EFFECT OF UNIFORM TIME ON THE TRANSMISSION OF SIGNALS IN RAIL OPEN SYSTEMS

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Abstract:

Railroads and the Rail Traffic Control Systems installed on them in Poland have recently been undergoing rapid technological development (Brodzik, 2019). Modern transportation solutions are susceptible to electromagnetic interference (Paś and Rosiński, 2017). Development of modern railroad infrastructure means not only stations and modern rolling stock, but also safe and reliable train traffic control systems based on the latest telecommunication and IT technologies (Ciszewski et al., 2017). In the last century these technologies were still considered dangerous and were introduced with great fear. Today, computerized systems for controlling railway traffic on the track are becoming the norm. Systems are created as "overlays" for existing relay systems or autonomous systems are built based on microprocessor systems (Burdzik et al., 2017). Today it is hard to imagine a modern control room without computer equipment. The introduction of microprocessor technology to railroad traffic control devices took place at the turn of the century. However, the use of modern radio systems in rail transport is the moment when technology based on the appeared in the world LTE (Long-Term evolution) standard. The development of modern data transmission technologies is integrally connected with the mobility of its users. In the presented article the author has tried to determine the impact of transmission synchronization on the basic transmission parameters of LTE signal (Chrzan, 2021). The convenience of using rail communications for its users is the possibility of uninterrupted access to data transmission services along the entire route of the train. Therefore, the research presented in this article was focused on the use of the public radio communication network for passenger data transmission and data transmission for railroad needs.
The article presents the influence of synchronisation of data transmission in open railway systems using GPS (Global Positioning System) technology. It presents a description of the physical phenomena associated with synchronisation, and presents the author's method for carrying out measurements on railway line No. 4. For this purpose, a diagnostic station was built and special software for data transmission encryption was prepared. The process of synchronisation of clocks with the use of uniform time was adopted as the basis. General measurement results and conclusions resulting from the use of open transmission in railway radiocommunication systems synchronised by the GPS system signal are presented.

Keywords: *open rail systems, GPS, data transmission*

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1. Introduction

Rapid development of telecommunication technologies and modern railroad infrastructure has forced the introduction of devices based on satellite navigation to the railroad transport. Until now, satellite systems, especially GPS system, were treated with some reserve when introducing its applications to railroad traffic control devices. Development of satellite technology caused that both producers of railroad equipment and, what is more important, institutions responsible for railroad transport look more favourably on solutions based on signals obtained from satellite systems. Introduction of satellite navigation in the European railroad system ETCS/ERTMS (*European Train Control System/ European Rail Traffic Management System)* can mainly improve the efficiency of connections on highly loaded lines (main lines) and reduce costs on lightly loaded lines and regional connections (Jacyna et al., 2018). The deployment of Galileo can contribute to high levels of transport safety worldwide, especially where trackside information equipment is not available. Railroad administrations for years have pursued a policy of upgrading the existing technical structures in order to provide an adequate level of service to passengers. To ensure the appropriate level of security of data transmission, its integrity and lack of delays various technologies are used to counteract these undesirable phenomena. Guidelines are created for building secure transmission networks based on existing telecommunications infrastructure. Adverse phenomena arising during the transmission itself, as well as those associated with the movement of the train in relation to the transmitters, cause the need to synchronize the telecommunications network. It is especially important because of the increasing speed of trains and large amounts of transmitted data. The article presents the author's measurement results using the software developed by the author to generate railroad telegrams using the procedures described in the PN-EN 50159-2011 (PN-EN 50129:2011, n.d., p. 2011) standard. The article is divided into theoretical basis of uniform time transmission using GPS technology, description of the transmission model, measurements, conclusions and comparison with earlier works of the author on this subject.

2. Literature review

Theoretical foundations from theoretical analysis are presented in (Gago and Siergiejczyk, 2020; Nguyen et al., 2016), which discuss the basics of LTE system modeling for different areas and applications. They indicate the research metodology and the results and analysis of computer simulations.

Relevant for this dissertation issues related to signal transmission between objects of railroad infrastructure are presented in (Chrzan, 2020; Kukulski et al., 2019), where the problems resulting from train movement and statistical issues related to the signal are discussed. The authors of these works pay attention to the problem of ensuring adequate system throughput and reliability. They present principles of mathematical modeling of the system and communication channel (Parichehreh et al., 2016).

