GLONASS application for synchronization 4G/5G mobile networks and radio signals measuring instruments

L.N. Isaeva, A.A. Nemykin, A.V. Lobzov
Moscow Technical University of Communications and Informatics
Moscow, Russia
l.n.isaeva@mtuci.ru

S.S. Kogan
LLC «T8»
St-Peterburg, Russia
kogan@t8.ru

***Abstract* — In this paper we discuss the aspects of the using GLONASS for synchronizing 4G and 5G base stations. The requirements for synchronization in 4G, 5G networks both in frequency and in phase/time have been identified. Methods for organizing synchronization in 4G, 5G networks are considered: transmission of a clock signal over a fiber-optic transport network, from receivers of a global navigation satellite system. The features of using GLONASS for synchronizing 4G and 5G base stations were discussed. Algorithms for filtering parameters that fluctuate due to uneven movement of a mobile object have been investigated in measuring electronic equipment located on a mobile object, in particular on the GLONASS satellite. It is shown that using GLONASS signal as reference frequency source increases accuracy of reference frequency generator of radio signal measuring equipment.**

Keywords — synchronization; GLONASS; 4G; 5G; measuring.

I. Introduction

As generations of mobile networks evolved to 5G and, in the future, 6G, synchronization requirements changed, which ensures that user terminals can seamlessly connect to a base station and provide smooth handoff when a user travels from one cell to another. In 4G long-term evolution (LTE) and 5G new radio (NR) networks with time-division duplexing (TDD), it is necessary to ensure synchronization of base stations both in frequency and in phase/time. The following requirements are applied to synchronization [1]:

- the frequency of local clock generators on the mobile network should be the same as the frequency of the primary reference generator located, as a rule, at the core of the network (CORE);
- the time interval between synchronizing pulses should be kept the same throughout the network infrastructure;
- synchronizing pulses/marks of exact time (one pulse per second) shall be transmitted to all radio units at the same time;
- for all neighboring TDD networks, it is necessary to use a similar frame structure (frame) with a single synchronization of frame start;
- all base stations must be phase synchronized to avoid interference in such a way as to limit the through error (mismatch) in time up to 1.5 μs when transmitting signals from the CORE level to radio units, which includes two components: 1.1 μs - absolute time error when transmitting a signal over CORE to the radio access network (RAN), and 0.4 μs - at the radio access section (Fronthaul), that is, immediately before the radio units;
- for implementation of coordinated multipoint (CoMP) and multiple-input, multiple-output (MIMO), time error (mismatch) between remote radio unit (RRU) belonging to one mobile communication cluster (for example, connected to the same electronic distributed unit (DU) in a Centralized-RAN or Cloud-RAN configurations), must not exceed ± 130 ns;
- frequency accuracy of the synchronization signal on the radio interface must be up to ± 50 ppb;
- the phase/time accuracy of the synchronization signal on the LTE radio interface (TDD) should be up to 10 μs (cell more than 3 km), up to 3 μs (cell less than 3 km), 5G NR (TDD) - up to 3 μs, 5G NR MIMO - up to 65 ns [2, 3].

Phase/time synchronization on 5G NR TDD networks should:

- minimize the number of protective frequency bands for TDD systems;
- preventing interference within and between cells of the mobile communication network so that users can switch between base stations;
- optimize the utilization of 5G network bandwidth.

This paper is devoted to the use of GLONASS signals for synchronizing base stations in 4G and 5G networks. The issues

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of improving accuracy of reference frequency generator of radio signal measuring equipment when using GLONASS signal as reference frequency source are considered.

II. Ways to Organize Synchronization in 4G, 5G Networks

In 4G and 5G networks, there are several ways to organize synchronization of base stations [4, 5, 6]. Synchronization signals can be delivered to base stations from:

- the primary reference time clock (PRTC) generator or telecom grandmaster (T-GM), usually located at the CORE network level, over the fiber-optic transport network or through a fully dedicated network;
- key centralized points in the network, where receivers of global navigation satellite system (GNSS) are installed, via fiber-optic transport network;
- receivers of the GNSS, such as the russian global navigation satellite system (GLONASS) or the american global positioning system (GPS) or the european Galileo or the Chinese BeiDou navigation satellite system, connected directly to base stations. It should be noted that today the american GPS system and the russian GLONASS are the only systems operating around the world.

