background jitter noise floor);
- via a 8-ports LAN mini-switch;
- via a campus IP network, including routers and LAN switches, carrying various real extra traffic (test carried out at daytime in the campus network of the Dept. of Electronics and Information, DEI, at Politecnico di Milano);
- via a public ISP connection to the DEI campus network.

First of all, the graph in Fig. 2 plots the inter-packet time intervals measured at the transmitter PC. The UDP traffic generator results rather accurate, because of the small number of outliers compared to the nominal value $\Delta T = 20$ ms.

A. Back-To-Back Connection: Background Jitter Noise Floor

In this section, we present one of the various sets of experimental results we measured on two PCs directly connected back-to-back by a short Ethernet-cross cable, in order to assess the background jitter noise floor of our setup.

These results are shown in Figs. 3, 4, 5, 6 and 7, which plot respectively: the sequence of difference samples $\{d_k\}$ between receiver and transmitter timestamps, the sequence of measured jitter samples $\{j_k\}$ estimated as (3), the histogram of measured jitter samples $\{j_k\}$ having removed the parabolic trend, the MAVAR of the measured jitter sequence $\{j_k\}$ with linear regression line for average slope estimation, the MTIE of the measured jitter sequence $\{j_k\}$.

In Fig. 3, the nearly constant slope of data represents the time and frequency offset between clocks ($\alpha \cong 111.6 \cdot 10^{-6}$, i.e. time drift ~10 s/day, estimated by linear regression).

In Fig. 4, we note that the background jitter noise floor of our setup, on the order of 10 µs, is very small with respect to the expected level of network jitter. Moreover, we note also some higher-order frequency drift between clocks.

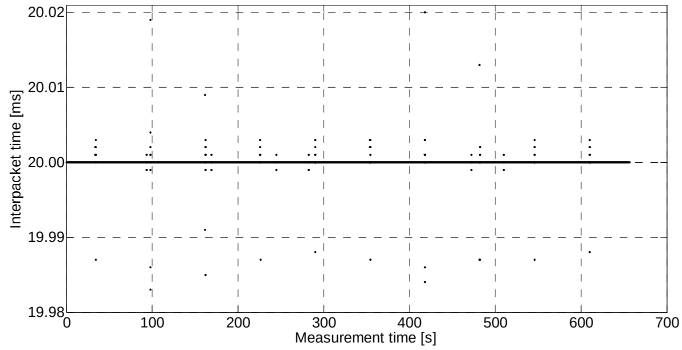

Fig. 2: Inter-packet time intervals measured on transmission.

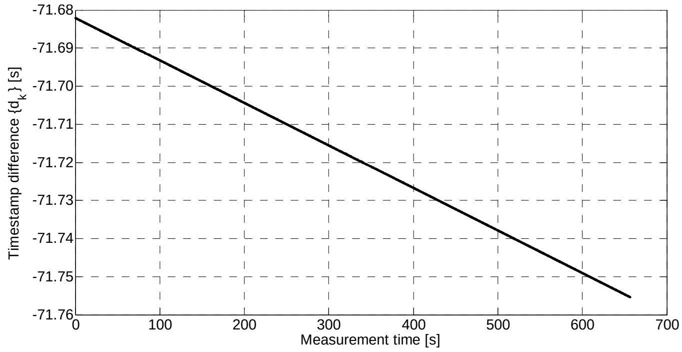

Fig. 3: Difference $\{d_k\}$ between receiver and transmitter timestamps (back-to-back connection).

In Fig. 6, the average slope of MAVAR in log-log plot, estimated by linear regression for $\tau < 2$ s, results $\mu \cong -3.13$, very close to the ideal value -3 of white noise [18]. Thus, the measured jitter sequence $\{j_k\}$ results white with excellent approximation, at least in the short term. The deviation of MAVAR from this linear trend, particularly evident for $\tau > 20$ s, is due to the drift of jitter $\{j_k\}$ trend on longer observation intervals.

In Fig. 7, we note that on any observation interval $\tau < 40$ s the peak-to-peak deviation of the packet jitter keeps ≤ 73 µs.

Other measurements carried out in the back-to-back configuration yielded similar or same results.

B. Connection via 8-Ports LAN Mini-Switch

We carried out measurements also on two PCs connected via a 8-ports mini-switch, at daytime in a campus LAN of the DEI. Although the LAN was normally operating, thus carrying various real extra traffic from many regular users, all results are practically the same as those measured on two PCs directly connected back-to-back.

The switch does not introduce any recognizable additional packet jitter, because in normal operation of high-speed LANs the traffic load is very low compared to switch capacity.

