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Positioning Error of Unmanned Aerial Vehicles in Integrated Mobile Communication and Radio Navigation Network

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ABSTRACT

The use of unmanned aerial vehicles (UAV) is impossible without determining their location in space. As recent global events have shown, relying on global positioning system (GPS) for this purpose carries significant risks, as the GPS signal can be blocked or distorted. One promising approach to ensuring autonomous flight for UAV in the absence of a GPS signal is the integration of mobile communication networks with a local radio navigation network (LRNN). The LRNN is a network of stationary ground-based radio navigation points that contains sources of radio navigation information, thereby forming an additional radio navigation field. This paper presents the structure of an integrated mobile communication and radio navigation network and proposes a method for determining the location of UAV based on a trilateration algorithm. Its advantage is that the solution to the problem of determining the location of UAV is carried out using its resources without the participation of a mobile communication network. Also, this study develops a software model for such a network with known coordinates of radio navigation information sources using the precision time protocol for synchronization. Using a software model, we studied the error in determining the location of UAV depending on the integrated network topology (the layout of radio navigation information sources) and synchronization errors in radio navigation information sources due to delays in the mobile network. The advantages and disadvantages of the proposed approach to determining the location of UAV are demonstrated, and directions for further research are outlined. Based on the conducted research, it has been shown that the degree of desynchronization of radio navigation information sources significantly affects the positioning accuracy of UAV. As the modeling results showed, the error in determining the position of UAV depends on two main factors: the absolute value of the synchronization error and the asymmetry coefficient of the delay time in the synchronization channels of the radio navigation information sources. Furthermore, there is a direct correlation: the greater the synchronization error and asymmetry coefficient, the greater the positioning error. It was also found that decreasing the distance between radio navigation information sources significantly increases the positioning accuracy of UAV.

Keywords: Unmanned aerial vehicles; Integrated mobile communication; Radio navigation network; Radio navigation field; Signal generator.

INTRODUCTION

Advances in telecommunications and robotics have led to the rapid development of unmanned technologies, one promising area of which is the practical implementation of the concept of a drone swarm (unmanned vehicles and systems). The drone swarms are finding application not only in the military, but also in the agricultural industry (parallel cultivation of agricultural land), logistics (autonomous delivery), three-dimensional mapping (rapid creation of detailed terrain models), rescue operations (covering large areas when searching for people) and other areas (Alqudsi and Makaraci 2025). In scientific and technical literature, the drone swarm refers to a system in which a group of drones operates together, coordinating with each other directly, rather than through a centralized control panel (Chen *et al.* 2020; Marek *et al.* 2023; Adoni *et al.* 2024).

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Coordinating drone behavior, necessary for collision avoidance and synchronized movement to a given point, is impossible without constant information exchange and the use of navigation technologies that allow for precise determination of drone positions in space. Information exchange between drones must be carried out using a communication network based on various dynamic routing algorithms that consider the relative position of the drones, *i.e.*, the changing network topology (Borodin *et al.* 2024). Such networks are usually called wireless ad hoc networks (Cheng *et al.* 2013), the main types of which are mobile ad hoc network (Hasan *et al.* 2020), vehicular ad hoc network (Rehman *et al.* 2013), and flying ad hoc network (FANET) (Bekmezci *et al.* 2013). As it is shown in Tareque *et al.* (2015), the fastest changing topology is FANET, the nodes of which are unmanned aerial vehicles (UAV). Therefore, the accuracy of determining their location is one of the most important factors.

Currently, the following navigation technologies for determining UAV location have found the greatest practical application (Dardari *et al.* 2012):

- Classical global navigation satellite systems (GNSS) + inertial navigation system (INS) positioning based on signals from GNSS—global positioning system (GPS), global navigational satellite system (GLONASS), Europe's global navigation satellite system (GALILEO), BeiDou satellite navigation system, and others—, and the use of an INS;
- Simultaneous localization and mapping (SLAM) technology used by UAV to simultaneously map an unknown area and determine their own position within it;
- Visual navigation using video cameras and object recognition algorithms.

When using GNSS+INS technology, the basis of UAV navigation systems is GNSS receivers combined with a block of inertial spatial orientation sensors (Hasan *et al.* 2009; Sokolovic *et al.* 2015; Mahmoud and Trilaksono 2018). The presence of GNSS signal is a prerequisite for autonomous UAV flight. The absence of GNSS signal makes it impossible to accurately determine one's own coordinates and, consequently, to fly along a predetermined route. Another problem with using GNSS signals is that the GNSS operator can selectively encode and distort the navigation signal if necessary. Furthermore, the open structure of navigation messages and the known radio parameters of GNSS signals make it possible to suppress navigation signals energetically, and in some cases, create substitute signals. This can lead to distorted positioning results and significantly limits the use of GNSS+INS technology.

SLAM technology is primarily based on two main algorithms that can be combined (Durrant-Whyte and Bailey 2006; Cadena *et al.* 2016; Gupta and Fernando 2022):

- Visual SLAM (V-SLAM), which uses cameras for mapping and orientation;
- LiDAR SLAM (L-SLAM), with laser rangefinders.

This technology has the following limitations: limited range (up to 300 m), long- data processing time, dependence on the UAV's speed, the need for auxiliary geodetic instruments for referencing to coordinate systems and several others.

Visual UAV navigation is based on receiving images from cameras, which are processed by an onboard computer, resulting in the UAV's coordinates (Cesetti *et al.* 2010; Cao *et al.* 2012; Mittal *et al.* 2019). Such images can be obtained from onboard daytime and infrared photo and video cameras, as well as synthesized radar images, digital terrain data, and satellite imagery. The disadvantages of this technology include the need for a high-speed onboard computer and an up-to-date database of terrain images, the inability to operate in cloudy or smoke-covered conditions, among others.