The end-to-end mobile network is based on a transport layer organized over a fiber-optic transmission medium with using optical wavelength division (WDM) technology. Evolution to 5G networks is not only due to the need to increase the performance, connectivity and flexibility of transport network nodes, but also to increase the throughput of optical transport sections (OTS), referring to the optical channels of WDM systems and providing low delay for service connections over the transport layer of the network. It should also be noted that when moving to Centralized-RAN and Cloud-RAN, fiber-optic solutions are increasingly used at the radio access level. Synchronization of 5G mobile communication networks should be organized in such a way as to ensure the proper synchronization quality of mobile base stations (cells), which means the stability and high quality of service provision both in the initial deployment and maintenance of operation, and in the future, in the further development and expansion of the mobile network.

Providing high-quality frequency, phase and time synchronization is not just compliance with the minimum possible standard, but a prerequisite for 5G networks in accordance to ITU-T G.8275.

There are three main components of network synchronization that can be implemented in the transport network [7, 8, 9]:

- frequency synchronization: frequency of clock generators in network nodes should be the same as the frequency of the primary generator in PRTC, which is usually located at the CORE of the network, wherein the time interval between the clock pulses in the network nodes must correspond to the primary generator in the PRTC, but the clock signals need not appear in all nodes of the network simultaneously; in accordance with the ITU-T G.8272, the PRTC may include a GLONASS satellite signal receiver module (GNSS timing receiver) - ITU-T G.803, ITU-T G.8260, ITU-T G.8261, ITU-T G.8263, ITU-T G.8264, ITU-T G.8265;
- phase synchronization: synchronizing pulses (1 pulse per second (PPS)) appear in network nodes simultaneously - ITU-T G.8271, ITU-T G.8272, ITU-T G.8273, ITU-T G.8274, ITU-T G.8275;
- time synchronization: synchronization messages include the time of the day (ToD) - ITU-T G.8271, ITU-T G.8272, ITU-T G.8273, ITU-T G.8274, ITU-T G.8275.

As evolution progresses from a network infrastructure focused primarily on time division multiplexing (TDM) to a packet oriented (predominantly Ethernet) infrastructure, the capabilities and methods of timing signal allocation change. Frequency synchronization in modern packet-oriented transport networks is implemented using synchronous Ethernet (SynchE) functionality, which provides clock transmission at the physical layer of the service Ethernet traffic. It must be ensured that the clock frequency on the input service ports of the dense wavelength division multiplexing (DWDM) transponders or muxponsors must match the clock frequency of the service signal in the structure of optical transport network (OTN) payload via the line ports of the transponders or muxponsors on the DWDM network.

Poor phase/time synchronization quality affects the quality of LTE-TDD, LTE-A and 5G NR systems. The phase/time synchronization on the packet oriented transport network provides for the delivery within a certain time interval both the data about absolute time error between the central master generator of PRTC or T-GM and the base station and the data about relative time error between neighboring base stations. The algorithm of the 1588v2 precision time protocol (PTP) is based on the exchange of packets with timestamps between the master (for example, T-GM) and slave (for example, telecom boundary clock (T-BC)) clocks. This device is located in the transport network nodes and includes the built-in PTP clock client connected to the PTP master clock. This configuration allows a network node (for example, an IP router, or Ethernet switch, or packet transponder/muxponder of OTN/DWDM FOCL with L2 functionality, or units serving a separate optical synchronization channel, for example, optical timing channel (OTC) of OTN/DWDM FOCL) synchronize the local clock (that is, T-BC in this node) from the signal from the higher signal sources (for example, T-GM/T-BC) and act as the master clock for any T-BC clock in the downstream network nodes.

III. Features of GLONASS Using for Synchronizing Base Stations of 4G, 5G networks

The GLONASS is designed to determine the location (geographical coordinates) of ground, water and air objects, as well as low-orbit spacecraft. GLONASS also allows to obtain the value of the speed and direction of movement of the signal receiver, signals of the time of the day. The GLONASS system

consists of space equipment and a ground segment (control systems) and provides full coverage and uninterrupted operation for the entire globe.

In 3G and 4G mobile networks, satellite receivers are embedded in NodeB and eNodeB (BBU) base stations. The controllers of these nodes receive ToD messages, that is, receive a clock pulse (1 PPS) every second and use it to synchronize the frequencies of all base stations. The controllers then transmit them further over the radio link to user equipment (UE). 3G and 4G networks need direct communication with only one satellite for frequency synchronization.