C. Connection via Campus IP Network

We carried out several measurements at daytime on two PCs connected via the campus network of DEI at Politecnico di Milano. The network scheme is shown in Fig. 8.

In the first test (Figs. 9 through 12), the two PCs were connected via one router, one switch and one 8-ports mini-switch. As expected, the measured jitter level (Fig. 9) is higher than in

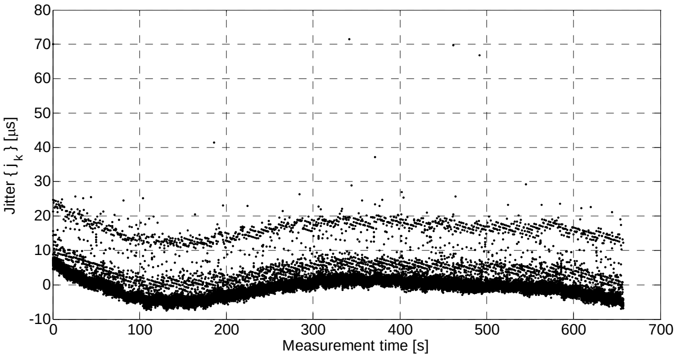

Fig 4: Measured jitter $\{j_k\}$ (back-to-back connection).

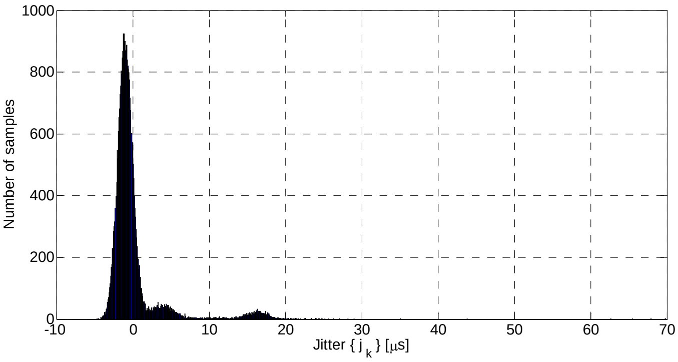

Fig. 5: Histogram of measured jitter $\{j_k\}$ after detrending (back-to-back connection).

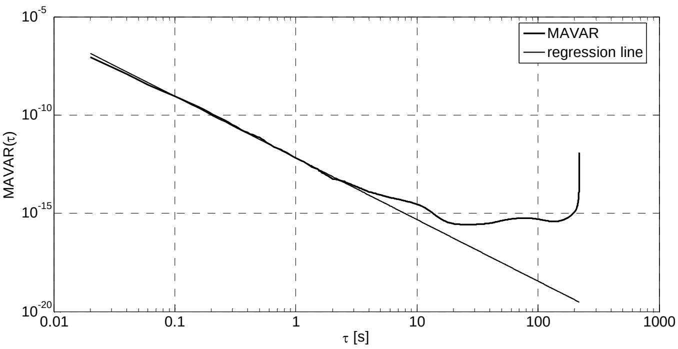

Fig. 6: MAVAR of measured jitter $\{j_k\}$ and regression line (back-to-back connection).

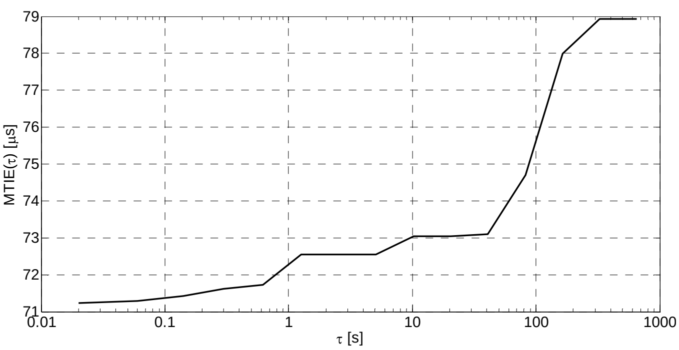

Fig. 7: MTIE of measured jitter $\{j_k\}$ (back-to-back connection).

the 8-ports switch connection: on the order of tens to hundreds of µs. The average slope of MAVAR (Fig. 11), estimated by linear regression for $\tau < 6$ s, results $\mu = -3.02$ (i.e., white noise in the short term). In Fig. 12, we note that the peak-to-peak jitter is about 260 µs even on short observation intervals.

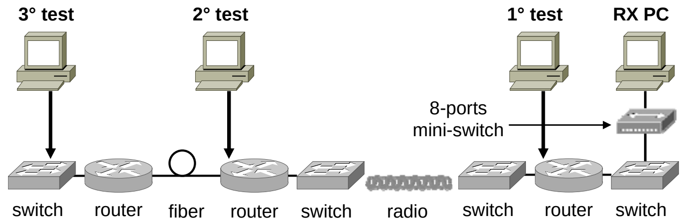

Fig.8: Scheme of DEI campus network and tests.