The issues related to the use of modern antenna systems (Bacanegra et al., 2019) based on adaptive antenna technology or multi-antenna MIMO systems (Shirly and Malarvizhi, 2020; Wu & MacAllister, 2017) are extremely important for the analysis of LTE system operation (Chrzan, 2021; Chen et al., 2017).

A significant number of works deal with modern solutions of systems supported by broadband technologies, this concerns both development trends and ready and tested final solutions .

Standards and recommendations have also been developed for the use of broadband technologies by the ITU-R (International Telecommunication Union), which characterize the basic problems of broadband signal transmission (Chen et al., 2017), also described in the 3GPP (Generation Partnership Project) (3GPP, 2020).

To reduce transmission delays (Rychlicki et al., 2020), satellite system synchronised signal transmission (Pallier et al., 2021) may be used in open rail networks (Siergiejczyk and Rosiński, 2019; Toruń et al., 2019).

The development of modern train operation systems requires the introduction of modern data transmission technologies, including wireless transmission at the necessary safety level. (Rosberg et al., 2021; Kornaszewski et al., 2017)

3. The role of consistent time in railway data transmission systems

If we assume that the second time stamps transmitted from the signal satellite are master signals. These second markers can then be taken as synchronisation markers. The uniform time generator, on the other turn, will be used as a master clock giving highly stable unit time intervals.

Synchronisation can be divided into four methods:
– using a single receiver to receive signals from a single satellite;
– by comparing the signals received by two receivers while simultaneously observing the same satellite (DGPS - *Differential Global Positioning System*);
– comparing signals received by two receivers simultaneously over a long period of time from a single satellite;
– comparing signals received simultaneously from several satellites with a single multi-channel receiver.

The method using a single receiver receiving signals from a single satellite is illustrated in Figure 1.
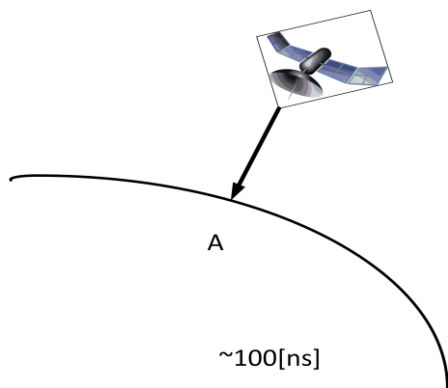

Fig. 1. User observation of one satellite

In this method the user outputs a time stamp signal by synchronising his own clock device with it. The total error of the method is estimated to be about 100 [ns] when using the D/A code, which is not a very small error of the acquired markers. The advantages of this method include:
– global area of application;
– need of using only one receiver of satellite signals;
– sufficient reception of only timestamps without other data;

– low complexity of the receiving equipment;
– possibility of handling an unlimited number of receivers.

In the second method, it is required to compare time indications at two remote points A and B on the Earth's surface by observing the transmitted time stamps by the same satellite. This is demonstrated in Figure 2.
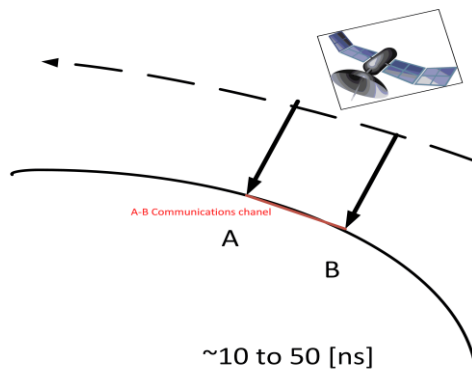

Fig. 2. Satellite observation by two observers

This method achieves a reduction in errors associated with the prediction of satellite time scale changes and errors associated with inaccurate knowledge of ephemeris. This method allows synchronisation of the user's time scale with the time scale of the system with a total error not exceeding 10 to 50 [ns], taking into account the knowledge of the coordinates of the position of the reception points A and B. The disadvantages of this method include the necessity of data exchange between receivers located on the Earth. This results in the necessity of creating an additional link between points A and B, which may limit the number of users, since the optimum link in such a case is a wired one, and in the case of a radio link, navigation corrections should be taken into account. An additional criterion for the use of the method is that one of the users must be stationary.