5G cellular networks use the same GLONASS satellites as 3G and 4G networks, but in a slightly different way. Synchronization in 5G requires direct visibility of multiple satellites. In order to properly use the ToD/PPS signal received from the satellite receiver, it is necessary to be able to compensate for the delay between when the satellite sends the ToD/PPS tag (message) and when the message arrives at the receiver. It is not easy to cope with this task, since the satellites are not motionless above the network. After calculating the exact position of the satellite receiver, it is possible to determine the signal delay between the satellites and the satellite receiver to "correct" the ToD value. Four variables must be taken into account in the calculations - longitude, latitude, altitude and time, and such a calculation will require a minimum of four satellites. The longer it takes to poll the satellites, the more accurately the position of the satellite relative to the satellite receiver is determined. The more accurately the position of the satellite receiver is set, the less time error will be between the cells of the mobile network and the lower the probability that overlapping cells will interfere as a result of interference.

The vulnerability of the GLONASS system is associated with the following circumstances:

- using radio frequency interface;
- malicious attacks, for example, high-power jammers, spoofing (substitution in which one person or program is successfully disguised as another by falsifying data);
- environment, for example, difficulties in installing base stations on sites, problems with antenna placement, sunlight, damage from lightning, etc.

In recent years, cases of both deliberate and unintentional hacking, jamming of GNSS have increased, which is associated with the use of cheap illegal GNSS silencers, with the military operations. New circumstances are forcing some countries to introduce legislation to ensure the protection and reliability of synchronization networks.

GLONASS receivers can be protected from some of these interference, but the measures taken for this increase the cost of maintaining the network. In addition, mobile operators should take into account that when moving to 5G networks, the number of cellular sites will quickly increase, including in those places where using GLONASS satellite receivers is difficult. In dense urban environments, for example, developing 5G networks and providing broadband services at a shorter distance would require small cells using millimeter-band radio spectrum. Such cells can be deployed in hard-to-reach places, for example, in the depths of shopping centers, on different floors of apartment buildings, etc.

IV. Analysis of Parameters Filtering Algorithms in Measuring Equipment Located on GLONASS Satellite

To ensure phase/time synchronization of base stations using GLONASS, it is necessary to keep in mind that the phase is such a radio signal parameter that is most easily "destroyed" during the propagation of the radio wave and when the radio signal passes through the circuits of radio electronic equipment. Calibration of high-precision phase-measuring devices in order to compensate for signal delay in the receiving path, which is due to the influence of the phase-frequency characteristic of the frequency-selective circuit (inaccurately tuned), as is done, for example, in the receiving device of GLONASS equipment with frequency division of channels, under the conditions of intense interference may be ineffective, since it does not take into account the phase estimation bias due to the asymmetry of the interference spectrum during inaccurate adjustment of the frequency-selective circuit [10, 11].

In measuring electronic equipment located on a mobile object, in particular on the GLONASS satellite, there is a problem of filtering parameters that fluctuate due to the uneven movement of the mobile object [12]. An example of such electronic equipment is also a receiver-processor, which is part of the equipment of the GLONASS satellite radio navigation system. At the same time, since the performance of the processor is limited and, moreover, it is entrusted with many additional functions, the problem of choosing an algorithm for filtering navigation parameters, which provides high filtering accuracy and does not require too much computational costs, is relevant.

Among the various algorithms for filtering parameters measured on a moving object under conditions of limited processor performance, are applicable [13]

- the equation of the state of the mobile object in discrete time when describing the motion parameters of the mobile object by the Gaussian diffusion process (Markov process) [14, 15] using a correlation matrix of estimation errors, the least squares method with processing of a single sample of measurements that does not use a priori information on the dynamic properties of the mobile object, in combination with extrapolation. In this case, linear extrapolation is performed in one step and dynamic noises and measurement noises are not correlated;
- construction of an optimal filter based on the method of linear filtration in the Gaussian approximation and discrete time [16]. In this case there is filtering a steady-state process, that is, when the elements of the matrix H change slowly and the dynamic properties of the moving object do not change over time (all elements of the matrix Q are constant) and the equations for the vector of estimates and the matrix coefficient of transfer of the filter coincide with the equations of multivariate optimal linear filtration (OLF) - Kalman filtration;

- quasioptimal linear filtering, in which an optimal second-order linear filter is applied in each channel to measure pseudo-range and pseudo-velocity. Then the filtering results are processed using the least squares method. Quasioptimal linear filtering occupies an intermediate position between the least squares method and the optimal linear filtration, which requires lower computational costs compared to multivariate optimal linear filtration. At the same time in each channel of pseudo-range and pseudo-rate measurement the second order optimal linear filtration is applied.