In the second and third tests, the two PCs are connected via more network elements and links. We shown only results of test 3 (Figs. 13 through 16), since they are quite similar to that of test 2. Here, we note that the measured jitter level is substantially higher than in test 1: on the order of ms.

The average slope of MAVAR is $\mu = -2.56$ (Fig. 15), estimated by linear regression over almost the whole range of observation interval. This means that the packet jitter sequence is not purely white, but it exhibits some degree of long-range dependence (LRD). The power spectral density (PSD) of the data sequence analyzed $\{j_k\}$ can be approximated as $S_j(f) \propto 1/f^{0.44}$ [18]. In Fig. 16, we note that the peak-to-peak jitter is above 2 ms, even on short observation intervals.

D. Connection via Public ISP Access

We carried out measurements also between two PCs connected one (TX) to a public ISP network (with fibre access) and the other (RX) to the DEI campus network. In this configuration, packets transit across about 20 routers. Results are shown in Figs. 17 through 20.

As expected, the measured jitter level (Fig. 17) is even higher than in previous tests. The average slope of MAVAR is $\mu = -2.86$ for $\tau < 4$ s (Fig. 19), corresponding to $S_j(f) \propto 1/f^{0.14}$ [18], revealing some light LRD. For $\tau > 4$ s, a lower regular slope is visible, showing the possible presence of an additional term $1/f^{\alpha}$ with $\alpha > 1$. In Fig. 20, we note that the peak-to-peak jitter is above 2.6 ms even on short observation intervals.

V. Conclusions

We developed an experimental setup to measure IP packet jitter by active probing, aiming at statistical characterization of packet jitter in real heterogeneous networks.

In this paper, we outlined the measurement setup and presented results obtained in four experimental configurations where two probing PCs were connected: back-to-back for measuring the background jitter noise floor, via LAN mini-switch, via campus IP network including routers and switches, via public ISP connection.

These results demonstrate that the background noise floor introduced by our setup is negligible, compared to the real network jitter, although the method used is quite simple. Moreover, the jitter introduced by the LAN mini-switch resulted not higher than this measurement jitter noise floor, due to the low traffic load of high-speed LANs in normal conditions.

Finally, the jitter introduced by IP networks resulted significantly higher, even on the order of a few ms.

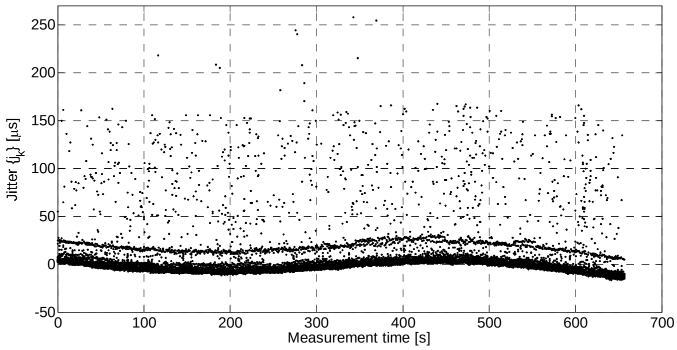

Fig.9: Measured jitter $\{j_k\}$ (connection via IP network - test 1).

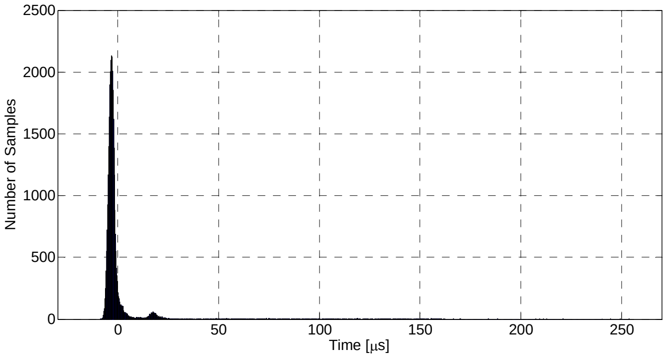

Fig. 10: Histogram of measured jitter $\{j_k\}$ after detrending (connection via IP network - test 1).