Therefore, a pressing scientific and technical challenge is the development of a positioning technology that ensures autonomous operation of UAV in the absence of GNSS signals and is free from the shortcomings of the above-described location determination technologies. One such promising technology is the control and positioning of UAV using mobile communication networks (MCN), which is being developed by major global operators AT&T, Telefonica, and Vodafone. UAV location can be determined using either the MCN itself or data from a local radio navigation network (LRNN). The LRNN is a network of stationary ground radio navigation points that forms an additional radio navigation field (RNF) (Shockley and Raquet 2006; Tiwary *et al.* 2010). However, for widespread practical use of this technology, which integrates MCN and LRNN, numerous technical issues must be addressed, including the optimal placement of source of radio navigation signal (SRNS) sources to ensure a specified UAV positioning error.

Numerous scientific and technical publications have addressed various aspects of local positioning systems (LPS), which include LRNN. For example, Kolodziej and Hjelm (2017) examined various approaches and technologies for solving problems related to mobile subscriber location determination. The principles of MCN construction and mobile subscriber location

determination concepts, the network architecture of LPS, and positioning procedures within them are presented in Küpper (2005). Also noteworthy in this regard is the study by Gilski and Stefanski (2015), which provides a detailed overview of several known solutions and methods for positioning in LPS.

Regarding the problem of optimal SRNS placement in LRNN, approaches to solving it have not received due attention, and publications in the open scientific and technical literature are insufficient. An analysis and assessment of the potential navigation accuracy in LRNN using time-division multiplexing of navigation signal transmission channels are presented in Borzov and Mikaelyan (2015). Based on the conducted research, the authors demonstrated that even at significant distances from the mobile subscriber to the base station (BS) (from 10 to 30 km), a sufficiently high accuracy of its location can be achieved. Gladyshev *et al.* (2023) presented a methodology for selecting the topology of ground BS in LRNN, taking into account the energy characteristics of BS signals, the size of service areas, and the degree of signal attenuation during transmission from the BS to mobile subscribers.

However, the results of these studies were obtained under the assumption that precise synchronization of SRNS is established, which is practically impossible to achieve when using MCN to synchronize different SRNS due to the varying delays of synchronization signals as they propagate through the network. However, even in LPS systems with a coverage area of approximately 1 km, such as Locata (Montillet *et al.* 2014), a 1 ns synchronization error in SRNS time scales results in a positioning error of approximately 30 cm. When using MCN-based positioning technology, it is fundamentally impossible to ensure perfect SRNS synchronization. This is because the synchronization signal paths through the network on the forward and reverse channels vary for different BS, and therefore, different BSs receive them with different delays, leading to LRNN desynchronization. Then, a pressing task is to analyze the error in determining the location of mobile subscribers in LRNN depending on the network topology (relative location of BS) for different values of BS synchronization error.

This article builds on the work of Borzov and Mikaelyan (2015) and Gladyshev *et al.* (2023) in examining this error, considering not only the SRNS location but also the specifics of precision time protocol (PTP) in MCN. The novelty of the authors' results lies in the fact that the developed software model allows for estimating the error in mobile subscriber location, considering known SRNS coordinates and BS synchronization errors caused by various time delays in synchronization channels. Using this software model at LRNN design stage will allow developers to select the optimal network topology (SRNS placement scheme), given the technical and economic constraints.

The objectives of this article are:

- Developing the structure of an integrated mobile communication and radio navigation network (IMCRN), in which the RNF is generated by the network infrastructure;
- Developing a software model of the IMCRN with its own RNF with known SRNS coordinates;
- Conducting experiments with the software model and studying the error in determining the location of mobile subscribers depending on the SRNS deployment scheme and their overall synchronization principles.

This software model enables IMCRN developers to quickly analyze UAV positioning error using LRNN, depending on the proposed network structure and configuration. This enables a set of measures to minimize this error already during LRNN design stage, providing the potential for building competitive IMCRN. Furthermore, the results obtained in this study may be useful not only for IMCRN developers, but also for creating monitoring systems in areas such as transportation, logistics, surveying, agriculture, construction, public safety, rescue operations, etc.

It should also be noted that since the relation and research results presented in the following sections are valid not only for UAV but also for most other mobile subscribers, henceforth we will use the more general term mobile station (MS) instead of UAV.

THEORETICAL BASIS

Currently, methods for determining the location of MS in MCN can be divided into three main groups, in which this problem is solved using resources:

- MCN;
- MS with support of MCN;
- MS.

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The essence of the first group of methods is that all location determination functions are implemented exclusively by the MCN without the participation of the MS. The most common method in this group is the cell ID one, which identifies the location of the MS with an accuracy of "up to a cell" (Naor *et al.* 2002). This method is based on the structure of the MCN, does not require any additional computational costs, and its accuracy depends on the network structure and varies from a few meters in a densely populated city to several tens of kilometers outside populated areas. It is possible to improve the accuracy of this method by using information about the signal radiation zone obtained from the sector antennas of the BS. Higher accuracy compared to cell ID is provided by the cell ID + TA method, based on determining the value of the signal propagation delay from the BS to the MS within the cell.

The core of the methods of the second group is the principle of joint use of MCN and MS resources. This approach allows for localization of the MS location problem within the MCN, making it possible to solve it without the use of additional external infrastructure (Gilski and Stefanski 2015). The most common of these methods are:

- Time of arrival, based on determining the location by calculating the signal propagation time (Khalaf-Allah 2015);
- Time difference of arrival, based on determining the location by calculating the difference in the reception time of signals emitted by different BS (Spencer 2010).

The third group of methods is based on the integration of a GNSS radio navigation receiver into modern MS. This receiver is capable of autonomously determining the location of MS (GPS), *i.e.*, without the support of a communications network. A variation of this method is the assisted GPS (A-GPS), in which the MS, in addition to GNSS signals, uses auxiliary data from a network of stationary GNSS reference radio navigation receivers (RRN) to determine its location. These RRN generate and distribute differential corrections. The MCN is used as a backhaul network for transmitting corrections to the MS, which then calculates its location (Goze *et al.* 2008).