The third method consists of receiving time stamps from the same satellite at two spatially distributed points A and B, with each point recording the local arrival time of the time stamps T_A and T_B. This is then illustrated in Figure 3.
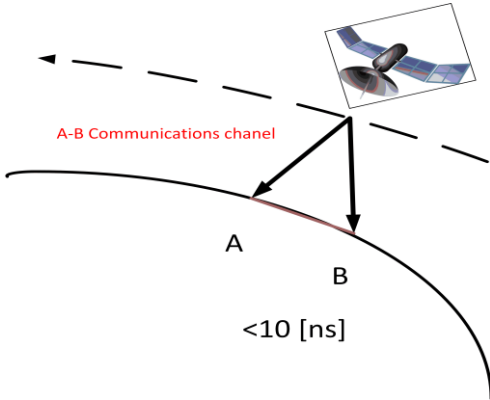
Fig. 3. Observation of a satellite by the two observers over a long period of the time

Knowing the coordinates of the satellite you can calculate the distance between the satellite and two points A and B, which correspond to the propagation time of the signals τ_A and τ_B. The divergence of time scales $\Delta\tau_{AB}$ at points A and B shall be determined from the equation (Chrzan and Jackowski, 2016):

$$\Delta\tau_{AB} = (T_A - \tau_A) - (T_B - \tau_B) = \\ (T_A - T_B) - (\tau_A - \tau_B) \tag{1}$$

From the dependence we see that when simultaneously receiving signals from the same satellite at two points, the error in determining the divergence of time scales is influenced not by the error connected with calculating the distance from the satellite to the individual points, but by the difference in the errors in determining the distance between points A and B. This method has many advantages. For example, if the plane of the satellite's orbit is perpendicular to the line connecting points A and B and the satellite is at equal distance from them, the value of the radial component of the ephemeris error and the component directed along the tangent to the satellite's orbits are compensated. When receiving time signals from the same satellite at two points, there is also a partial compensation of the time deviation caused by the ionosphere. This error decreases to 5 [ns] at distances between points A and B of several thousand kilometers and to 2 [ns] at distances not exceeding one thousand kilometers. To sum up, it can be said

that the third method gives the greatest possibilities, using a relatively simple apparatus for receiving signals from a satellite, to reduce the deviation of the time scale at the points of reception A and B to the value not exceeding 10 [ns]. However, in this method it is necessary to construct a link between reception points, which limits its usefulness for mobile subscribers.

With such solutions, in spite of using the same synchronizing markers to correct the readings of any two countdown clocks, their readings will differ. The difference in indications may occur for several reasons:

- non-uniform frequency patterns used in each clock which are the cause of systematic errors in the indications of each clock;
- temporal, climatic, electrical, etc. instability of the frequency standards, resulting in random errors;
- ambiguity in the start of the countdown by different clocks, which is the source of the systematic clock error.

The systematic error of two clocks resulting from the non-identical frequency patterns will be addressed first. The difference in the length of the time segments counted down by two different clocks can be expressed by the equation:

$$T_{12} = |T_{01} - T_{02}| \tag{2}$$

where:
T_w - a time unit counted down by a master clock;
T_{01} - unit of time counted down by the first clock;
T_{01} - unit length of time counted down by the second clock.

It is easy to see that when the clocks are initially coincident, their readings will become increasingly different as time passes. For the user it will be important to know that part of each segment of time deducted by two clocks is common when they are not identical. Determining the coefficient of overlap between the time segments counted down by different clocks is expressed by the equation:

$$h_k = \frac{T_{01} - k\Delta T_{12}}{T_w} 100\% \tag{3}$$

where:
h_k - time overlap factor.

If we assign by T_{wsp} the common time segment when the clocks are not the same, then we can write the equation:

$$T_{wsp} = T_w - T_{r1} - T_{r2} =$$
$$T_w - \left[(k-1)T_{01} - (k-1)T_w\right] - \left[kT_w - kT_{02}\right] = \quad (4)$$
$$T_{01} - k\left|T_{02} - T_{01}\right| = T_{01} - k\Delta T_{12}$$

The above relationships are illustrated graphically in Figure 4 (Chrzan and Jackowski, 2016).

An important element is the restoration of the concurrency of the clocks if there is a discrepancy exceeding an acceptable value:

$$n = \frac{T_w\left(1 - \dfrac{h_{12}}{100}\right)}{\Delta T_{12}} \quad (5)$$

where:

n - expresses the number of time periods ΔT_w counted down by two clocks, after which the initial concurrency must be restored.

