Optimization of concurrent data and high-precision time transfer modes in meteor burst synchronization equipment

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Abstract— **We present the capacity of meteor synchronization equipment in data transfer mode with data rate depending on current synchronization state. The equipment works in two modes: time transfer and data transfer, both consume available meteor trails. For the particular application discussed, the amount of bits transferred on a single meteor trail is a logarithmic function of time-scale shift estimate error. The additional requirement of the application is both modes may not share the same meteor trail.**

I. Introduction

Meteor burst channel provides a way to transfer information at distances up to 1800-2000 km during short random intervals when reflecting trails exist on the current radio-path. In spite of peculiar properties it can afford sub-nanosecond precision when used for distant time transfer. This precision makes it competitive with the best means of distant synchronization currently used. Along with high precision, the distinctive features of meteor synchronization equipment are independence and relative simplicity. Other notable property is its high stability—the ability to withstand many natural and artificial factors interfering with radio wave propagation.

The clearly visible drawback of meteor communication in general is its absolute dependence on interruptible natural phenomenon: meteor bursts. Meteor bursts and reflective trails created by them occur and disappear sporadically and exist only a tiny fraction of the whole communication session, thus curtailing the channel capacity. Low capacity and not being available "on demand" push meteor communication away from more convenient methods into the area of special applications. On this side, meteor communication has some interesting ways of using it, especially when its unusual behavior can be turned into advantage.

II. Time transfer precision

The high potential precision of time transfer by meteor channel is mainly the result of its good reciprocity.

A. Carrier frequency phase measurements

In Kazan State University (KSU) the adequate phase reciprocity of meteor channel has been noticed in late 1970s. This allowed successful utilization of two-way time transfer method, which had since been gradually adopted by all variants of meteor synchronization equipment. Estimates of two-way phase transfer accuracy showed that after the removal of distinct and attributable to well-known factors parts of non-reciprocity error, the residual does not exceed 0.3 ns (by standard deviation). This leftover non-reciprocity remains the only part limiting precision of time transfer as carrier frequency phase.

The last sets of KSU meteor equipment [1] that served as a base for production model had two distinct error sources: non-reciprocity and random noise. The non-reciprocity error not excluded by the equipment is caused by winds shifting (and eventually destroying) meteor trails. These errors vary from burst to burst, but tend to remain stable on the whole interval of the trail existence. We chose to present these errors as random addition to the wave propagation time on a meteor path, independent of the carrier frequency. Random noise errors may vary both on different bursts and throughout the burst. We presented the equipment parameters and sample carrier frequency two-way phase measurements in [2]. It was shown that random noise present in a single two-way carrier frequency measurement does not exceed 0.05 cycles, which gives a precision of 0.44 ns (carrier frequency is 57.25 MHz).

The equipment automatically performs two-way measurements every 0.02 seconds while the trail exists. Some of these contain clearly visible non-reciprocity shift at the start of the registration. This shift is due to meteor particle movement during the trail formation, which together with asymmetrical position of the reflection point against communicating stations and small delay between forward and backward signals leads to increase of measured phase difference. Theoretically, this shift can be compensated, but as of now, such measurements are simply dropped. One reason we can afford this is the fact that such shifts occur only on long lasting trails and occupy an insignificant part of them. Other measurements can also be dropped if they have too much random noise present, but these are rare. The resulting single-meteor measurement is an averaged value of all usable real measurements given by the trail. From now on, unless specifically stated, when we talk about phase measurement we use a single-meteor averaged value. It is clear that high-energy meteor trails may give smaller random errors just by being "longer". Random error of a carrier frequency measurement is almost always a great deal smaller than the 0.3 ns residual non-reciprocity limit. This becomes important during phase ambiguity resolution (described further)—step-by-step procedure of calculating