The essence of the IMCRN discussed in this article is that within the known MCN structure, SRNS are installed within the network coverage area, resulting in the formation of a RNF (Fig. 1). SRNS continuously or on request transmit radio navigation information, which MS uses to determine their location, speed and direction of travel, as well as other necessary characteristics. SRNS locations may coincide with the locations of individual BS or be located separately, for example, at the boundaries of network coverage areas. SRNS may also be installed in locations where BS are absent, but where SRNS can connect to the MCN. Algorithms for initial MS registration in the network and for determining their location, speed and direction of travel when crossing the service areas of neighboring BS, as well as a description of roaming, handover and other aspects of IMCRN operation, are provided in Bogdanov *et al.* (2013).

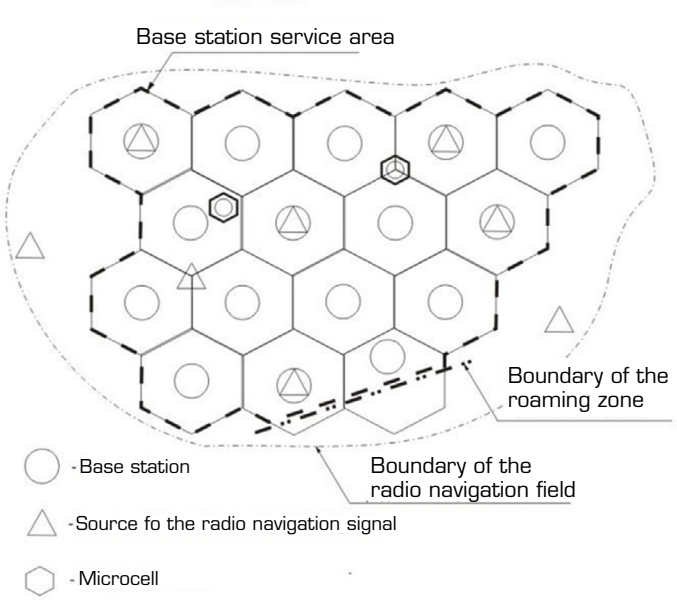
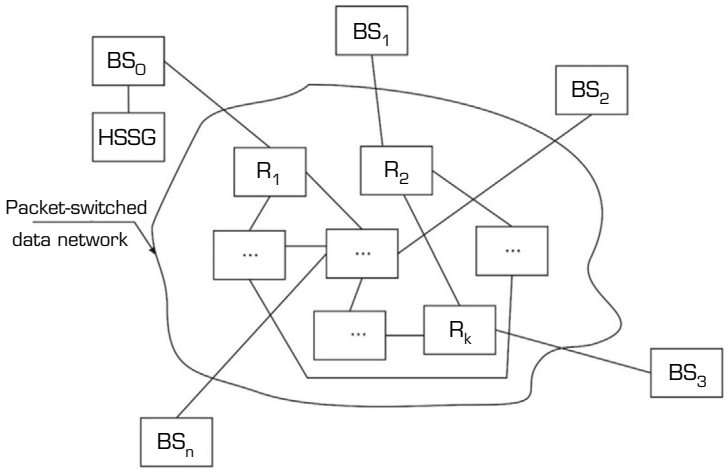


Figure 1. Structure of the integrated mobile communication and radio navigation network.

One of the key issues in developing an IMCRN is assessing the impact of synchronization errors on network performance, as the presence of a BS synchronization error leads to MS positioning errors. To determine location in an IMCRN, BS synchronization is necessary, and given the prevalence of packet-switched data networks (PSDN), it is advisable to implement this procedure using the PTP algorithm. Using this BS synchronization model allows one to study possible delays in the propagation of synchronization packets, considering the SRNS location.

Figure 2 shows the structure of an LRNN in which PSDN is used as a network for synchronizing various SRNS. The data network consists of a set of routers R1, R2, … Rk, each of which is connected to neighboring routers via a communication link. Since in general a public data network can be used as the network for synchronizing SRNS, the number of routers in the data network, the length of the connecting links, the total number of routers, and the intra-network connection scheme are unknown quantities.



BS: base station; R: route.

Figure 2. Local radio navigation network structure using packet-switched data network for source of radio navigation signal synchronization.

Connected to the data network, routers provide the connection of BS_0, BS_1…, BS_n to the data transmission network. We assume that BS_0's equipment includes a highly-stable signal generator (HSSG), which provides BS_0 with a highly-stable synchronization signal. BS_0, relative to other BS, is the source of a highly-stable synchronization signal for the synchronization system, which we will call the master base station (MBS), while the remaining BS are called slave base stations (SBS). Synchronization in the system is accomplished using the PTP. Since the PSDN structure is generally unknown, the synchronization signal path from the MBS along the forward and reverse channels will differ for different SBS. Therefore, different SBS will receive the synchronization signal with different time delays, meaning a synchronization error will occur.

The current version of PTP protocol is PTPv2.1 (IEEE 1588-2019) (Langer et al. 2020). It enables nanosecond synchronization accuracy and has its own specialized development for mobile networks described in ITU-T G.8275.1 and ITU-T G.8275.2. The basic algorithm, as applied to the developed model, is based on a two-step operating mode, without taking into account the peculiarities of the protocol cryptographic protection, which consists in the fact that HSSG, being the master node, sends a synchronization packet and records the sending time t_1 at the hardware level. BS, using a local clock, records the reception time of the specified message t_2 and sends back Delay_Req response message recording the sending time t_3. Upon receiving the specified message, HSSG generates Delay_Resp message with a timestamp t_4 (Fig. 3).