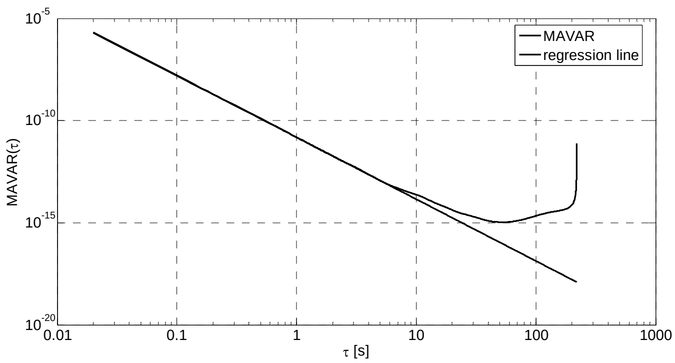

Fig. 11: MAVAR of measured jitter $\{j_k\}$ and regression line (connection via IP network - test 1).

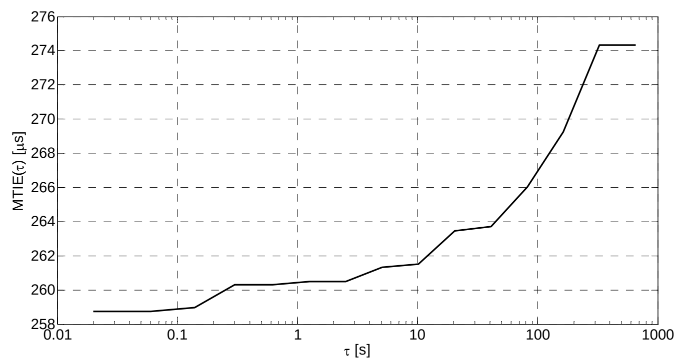

Fig. 12: MTIE of measured jitter $\{j_k\}$(connection via IP network - test 1).

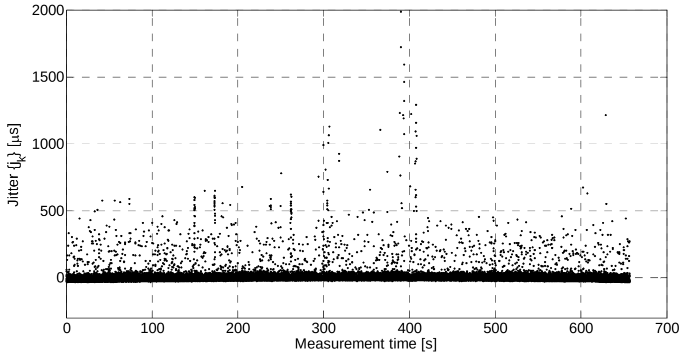

Fig. 13: Measured jitter $\{j_k\}$ (connection via IP network - test 3).

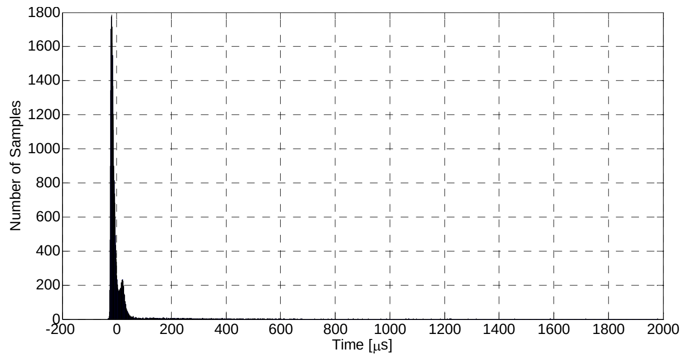

Fig. 14: Histogram of measured jitter $\{j_k\}$ after detrending (connection via IP network - test 3).

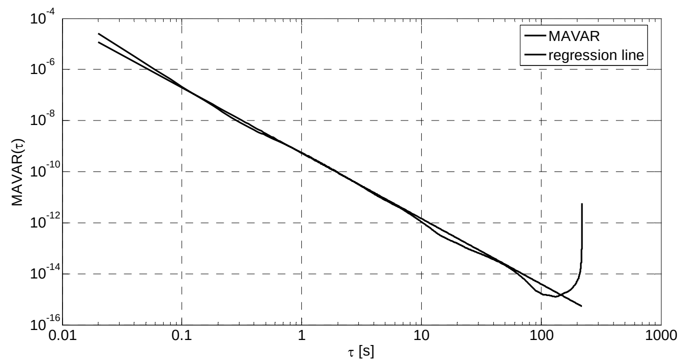

Fig. 15: MAVAR of measured jitter $\{j_k\}$ and regression line (connection via IP network - test 3).