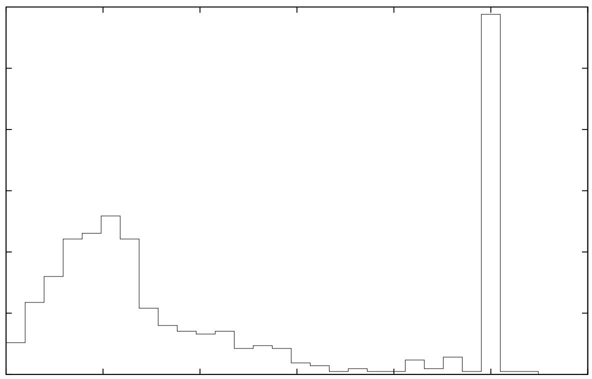

Fig. 1. Distribution of the random part of single-meteor time-transfer measurement errors

the right number of periods for more precise and having smaller ambiguity period phase measurements. Fig. 1 shows the distribution of random noise error standard deviations for two-way phase measurements, seen during the time-transfer experiment on Moscow-Kazan (720 km) meteor path. The peak corresponding to standard deviation of 0.05 occurs because we assign this error value to short-lived trails that do not last more than 0.02 seconds after hand-shake completes and there is nothing to average. We assume the value 0.05 cycles to be the greatest possible error because of the way the amplitude of the reflected signal behaves. The short interval the signal amplitude appears above the noise threshold is the peak, where dynamic non-reciprocity corresponding to the formation of meteor trail is already gone, thus there is no reason to assign such a measurement a higher error. With higher inter-meteor measurement rate this peak should "spread" in the neighborhood of value 0.05.

B. Multiple frequencies for phase ambiguity resolution

Phase-based time transfer equipment constructed in KSU uses multiple frequencies as a way of phase ambiguity resolution. This makes it distinct from meteor synchronization systems that use one wide-band impulse and relying on rare high-energy meteors.

Suppose we transmit a time-signal as narrow-band impulses on carrier frequencies $f_1, \ldots, f_n$ where $f_1 > f_2 >, \ldots, > f_n$, and get initial phases $\phi_1, \ldots, \phi_n$ at the reception point. The first estimate of time-scale shift is made by phases of two closest frequencies $\tau_1 = \frac{\phi_1 - \phi_2}{f_1 - f_2}$. τ_1 has the ambiguity period $T_1 = \frac{1}{f_1 - f_2}$ and gives a measurement, more precise than the initial estimate τ_0, made by taking the impulse's envelope position. We choose the right number of T_1 to add to τ_1 so that the resulting measurement is the closest to τ_0, thus resolving τ_1's ambiguity. At the next step, we take the estimate $\tau_2 = \frac{\phi_1 - \phi_3}{f_1 - f_3}$, still more precise than τ_1, but having smaller ambiguity period T_2. Ambiguity of τ_2 is resolved by τ_1. We proceed this way until we have τ_{n-1}—measurement by the maximal differential frequency $f_1 - f_n$ with ambiguity resolved. After that, there is only one step left: going from τ_{n-1} to the phase of any of the carrier frequencies and τ_n. τ_n has the best possible precision.

We make this final step stand out because implementing the carrier frequencies span, required for trustworthy transition from τ_{n-1} to τ_n *on a single meteor trail* makes a noticeable increase in equipment complexity and may not always be affordable or desirable.

C. Filtration of time-transfer measurements

To estimate the time-scale coordination errors we use the results of optimal linear filtration. Time coordination supposes giving the current estimate of time-scale shift not only when a time-transfer measurement arrives, but as needed, based on the current prognosis. Optimal linear filtration requires a model of measurements and of a process whose parameters we want to obtain. Measurements in our model are carrier-frequency phases corresponding to a doubled time-scale shift between remote stations. We suppose the error of a measurement is the sum of a random noise error and a non-reciprocity error. Random noise errors are Gaussian, with standard deviations, distributed as shown in Fig. 1. Non-reciprocity errors are also Gaussian, but with constant standard deviation of 0.3 ns.

The time-scale shift generating process is a combined instability of frequency standards on both stations. In the experiment the H-maser (primary station) and the cesium standard were used, so we use their parameters. We ignore the short-term instability of H-maser but take into account its possible inaccuracy. Instability of the cesium standard used on the secondary station is white Gaussian frequency noise. For our purposes (discrete measurements) we use Gaussian frequency errors with dispersions inversely proportional to intervals between measurements, while intervals between measurements are distributed exponentially.

The filter construction details can be found in [2].

Having Gaussian errors on the input of filtration model we also have the resulting time-scale coordination errors also Gaussian [3].