As a result of the described exchange, BS calculates the average propagation time of the synchronization packet (Eq. 1):

$$t_{del} = \frac{(t_4 - t_1) - (t_3 - t_2)}{2} \quad (1)$$

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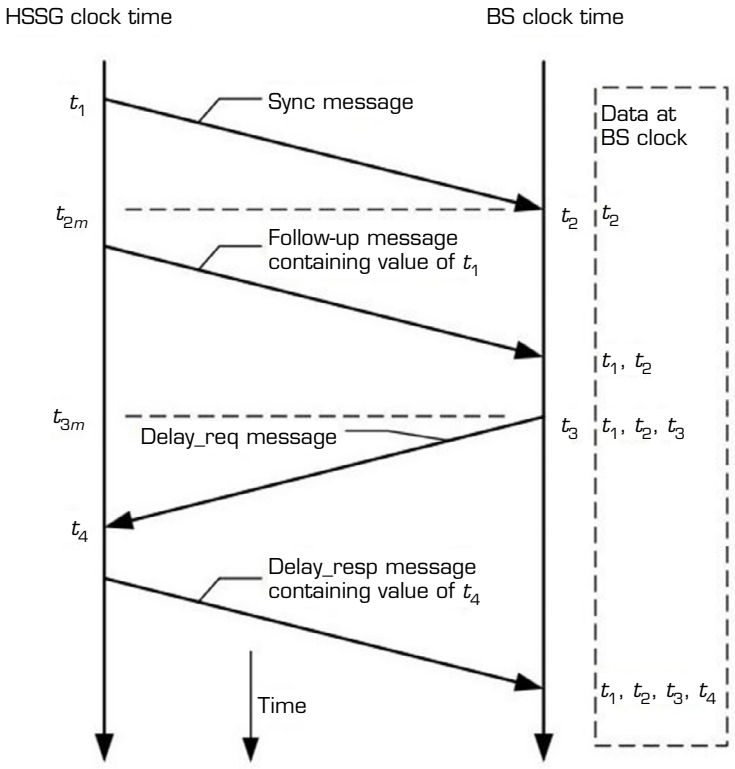


HSSG: highly stable signal generator; BS: base station.

Figure 3. Precision time protocol algorithm timestamps.

Also, it calculates the desynchronization of BS clock – HSSG, which allows the BS to perform synchronization (Eq. 2):

$$\delta = (t_2 - t_1) - t_{del} \tag{2}$$

Since this approach is based on the assumption of communication channel symmetry (the forward and reverse latency of synchronization messages is the same), it cannot be directly applied to the proposed LRNN synchronization system model, as the synchronization network used is asymmetric. To compensate for the asymmetric propagation of synchronization packets, it is advisable to use the transparent clocks method provided in PTPv2.1, which takes into account the dynamic latency within routers and the resulting queues. According to this method, each router measures the physical layer synchronization packet dwell time as the difference between the exit and entry times, independently for the forward and reverse channels (Eq. 3):

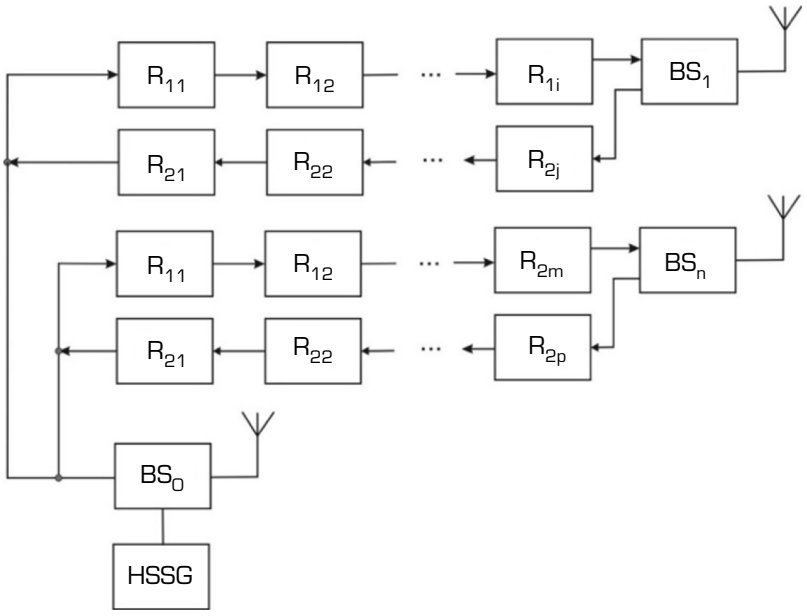
$$\Delta t_{ij} = \left(t_{out\,ij} - t_{in\,ij}\right) \tag{3}$$

The router includes the measured time in the correction field, which is adjusted each time it passes through each router, thereby accumulating the total delay. BS takes this field into account when calculating the delay of synchronization packet, thereby eliminating dynamic asymmetry (Eqs. 4 and 5).

$$\delta = (t_2 - t_1) - t_{del} - \Delta T_s \tag{4}$$

$$\Delta T_s = \sum \Delta t_{ij} \tag{5}$$

Considering the LRNN structure, in which PSDN is used to synchronize SRNS, the synchronization system model can be represented as shown in Fig. 4.



BS: base station; HSSG: highly stable signal generator.

Figure 4. Synchronization system model of the local radio navigation network.

The presented model describes the propagation of a synchronization sequence in the forward and reverse channels through a set of routers connected in daisy-chains, generating a delay in the synchronization signal in the forward and reverse channels. System synchronization is performed by BS_0, which has an HSSG installed. Consequently, the signal emitted by BS_0, used for positioning, is considered reference, *i.e.*, free of synchronization error. According to the PTP synchronization algorithm, each BS is characterized by a forward and reverse synchronization channel. The number of routers in each channel is random and therefore varies in the forward and reverse channels depending on the synchronization cycle.

The time delay during packet transmission (Gulevich 2014) at each router consists of the serialization delay and the switching delay. The serialization delay is the time required by a device to transmit a synchronization message at a given communication line bandwidth. The serialization delay depends on both the bandwidth of the information transmission channel and the size of the transmitted packet (Eq. 6):

$$t_{ser} = \frac{l_{cc}}{S} \tag{6}$$

Where: l_{cc}: the size of synchronization message (bits); S: the data transfer rate in a communication line (bit/s).

Switching latency is the time interval from the receipt of a synchronization message by a router until it is transmitted to the next network device. Generally, each packet belonging to the same traffic flow is transmitted with a different latency. Packet transmission latency varies depending on the network conditions.

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If the network is not congested, packets are not queued at routers, and the total packet transmission latency consists of the sum of the serialization latency and the propagation latency at each intermediate hop. In this case, the synchronization message transmission latency tends to be as minimal as possible. The serialization latency becomes insignificant compared to the propagation latency when transmitting a packet over a high-bandwidth link.