We will estimate the effect of the sampling step (Δt) on the accuracy of determining navigation parameters, in particular the coordinates of a moving object, using various filtering algorithms, since the Δt value largely determines the performance requirements of the computer performing filtering.

Figure 1 shows the calculated dependencies of the radial standard deviation of the determination of the coordinates of the mobile object (σ_r) on Δt when filtering them using the least squares method, multidimensional optimal linear filtration and quasioptimal linear filtering.

In this case, the on-board reference generator is supposed to be accurate (the time shift of the scale (Δ) is negligible), and navigation determination is carried using three navigation spacecrafts. The geometric dilution of precision was assumed to be 2.65; standard deviation of measurement of values of pseudo-ranges and radial pseudo-velocities σ_ρ = 6 m и σ_V = 0,6 m/s; effective bandwidth of variations of speed of mobile object α = 0,02 s^{-1}; standard deviation of vibrations (fluctuations) of velocity of a moving object, which characterizes the intensity of fluctuations σ_{Vmo} = 2,24 m/s, all this corresponds to one-sided spectral density.

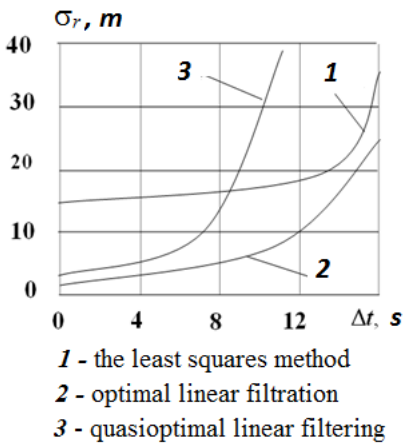

Fig. 1. Calculated dependencies of the radial standard deviation of the determination of σ_r on Δt (σ_ρ = 6 m, σ_V = 0,6 m/s, α = 0,02 s^{-1}, σ_{Vmo} = 2,24 m/s)

Figure 2 shows the dependencies of σ_r on Δt when filtering navigation parameters using the least squares method and the multivariate optimal linear filtration for the most interesting pseudo-standard version of navigation definitions with signal processing from four navigation spacecrafts. The calculation was carried out with the following parameters: relative instability of the on-board reference generator σ_f/f = 10^{-9}, σ_ρ = 5 m и σ_V = 0,1 m/s, σ_{Vmo} = 1 m/s, α = 0,05 s^{-1}.

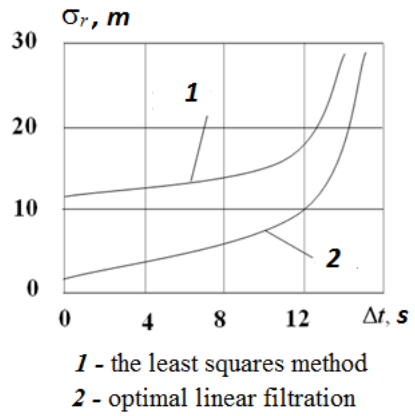

Fig. 2. Calculated dependencies of the radial standard deviation of the determination of σ_r on Δt (σ_ρ = 5 m, σ_V = 0,1 m/s, α = 0,05 s^{-1}, σ_{Vmo} = 1 m/s)

As can be seen from Figures 1 and 2, with small Δt, using of optimal linear filtration provides a significant gain in accuracy compared to the least squares method. This mainly depends on the geometric factor and the measurement accuracy of the accompanying parameters: the radial pseudo-velocity of the mobile object and the displacement of the onboard time scale.

The results of the calculations also show that at small Δt, the error when using the quasioptimal linear filtering slightly exceeds the error of the optimal linear filtration, but as Δt increases, this error grows rapidly and even from a certain moment exceeds the error that occurs when using the least squares method. This can be explained by the loss of information on the correlation of measurement errors in different channels.

Thus, the use of the optimal linear filtration and the quasioptimal linear filtering to filter the navigation parameters is only advantageous if the processor is highly capable of processing navigation information in a small sampling step. In this case, the gain in accuracy from their use compared to the least squares method is significant (by about an order of magnitude).

With the low performance of the processor, the use of the optimal linear filtration is impractical, since it ensures the accuracy of navigation parameters filtering, close to the accuracy implemented using a much simpler the least squares method. Moreover, in this case, it is not advisable to use the quasioptimal linear filtering, which gives worse accuracy than when using the least squares method.