III. Concurrent time and data transfer

Meteor synchronization equipment can be also used for data transfer, that can be anything, from plain text messaging with typical transfer rate of 10–40 bits per second, to performing various independent measurements. When both synchronization and data transfer modes are required during the communication session they must share the scarce resource of available meteor trails. The relative importance of both modes depends on the particular application. We use data transfer for a special situation where synchronization is a prerequisite for data transfer, that is data can not be transmitted is if current time-scale shift error exceeds a required minimal value. There is also another dependency present: data transfer rate might also be higher with better synchronization.

A. Random key exchange using meteor channel

The data transfer relying on synchronization state in our case is random key exchange by meteor channel. The idea of meteor key exchange is based on the channel's known property of being hard for eavesdropping, and a natural random process underlying it.

During the meteor communication session the length of a wave-path varies on different meteor trails, with typical spread of propagation time about 500 μs. We can say that our free passive retransmitters (meteor trails) randomly appear from nowhere and disappear shortly thus making the current radio path completely unpredictable. Thus the length of the current wave-path is a naturally random process, and the propagation time modulo 500 μs is one of its varying components. If two communicating points have synchronized time scales, they can simultaneously transmit a mark signal and measure the current propagation time. Measuring it with precision of 1 ns with probability of error 0.003 gives about 18 random bits, identical on both stations. Due to mirroring property of a meteor wave-path the accuracy of measurements is best at the reception point and decreases with distance. Past a certain point a passive eavesdropper will not be able to receive any signal at all, but this is not an absolute requirement. We need only to make sure the adversary not be able to get so close to the receiving point that his measurement error is smaller than the measured quantity.

The additional application requirement is evident: for the reason of secrecy we can not use the same meteor trail for both time and data (key) transfer.

B. Exchange with carrier phase ambiguity resolved on each meteor trail

The simplest case of concurrent key exchange and time transfer occurs when the ambiguity of carrier phase can be resolved on every meteor trail simply by following the respective differential frequencies. This requires of the equipment to have carrier frequencies chosen so that all ambiguity resolution steps can be made on every time transfer measurement. The 10 MHz maximal range should be enough for that. The difference of key-transfer mode is in the start of the ambiguity resolution. We begin from the initial span of about 2 kHz, which is roughly enough to make the initial estimate of the variable part of the propagation time. Also the bandwidth of the signal in key-exchange mode must be chosen relatively low. This way the signal's envelope position would not inadvertently give away some of the most significant bits of the key by being precise enough.

The decision of when to transfer data is made by a threshold value. If current time-scale shift estimate error grows in the absence of time-transfer measurements above the threshold, synchronization mode is forced. Otherwise the signal that makes it possible to measure the propagation time is transferred with the number of random bits actually achieved depending on the time-scale shift error.

The number of bits exchanged on every trail used for data transfer is a logarithmic function of current time-scale shift estimate error. In the best case (the eavesdropper is pushed away far enough) we can start from the value of about 50 μs (1 bit) and go as high as our best precision affords. Our channel non-reciprocity limit is 0.3 ns, this gives the largest value of 18 bits exchanged on a single trail. We can use this function as the number of bits transferred $N(\sigma) = 18 - \log_2(a\sigma)$ (Fig. 2). The coefficient a corresponds to the error rate of a key-exchange measurements. We use the value 6, which corresponds to the probability of error 0.003 and is a known criterion for Gaussian errors.

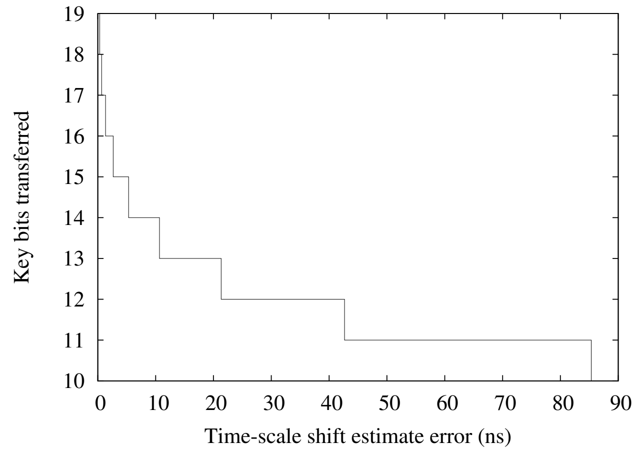

Fig. 2. Number of key bits transferred on a single trail, depending on current time-scale shift estimate error standard deviation

C. Smoothing estimate for improved key-exchange rate

Working with meteor channel equipment we take for granted the automated repeat request facility. We can use this feature to improve the key exchange rate by taking into account the smoothing estimates of time-scale shift and negotiating the number of bits of transferred key used by both stations.