If the network is congested, queuing delays at routers begin to significantly impact the overall packet transmission latency and lead to differences in the latency of different packets in the same flow. Jitter determines the maximum delay in receiving packets at the SBS destination.

The total amount of delay introduced by the synchronization system is calculated by Eq. 7:

$$T_{ss}^{i} = \sum_{j=0}^{r} t_{j}^{i} \tag{7}$$

Where: t_j^i: the delay introduced by the j-th router of the i-th communication channel (forward or reverse); r: the number of routers in the i-th communication channel (forward or reverse).

METHODS

To study the MS positioning error in IMCRN, the authors developed a C++ programming model that allows for determining this error, taking into account the SRNS location and the LRNN synchronization network structure already described. The input data for the programming model are:

- The number of BS and their relative coordinates;
- The MS movement step size within the mobile network service area (determines the number of calculation points);
- The maximum synchronization error values in the forward and reverse channels of the synchronization system;
- The relative MS movement interval, *i.e.*, an additional field in which the positioning error for locations outside the BS boundaries will be calculated.

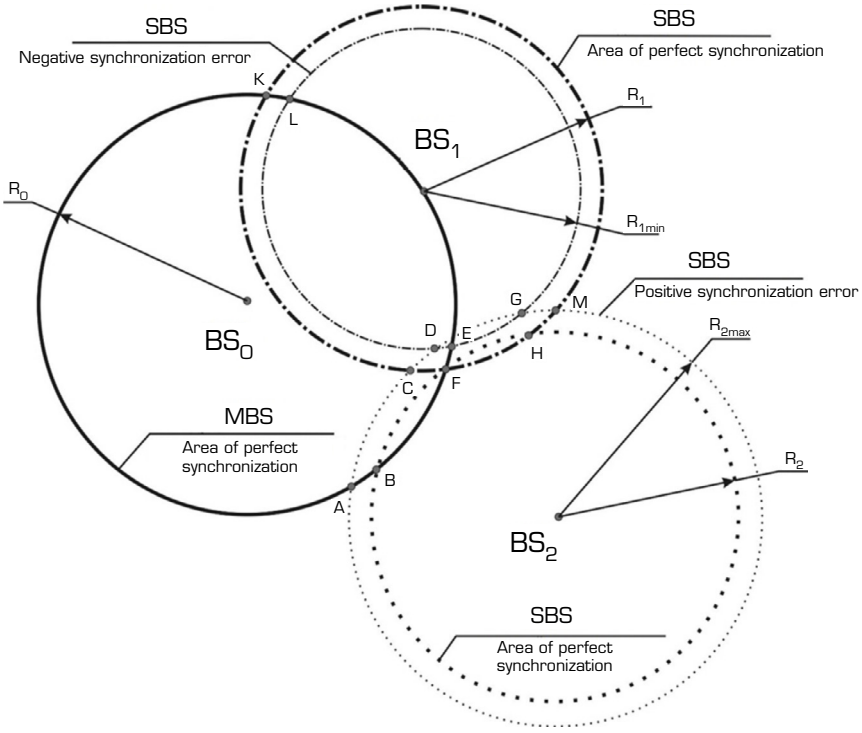
The MS position was determined during the simulation using the trilateration method, which has found widespread use for estimating the positions of various objects (Flick 2018; Kavitha *et al.* 2020). It was also assumed that the simulation was performed on a plane using a Cartesian coordinate system, and the SRNS were located on the BS.

As it is known, using the trilateration method to determine the MS position assumes the presence of three BS: BS_0, which is the MBS, and BS_1 and BS_2, which are the SBS. In terms of synchronization errors between BS1 and BS2 relative to BS0, the following four cases of their mutual synchronization are possible, which are presented in Table 1.

Table 1. Ability to determine location in the presence of a synchronization error.

Synchronization error		Location detection capability
BS_1	BS_2	
Positive	Negative	Yes
Positive	Positive	No
Negative	Positive	Yes
Negative	Negative	No

Location determination is only possible if there are synchronization errors BS_1 and BS_2 relatively to BS_0 will have different signs: positive and negative, or negative and positive. This is because that only in this case the areas formed due to the presence of a synchronization error BS_1 and BS_2, and also the circle formed due to the absence of the BS_0 synchronization error will have mutual intersection. Therefore, the problem of determining the location of the MS will have a solution (Fig. 5).



BS: base station; MBS: master base station; SBS: slave base station.

Figure 5. Subscriber location determination under conditions of imperfect source of radio navigation signal synchronization.

The presence of a synchronization error between BS_1 and BS_2 leads to an error in MS location determination, which corresponds to the MS's position on the FE arc. In other words, the FE arc corresponds to the probable location of the MS given the synchronization errors in the forward and reverse channels. Therefore, during the simulation, the MS positioning error is calculated as the total length of the FE arc.

Broadly speaking, the model consists of three stages:

- Finding the coordinates of all intersection points of a circle of radius R_0 with circles of radii R_{1min}, R_{1max}, R_{2min}, R_{2max}, *i.e.*, solving the following system of equations (Eq. 8):

$$\begin{cases}(X-X_0)^2-(Y-Y_0)^2=R_0^2\\(X-X_i)^2-(Y-Y_i)^2=R_i^2\end{cases}$$

$$\begin{cases}(X-X_0)^2+(Y-Y_0)^2=R_0^2\\(X-X_1)^2+(Y-Y_1)^2=R_1^2\\\cdots\\(X-X_i)^2+(Y-Y_i)^2=R_i^2\end{cases} \quad (8)$$

Where: i: the conditional number of BS; X_i, Y_i: the coordinates of i-th BS; X_0, Y_0: the coordinates of BS_0; R_0^2: the distance from BS_0 to MS; R_i^2 : the distance from i-th BS to MS.

- Determining the distances from the calculated location of the MS to each obtained intersection point and arranging them in ascending order;
- Calculation of the arc length FE corresponding to the MS positioning error.

Figure 6 shows a block diagram of the software model, which illustrates in detail the algorithm of its operation.