V. Increasing Accuracy of Reference Frequency Generator of Radio Signal Measuring Equipment

Modern measuring equipment of radio signals, such as spectrum analyzers, are equipped with an integrated function of the GNSS signal receiver (GLONASS, GPS, Galileo, Beidou), which, in addition to receiving information about latitude, longitude, altitude and Universal Time Coordinated (UTC), increases the accuracy of the reference frequency generator.

This applies, for example, to MS2090A spectrum analyzers manufactured by Anritsu Company (USA), RFHawk H600 manufactured by Tektronix (USA), R&SəFSW manufactured by Rohde & Schwarz (USA), ThinkRS5700 manufactured by Think RF Corporation (Canada), etc.

Let's consider the built-in function of the GNSS signal receiver using the example of MS2090A spectrum analyzer manufactured by Anritsu Company (USA) [17]. First of all, you need to connect the GNSS antenna to the corresponding connector of the spectrum analyzer, select the GPS menu, activate the GPS/GNSS function, set the antenna supply voltage. After establishing a reliable connection with satellites, the output the following information with a constant update: connection state, tracked satellites, latitude, longitude, altitude, UTC time begins. After setting the GNSS location, the internal reference oscillator starts its frequency correction procedure according to the GNSS reference signal. After setting the internal frequency according to the GNSS reference signal, the Status menu to the left of the measurement screen displays the GPS High Accuracy status. If GNSS is not enabled, the Status menu for the reference source displays the Internal Standard Accuracy state or the external reference frequency selected by the user. Not more than 3 minutes after finding the satellites, the accuracy of the reference frequency generator will be at least $\pm$ 2,5 $\cdot$ 10^{-8}. The intrinsic standard accuracy of a thermostated quartz generator is $\pm$ 0.3 $\cdot$ 10^{-6}. Correction factor applied to internal quartz generator, allows the device to maintain the GNSS frequency accuracy at least $\pm$ 5 $\cdot$ 10^{-8} for three days, even if the device is not able to receive signals from GNSS satellites.

Synchronization from an internal source or an external source (not GNSS) ensures the accuracy of the reference generator is at least $\pm$ 3 $\cdot$ 10^{-7} (permissible relative error of reference generator frequency within the temperature range from 0 ºC to 50 ºC at release from production or after adjustment) to which $\pm$ 1 $\cdot$ 10^{-6} (the relative time drift of the frequency of the reference generator for 10 years) is added.

To receive data from GNSS satellites, the user must be in the line of sight of the satellites, or it is necessary to install an antenna outside and ensure that there is no interference. If there is no connection to the GNSS for more than three days, the status of the reference source changes to Internal Standard Accuracy. After connecting the GNSS, establishing communication with the satellites and completing the configuration process (which may take several minutes), the state of the reference source will change to GPS High Accuracy. In case of subsequent loss of communication with satellites (for example, disconnection of the High function or lack of signal due to physical obstacles), the device goes to the Internal High Accuracy status after a while. If there is no GPS connection for three consecutive days, regardless of whether the device is turned on or off, the device transitions to Internal Standard Accuracy status. The spectrum analyzer automatically selects the reference source in the following order of order: external, GNSS, internal reference generator.

Also, spectrum analyzers can use the GNSS clock as a trigger to activate the standby scan function, which allows the scan to be synchronized with the event so that the analyzer collects data at the desired time. This function is generally useful for measuring time domain signals such as pulse high-frequency signals, time multiplexed signals, or pulse modulated signals.

VI. Conclusions

This paper identifies the requirements for the synchronization of base stations in 4G, 5G networks both in frequency and in phase/time. Methods for organizing synchronization in 4G, 5G networks are considered: transmission of a clock signal over a fiber-optic transport network, from receivers of a global navigation satellite system. The advantages and disadvantages of using GLONASS for synchronizing base stations of 4G and 5G networks are highlighted. Algorithms for filtering parameters that fluctuate due to uneven movement of a mobile object have been investigated in measuring electronic equipment located on a mobile object, in particular on the GLONASS satellite. The influence of the sampling step on the accuracy of determining navigation parameters, in particular the coordinates of a moving object, using various filtering algorithms was evaluated, since the sampling step largely determines the performance requirements of the processor performing filtering. An example of a spectrum analyzer MS2090A manufactured by Anritsu Company (USA) shows that the use of the GLONASS signal as a reference frequency source increases the accuracy of the reference frequency generator of radio signal measuring devices.

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