In order to maintain the overall concurrency of the clocks in the system, the coefficient of overlap of the time segments with the satellite time must be at least equal to:

$$h_{min} = \frac{T_w - 2n\Delta T_w}{T_w} \quad (6)$$

from here:

$$n = \frac{T_w\left(1 - \dfrac{h}{100}\right)}{2T_w} \quad (7)$$

Moving on to the impact of random error on the clock, we will consider the influence of factors determining the duration of a unit segment T_w counted down by the clock. The factors determining the duration of a unit section include T_w we can include:

– temperaturę;
– humidity;
– supply voltage fluctuations;
– aging of the frequency standard elements;
– electromagnetic field disturbances;
– shocks and vibrations.

These factors cause changes in the frequency of the standard of a random nature, just as random interactions of these factors are. The fourth method of synchronisation consists in receiving signals simultaneously from several satellites by a single multi-channel receiver. This method uses a multi-channel receiver that receives and compares signals from several navigation satellites simultaneously. Comparison of the received time stamps from each channel results in their output averaging, thus increasing the accuracy of the received time stamps. This capability was exploited during the research.

4. The phenomenon of Doppler

With the development of high-speed railways, trains can reach speeds of 350 km/h and higher, so the requirements of signalling systems for higher and high-speed railways become higher in terms of signal constancy and correctness. A widely considered candidate to achieve higher data transmission rates for railway telegrams while reducing latency is the LTE system, which could become a natural successor to GSM-R (*Global System for Mobile Communications – Railway*). In high-speed railways, the time-varying frequency shift caused by the Doppler effect causes a frequency shift, which may influence the limitation of the LTE (*Long Term Evolution*)
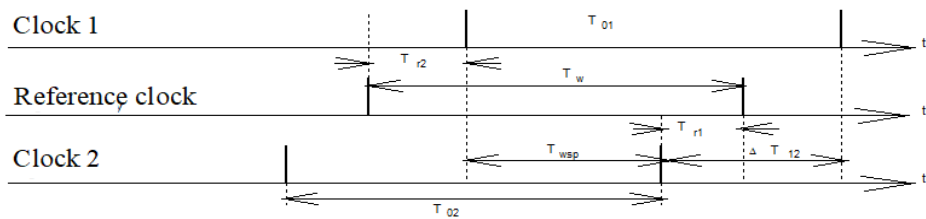

Fig. 4. Illustration of the time relation for the determination of T_{wsp}

system in the range proposed for railways. This issue is being studied worldwide, especially in the field of Doppler estimation of frequency shift and its compensation (Perichehreh et al., 2016).

Because of the rapid movement of the UE mobile station (train) relative to eNodeB, (*evolved NodeBs*) the Doppler phenomenon starts to play a significant role in signal fading. The received signal components arriving at the receiver undergo a frequency shift which depends on the value of the carrier frequency fc, the speed v of the train and the angle between the direction of movement of the train and the direction of arrival of the signal. Doppler frequency f_d depends on the given factors as follows:

$$f_d = f \cdot \frac{v}{c} \tag{8}$$

where:

c – light speed, $c = 299\ 792\ 458$ [m/s].

Table 1. Doppler frequency value for different frequencies of 4G systems at different train speeds determined from (8)

Frequency [MHz]	Doppler frequency [Hz] at the train speed [km/h]			
	50	**120**	**140**	**160**
791	36,646	87,950	102,608	117,266
821	38,036	91,285	106,500	121,714
832	38,545	92,508	107,927	123,345
862	39,935	95,844	111,818	127,792
876	40,584	97,401	113,634	129,868
880	40,769	97,845	114,153	130,461
915	42,390	101,737	118,693	135,649
921	42,668	102,404	119,472	136,539
925	42,854	102,849	119,990	137,132
1710	79,221	190,132	221,820	253,509
1785	82,696	198,471	231,549	264,628
1805	83,623	200,694	234,143	267,593
1880	87,097	209,033	243,872	278,711
2100	97,290	233,495	272,411	311,326
2500	115,821	277,970	324,298	370,627