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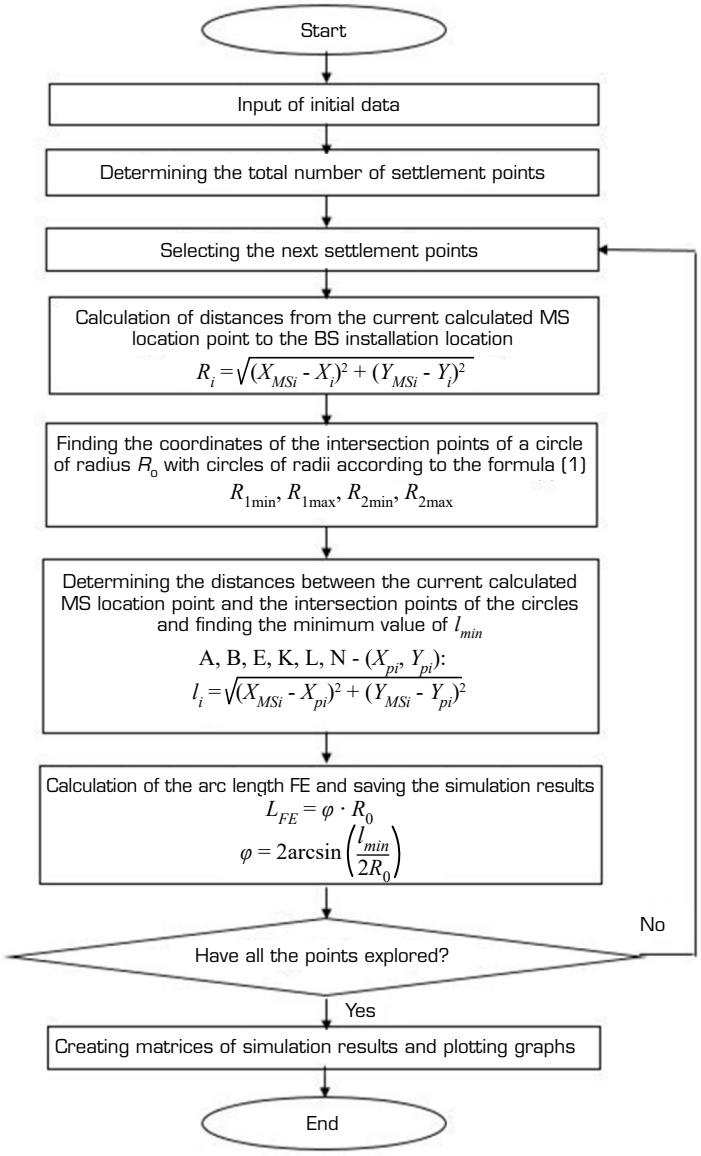


MS: mobile station; BS: base station.

Figure 6. Block diagram of the software model.

The following values are used as initial data for modeling: the number of BS and their coordinates, MS movement step, and the maximum synchronization errors in the forward and reverse channels. The output data of the model are tables with the calculated error in determining the MS location for each point on the plane, which makes it possible to construct a three-dimensional graph of the error depending on the position of the MS on the Earth's surface in the BS service area.

RESULTS

To conduct the simulation, the authors developed software code that automates the necessary calculations in the C++ algorithmic programming language. Processing of the obtained dependencies and plotting of the graphs were performed using the Origin software package, designed for numerical data analysis and scientific graphics. A text file containing the results of the experiment was used as the initial data for processing.

Using the developed software model, a series of experiments were conducted, differing in their relative positions. BS_0, BS_1, and BS_2, and for each of the series, graphical dependencies of the location determination error were constructed:

- For a fixed position of the BS set from different values of synchronization error of each BS;
- For different relative positions of the BS.

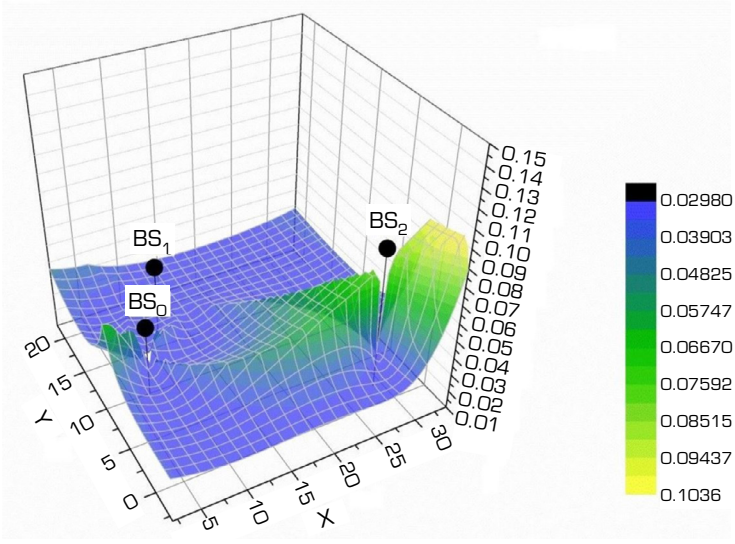
The initial data for conducting experiments to calculate the error in determining the MS location for one of these series are given in Table 2.

Table 2. Initial data for conducting experiments.

Input data	Experiment number					
	1	2	3	4	5	6
Relative coordinates (x, y) BS_0, km	(7, 10)	(7, 10)	(7, 10)	(7, 10)	(7, 10)	(2, -5)
Relative coordinates (x, y) BS_1, km	(12, 17)	(12, 17)	(12, 17)	(12, 17)	(12, 17)	(12, 17)
Relative coordinates (x, y) BS_2, km	(29, 2)	(29, 2)	(29, 2)	(29, 2)	(29, 2)	(25, 10)
The number of BS in the experiment	3	3	3	3	3	3
The magnitude of the relative displacement MS	5	5	5	5	5	5
The step of changing the position of MS, km	0.5	0.5	0.5	0.5	0.5	0.5
Delay time of the synchronization message in the synchronization channel BS_1, nsec	100	50	100	-50	-25	100
Delay time of the synchronization message in the synchronization channel BS_2, nsec	-100	-50	-25	100	100	-25
The asymmetry coefficient (modulus of the ratio of row 7 to row 8) of the delay time over synchronization channels	1	1	4	0.5	0.25	4

BS: base station; MS: mobile station.