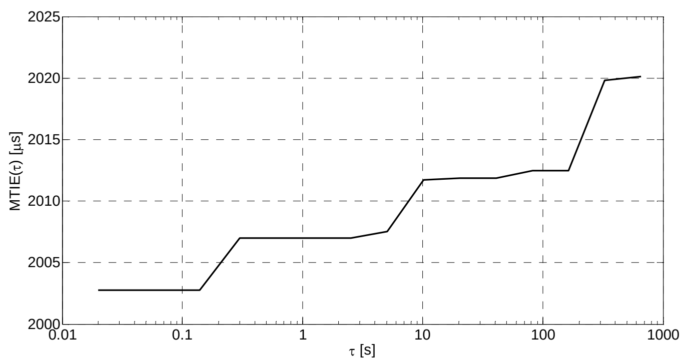

Fig. 16: MTIE of measured jitter $\{j_k\}$ (connection via IP network - test 3).

By MAVAR results, we recognized that the network packet jitter is not purely white, but it exhibits some various degree of LRD (Figs. 15, 19). The PSD of the measured jitter series $\{j_k\}$ can be approximated as a power law $S_j(f) \propto 1/f^{\alpha}$ ($\alpha > 0$).

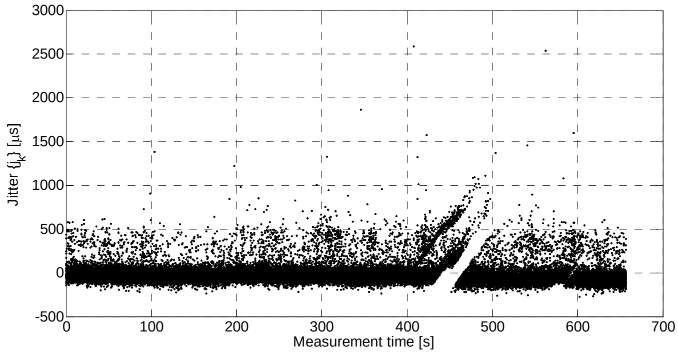

Fig. 17: Measured jitter $\{j_k\}$ (connection via ISP access).

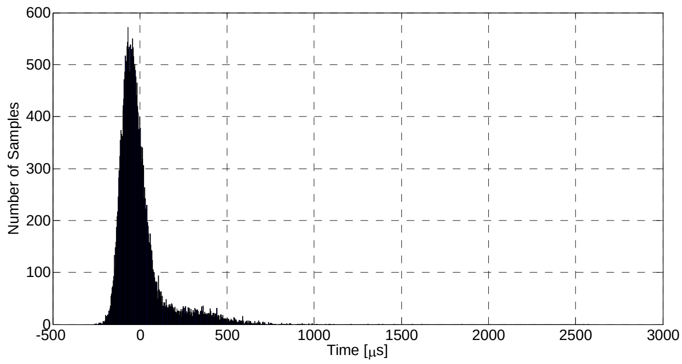

Fig. 18: Histogram of measured jitter $\{j_k\}$ after detrending (connection via ISP access).

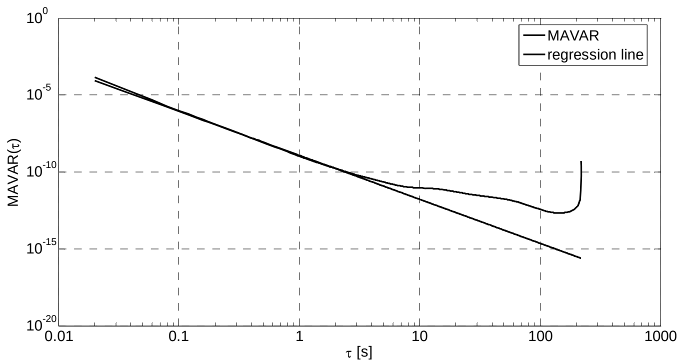

Fig. 19: MAVAR of measured jitter $\{j_k\}$ and regression line (connection via ISP access).

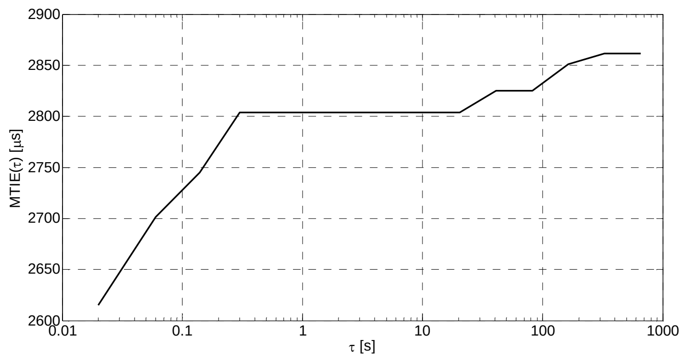

Fig. 20: MTIE of measured jitter $\{j_k\}$ (connection via ISP access).

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