However, the change in the Doppler frequency depending on the angle of arrival of the signal is f_s :

$$f_s(t) = f_d \cdot \cos\theta(t) \tag{9}$$

where, the angle Θ of the signal arrival depends on the distance of the EU vehicle from the eNode base station and its speed with the relation:

$$\cos\theta(t) = \frac{D_s/2 - vt}{\sqrt{D_{min}^2 + (D_s/2 - vt)^2}}, 0 \le t \le D_s/v$$

$$\cos\theta(t) = \frac{-1,5D_s + vt}{\sqrt{D_{min}^2 + (-1,5D_s + vt)^2}}, D_s/2 \le t \le 2D_s/v \tag{10}$$

$$\cos\theta(t) = \cos\theta(t \bmod(2D_s/v)), t \ge 2D_s/v$$

5. Measuring station

In order to carry out the measurements, a transmission measurement system for the LTE open system has been built, shown in Fig. 5. For the tests, a system will be used, similar to that in (Chrzan, 2020; Chrzan, 2021) in which the transmission takes place in the first stage of the tests between a server and a virtual traffic control device located on the train route. The measurements used non-real-time systems from the Microsoft Windows and Android operating system. GSM-R transmission parameters were assumed for modelling, with the assumption that meeting these conditions fulfils the transmission safety conditions. Measurements were made in accordance ETSI TS 102 250 (*European Telecommunications Standards Institute*).

The vehicle used for the tests was an MI8 phone running Android ver.12 (Fig. 6) with a built-in LTE modem, with the following parameters:

FDD LTE: 2600, 2100, 1900, 1800, 1700, 1500, 900, 850, 800, 700

TDD LTE: 2600, 2500, 2300

where:

– **FDD** - *Frequency Division Duplex.* A way of organising access to a radio network by using two frequency bands in a cell. One is used by terminals to transmit towards the base station, and the other is used by the base station to transmit towards the terminals. This term is used inter alia in the 3GPP specifications in the context of the radio network access mode in UMTS (*Universal Mobile Telecommunications System*) and LTE systems. Another mode of access to these networks is TDD. Often, to avoid ambiguity related to the type of standard used to provide radio network access, the terms UTRAN FDD for UMTS systems and eUTRAN FDD for LTE systems are used. UMTS networks operating in FDD mode use WCDMA (*Wideband Code-Division Multiple Access*) technology. (Nguyen, 2016)

Fig. 5. Measurement scheme

– **TDD** - *Time Division Duplex*. A way of organising access to a radio network by using, in a given cell, the frequency range in which data transmission is carried out in both directions between base stations and terminals

– and terminals. The time in which the transmissions are carried out is divided into so-called time slots. In particular time slots, transmission is carried out in one direction only - to the base station or towards the terminals. This term is used, among others, in the 3GPP specifications in the context of the radio network access mode in UMTS and LTE systems. Another mode of access to these networks is FDD. Often, to avoid ambiguity related to the type of standard used to provide radio network access, the terms UTRAN TDD for UMTS systems and eUTRAN TDD for LTE systems are used. UMTS networks operating in TDD mode use TD-CDMA (*Time Division Code Division Multiple Access*) or TD-SCDMA (*Time Division Synchronous Code Division Multiple Access*) technology.

Fig. 6. Mobile measuring stand on the train

On the receiving end, there was a Windows 10 server connected to the Internet via an LTE broadband network via a MOXA OnCell G3470A-LTE gateway (Figure 10) with the following parameters:

– supported standards: GSM/GPRS/EDGE/UMTS/HSPA/LTE;

– transmission bands: LTE 2100/1800/2600/900/800 MHz (B1/B3/B7/B8/B20), UMTS/HSPA 2100/1900/850/800/900 MHz;

– transmission speed: LTE – 20 MHz bandwidth: 100 Mbps DL, 50 Mbps UL

– HSPA – 42 Mbps DL, 5.76 Mbps UL

– EDGE – 237 kbps DL, 237 kbps UL

– GPRS – 85,6 kbps DL; 42,8 kbps UL

– interface ports LAN RJ-45 10/100/1000Mbps;

– mobile network antenna connectors: 2, SMA;

– console port: RS-232 (RJ-45);

– network protocols: ICMP, DDNS, TCP/IP, UDP, DHCP, Telnet, DNS, SNMP, HTTP, HTTPS, SMTP, SNTP, ARP;

– routing/firewall: NAT, port forwarding, filtrowanie IP/MAC/Port;

– VPN: maximum number of tunnels – 5, IPSec (DES, 3DES, AES, MD5, SHA-1, DH2, DH5), PSK/X.509/RSA;

– configuration and management options: SNMP v1/v2c/v3, Web / Telnet / Serial Console, SSH, Remote SMS Control;

– Number of cards SIM: 2;

The computer with the MOXA gateway was used as a server.