Below there are some of the results of the simulation in the form of three-dimensional graphs of the positioning error in the mobile network coverage area for each of the six experiments. The vertical axis corresponds to the value of the MS positioning error (unit of measurement is km). Figures 7–11 reflect the value of the MS positioning error at a fixed location of BS_0, BS_1, and BS_2, and Fig. 12 shows it when changing the location BS_0 and BS_2 relatively to BS_1. The column on the right of each graph is a color chart corresponding to specific values of the MS positioning error.



BS: base station.

Figure 7. Distribution graph of mobile station positioning error in the experiment 1.

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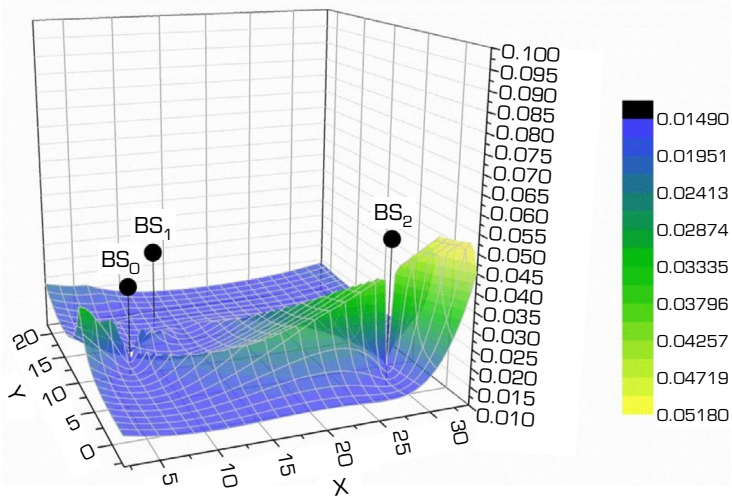
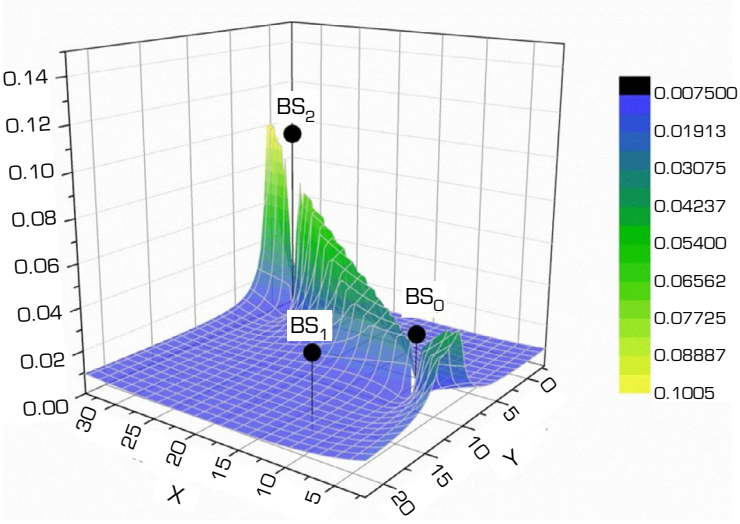


BS: base station.

Figure 8. Distribution graph of mobile station positioning error in the experiment 2.



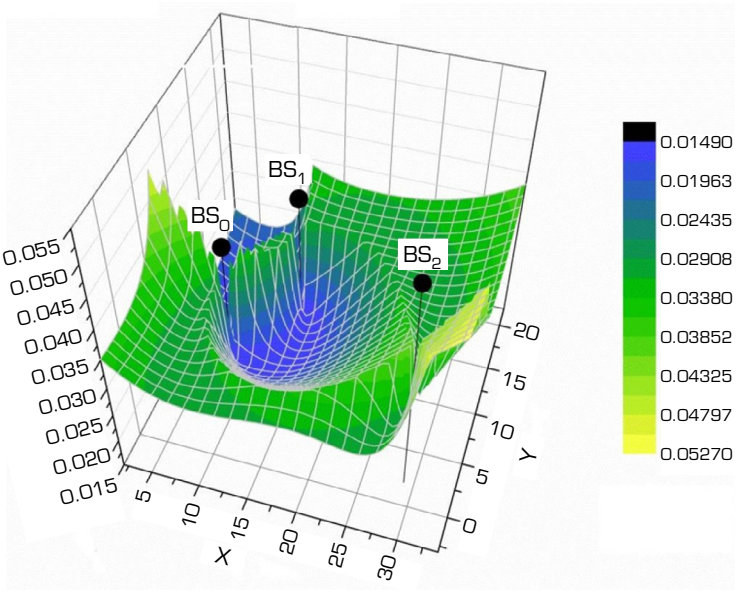
BS: base station.

Figure 9. Distribution graph of mobile station positioning error in the experiment 3.

Figure 7 shows the dependences of the MS positioning error in the experiment 1 for the case of a symmetric synchronization error with a delay in the synchronization message in the synchronization channel—BS_1 and BS_2 100 ns and -100 ns, respectively. Figure 8 shows the dependencies obtained for experiment 2 with a symmetrical synchronization error reduced by two times relative to the experiment 1.

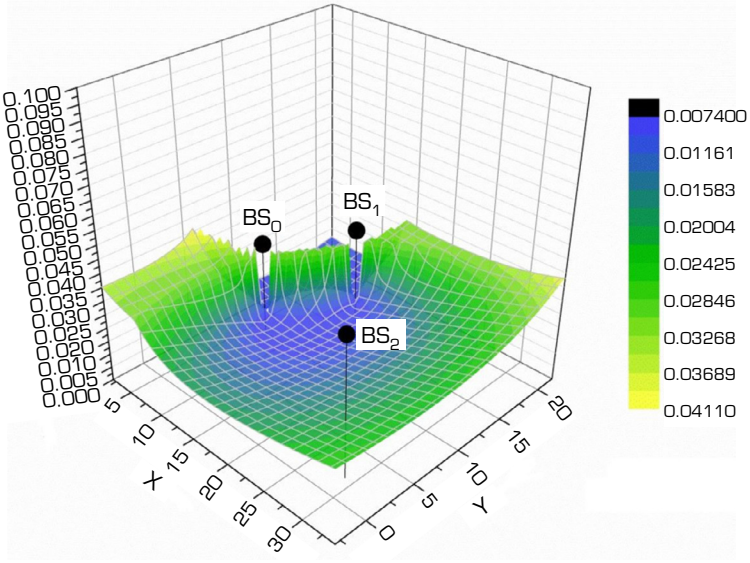
Figures 9–11 show the dependencies obtained for the experiments 3, 4, 5 during the simulation with an asymmetric synchronization error of BS_1 and BS_2 and a coefficient of asymmetry of the delay time along the synchronization channels equal to 4, 0.5, and 0.25, respectively.