Suppose we had a time-scale shift estimate error of X ns at the time t of data transfer, which gave us N bits of key. After some time, a new, better estimate X is available for point t and we can use it to find some more least-significant bits of the transferred key. During the following hand-shake the secondary station submits its updated view of the value N for previous point t.

Although smoothing gives a better estimate of time-scale shift, the decisions of whether to perform synchronization on a current meteor trail must still be made when it arrives, i.e. by current estimate.

Our application's logarithmic function $N(\sigma)$ does not allow remarkable increase in channel capacity though. In order to add one more bit of key we must double the precision and smoothing estimate does not provide much more than that.

The key transfer capacity is shown on Fig. 3.

D. Exchange with carrier phase ambiguous

In order to simplify the equipment we may not have the required 10 MHz maximal carrier frequency span. In this case

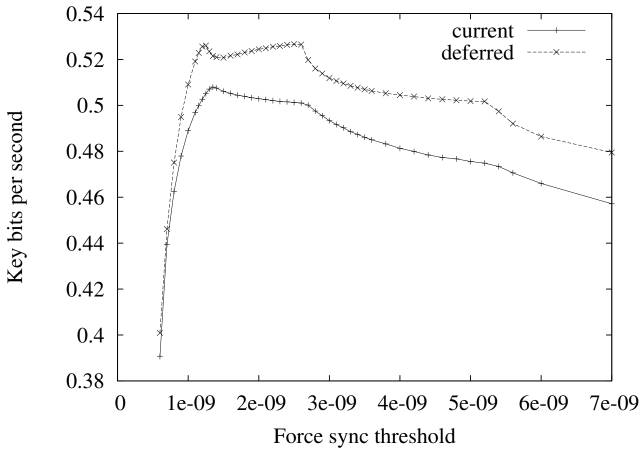

Fig. 3. Key transfer channel capacity depending on the force-synchronization threshold value

we do not have the ability to resolve the ambiguity of a single carrier frequency measurement, and we must either accept a less precise maximal differential frequency measurement or wait. We may still be able to make the final resolution of carrier frequency measurement τ_n but this time we base the decision on the time-scale shift estimate, most probably only by the time we have a smoothing estimate. The same criterion 6σ is used during final ambiguity resolution step, which corresponds to a resolution threshold level of 1.49 ns.

Modeling has shown that the threshold based decision making is not a good choice in that case, because we find extended intervals of no carrier frequency measurements at all. Other important fact is dependence of estimates on ambiguity resolution decisions. In case of current estimate used to get the right number of periods, the single error kills only the key-exchange measurements following it, up to the next time transfer. The influence of such error on smoothing estimate, although less probable makes neighboring points also dependent on the erroneous value, which may propagate and influence further decisions and estimates.

The promising approach here is differentiation of meteor trails by conjecturing their probable length at the time of hand-shake and using long ones for synchronization and short ones for data transfer. We leave this for the future work.

IV. Conclusion

We have modeled the random key-exchange procedure with equpment parameters close to that of the experiment on Moscow-Kazan route (1992).

The potential key-exchange rate for the equipment using the carrier frequency span of 10 MHz and no carrier phase ambiguity problem is 0.5 bits/second, available as meteor trails arrive. This value can be slightly improved by later re-estimation of time-scale shift and negotiating the number of key bits that may be used.

The threshold at which the best key-exchange rate occurs corresponds to infrequent time-transfer measurements and effectively makes intervals between them almost equal. For every trail used for time transfer there are 15–20 trails used for data.

Data transfer mode being much less sensitive to random noise errors when used for key exchange, it is highly desirable to identify trails at formation time and use long ones for time transfer, leaving short for key exchange. This will increase the efficiency of time-transfer and should make it possible to use lesser maximal carrier frequency span.

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