Fig. 7. Server-side test bench (Chrzan, 2021)

Measurements were made on the route Warsaw Central - Kraków Główny running on railway line no. 4 - Central Railway Main Line in Poland (Fig. 8) on 31.08.2021 between 7 and 11 a.m. taking into account the train timetable, with the train speed up to 160 km/h. Train speed was monitored using a Mi8 mobile phone with RFBenchmark (Fig. 9) and Cellsignall (Fig. 10) software. For this purpose, a window seat was taken in the vehicle for better reception of the GPS signal.
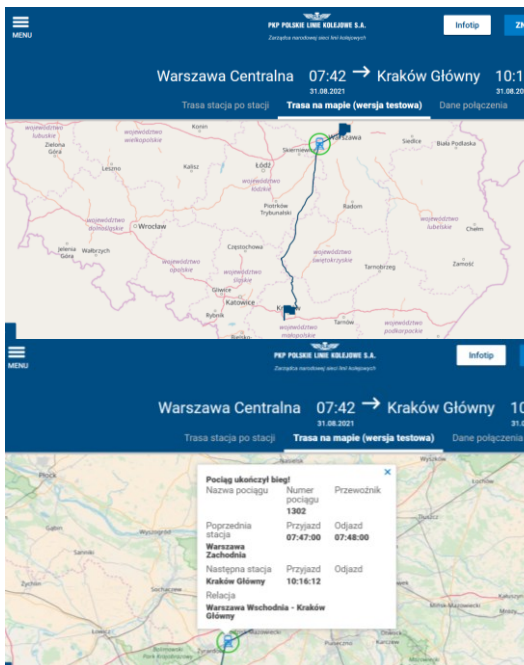

Fig. 8. Measurement route

In order to make measurements, the phone software was modified to allow data recording. The mobile phone system allows you to report network signal strength using different types of signal measurements. You can then use these reported signal strengths to control how signal statistics are displayed on your mobile device and adjust the modem signal strength reporting criteria. Starting with Android 11, you can customise the multiple signal measurement types that the platform uses to report 4G LTE Radio Access Network (RAN) signal strength.

The software structure uses three functions to report signal strength: signal strength reporting criteria, signal strength thresholds and signal levels. These functions directly affect the way the Android system communicates with the modem interface, for example preventing unnecessary signal strength reporting by the modem to reduce power consumption and improve system health. The functions are defined as (3GPP Specifications, 2020):

– signal strength reporting criteria: conditions defined by the Android system
– system to trigger signal strength reporting from the modem;
– signal strength thresholds: a list of four integers used to suggest signal level and signal strength reporting criteria;
– signal levels: five levels (No signal, Poor, Fair, Good, Excellent) that correspond to signal strength.

For devices running Android 11 or later, the following types of signal measurements can be customised for EUTRAN (4G LTE) networks. These measurements are used for signal strength reporting criteria, signal strength thresholds and signal level functions. To enable the phone to set signal strength reporting criteria for each RAN, the hardware interface had to be modified.

Multiple signal measurement types are supported for each RAN. If none of the reporting criteria for measurement type is enabled for a RAN, the reporting criteria for that RAN are defined by the Android platform. When measurement type reporting criteria is enabled for a RAN, reporting criteria for other measurement types is disabled.

To define the signal strength thresholds for the 4G network, the operator configuration keys had to be modified.

Two software packages were used for the measurements: RFBenchmark (Figure 9) and Cellsignall (Figure 10). In order to ensure that services could be measured for networks using national roaming, no