Figure 12 shows the dependencies obtained for experiment 6 during the simulation with an asymmetric synchronization error: BS_1 and BS_2 when changing position of BS_0 and BS_2 relatively to BS_1.



BS: base station.

Figure 10. Distribution graph of mobile station positioning error in the experiment 4.



BS: base station.

Figure 11. Distribution graph of mobile station positioning error in the experiment 5.

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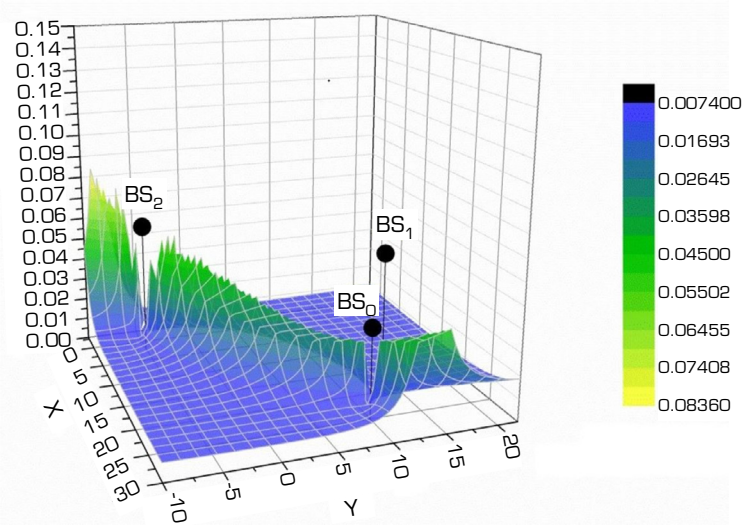

Figure 12. Distribution graph of mobile station positioning error in the experiment 6.

DISCUSSION

According to the authors of the current article, the main advantage of the proposed approach to MS location determination in IMCRN is the fact that the MS location and handover tasks are transferred from the MCN to the MS, and the MS location process itself is performed primarily using its resources. This reduces the load on the MCN and redistributes the freed computing and channel capacity to other tasks.

A disadvantage of the proposed model is that the possible MS position is a fragment of an arc, and its location is studied for cases in which BS synchronization errors have the opposite sign. Furthermore, since a Cartesian coordinate system was used in the modeling, the possible UAV location is essentially a projection onto the Earth's surface. However, in aviation, altitude determination is traditionally carried out using various aircraft altimeters.

Considering the above, relevant areas for further research are:

- Refinement of the software model for cases in which synchronization errors have the same sign (positive or negative);
- Introduction of additional SRNS into the software model, which will expand its scope of application by taking into account UAV flight altitude, for example, for airships operating at altitudes of up to several tens of kilometers.

CONCLUSION

The conducted analysis of the results of a series of experiments with the software model allowed us to draw the following conclusions:

- The shape of the MS positioning error distribution in the LRNN coverage area does not depend on the absolute value of the synchronization error;
- The shape of the MS positioning error distribution in the LRNN coverage area depends significantly on the delay asymmetry coefficient across the synchronization channels;
- The absolute value of the MS positioning error, given a fixed shape of its distribution, grows with increasing total synchronization error SRNS;
- The absolute value of the MS positioning error, given a fixed shape of its distribution and a delay asymmetry coefficient across the synchronization channels equal to unity, does not exceed L = Ct, where C is the radio wave propagation speed and t is the synchronization error value;

- The shape of the MS positioning error distribution, given a delay asymmetry coefficient across the synchronization channels greater than or equal to unity, is symmetrical with respect to the straight line drawn through the locations of BS_0 and BS_2, and shifts toward the BS_0 - BS_1 straight line as the asymmetry coefficient decreases;
- A decrease in the absolute distance between BS does not affect the shape of the MS positioning error distribution but leads to a significant decrease in the positioning error.

CONFLICT OF INTEREST

Nothing to declare.

DATA AVAILABILITY STATEMENT

All data sets were generated or analyzed in the current study.

AUTHORS' CONTRIBUTION

Conceptualization: Bogdanov A., Kolesnichenko V. and Shevtsov V.; **Methodology:** Bogdanov A., Kolesnichenko V. and Shevtsov V.; **Investigation:** Bogdanov A., Kolesnichenko V. and Shevtsov V.; **Software:** Bogdanov A., Kolesnichenko V. and Shevtsov V.; **Data curation:** Bogdanov A., Kolesnichenko V. and Shevtsov V.; **Formal analysis:** Bogdanov A., Kolesnichenko V. and Shevtsov V.; **Validation:** Bogdanov A., Kolesnichenko V. and Shevtsov V.; **Funding acquisition:** Bogdanov A., Kolesnichenko V. and Shevtsov V.; **Project administration:** Bogdanov A., Kolesnichenko V. and Shevtsov V.; **Supervision:** Bogdanov A., Kolesnichenko V. and Shevtsov V.; **Writing — original draft:** Bogdanov A., Kolesnichenko V. and Shevtsov V.; **Writing — review and editing:** Bogdanov A., Kolesnichenko V. and Shevtsov V.; **Final approval:** Kolesnichenko V.

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DECLARATION OF USE OF ARTIFICIAL INTELLIGENCE TOOLS

The authors declare that Artificial intelligence tools were not used.

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