mechanisms were used to block this mode of operation at the measurement terminals.The averaged measurement results for the tested route are presented in Tables 2 and 3.
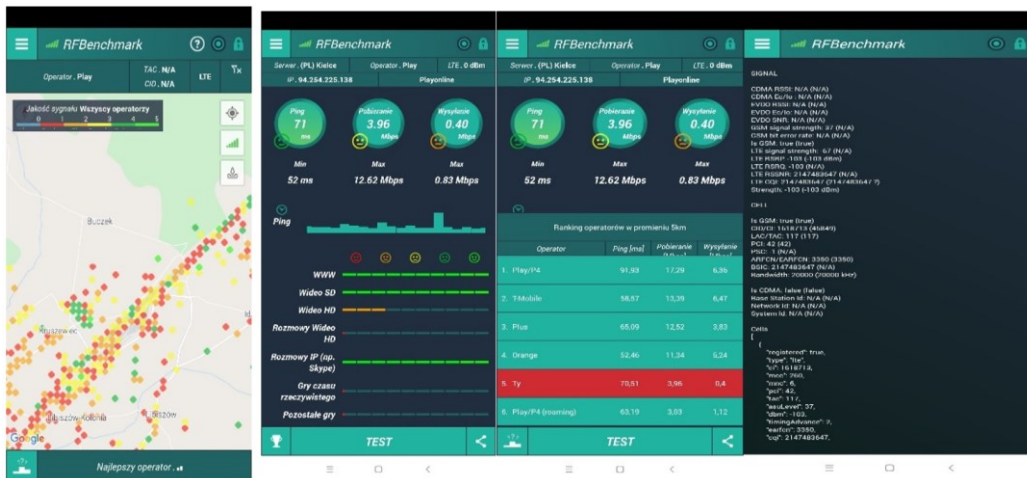
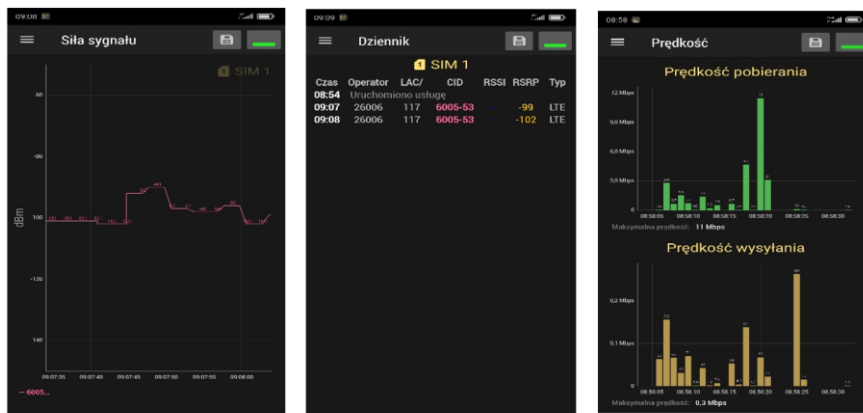

Fig. 9. Example screenshots from RFBenchmark measurements

Fig. 10. Example screenshots of measurements in CellSignall

Table 2. Packet loss and delay indicators before the GPS synchronisation

		Orange	Play	Plus	T-Mobile
Round Trip Time	RTT [ms]	150,23	130,28	123,34	172,13
IP packet loss ratio	IPLR [%]	14,56	16,17	8,5	16,13
IP packet delay variation	IPDV [ms]	120,18	113,17	119,45	97,34

Table 3. Packet loss and delay indicators after GPS synchronisation

		Orange	Play	Plus	T-Mobile
Round Trip Time	RTT [ms]	145,11	125,13	111,10	153,12
IP packet loss ratio	IPLR [%]	10,54	10,18	5,4	9,13
IP packet delay variation	IPDV [ms]	99,28	90,14	99,75	92,31

6. Conclusions

Modern data networks, including railways, require high data security and transmission stability. In a study supported by existing telecommunication solutions, this paper presents the possibilities of using public radio networks of the LTE standard for railway applications. The study was carried out on Polish Line 4 (Figure 8). The use of their services in a wide range of possibilities. The test bed, shown in Figure 5, and software based on the PN-EN 50159:2011 standard has made it possible to verify the possibility of data transmission in LTE public networks for railway tasks.

On the other hand, the studies described in Tables 2 and 3 suggest that appropriate spatial planning of LTE systems using network synchronisation with GPS technology can reduce data transmission delays. An open LTE system can be used for railway purposes, both for train traffic control and passenger data transmission.

The tests showed low signal strength (Figure 9 and Figure 10) or signal loss in some parts of the railway line, which is due to the fact that the communication infrastructure was planned to cover urban areas and roads rather than areas covered by railways. The study also did not take into account the impact of interference from rolling stock.

If the network is expanded to include railways, huge savings can be made. Dedicated communications infrastructure for railways is not needed in this case because it can be replaced by an open LTE network or, in the future, by 5G with appropriate message coding in accordance with PN-EN 50159:2011 and all the elements necessary to ensure widely understood transmission security.

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