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POLLUTANT TRANSPORT MODELING USING GAUSSIAN APPROXIMATION FOR THE SOLUTION OF THE SEMI-EMPIRICAL EQUATION
Part II:

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ABSTRACT

The paper presents the process of modeling air pollution processes and constructing concentration fields at small and medium distances from the emission source (which most accurately reflects the physical picture of atmospheric pollution with constant emissions) based on two approaches –on scattering according to Gaussian formulas, which includes an estimate of the concentration distribution pollutants along the coordinate axes and on the theory of mass transfer (the so-called "gradient" models or K-models based on solving the equations of turbulent diffusion. According to this method, the process of transport of harmful substances is described by the equations of turbulent diffusion in the atmosphere. Applying then averaging techniques pass from the diffusion equation for instantaneous concentrations to the equation of turbulent diffusion for average values of concentrations.

Keywords: *Monitoring, Intelligent system, Big data, Dynamic data, Sensors*

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1. INTRODUCTION

Natural environments exposed to anthropogenic factors are complex systems that interact with each other. Complex monitoring of such complex systems consists of a combination of contact and remote measurements of characteristics of almost always inhomogeneous media, identification of their space-time dependencies, and prediction of possible States of these media. Active targeted monitoring of the environment also implies optimal management of controlled changes in their States. The main feature of systems with natural components is their multidimensionality, incomplete predictability of their behavior, due to the stochasticity of the processes occurring in them, the uncertainty of their functioning goals, and the inaccuracy of describing their state. This makes it much more difficult to conduct full-scale experiments with such systems. Therefore, an important role in conducting research with them is played by their mathematical modeling, numerical experiments, and active monitoring, that is, monitoring the state of the environment, accompanied by a purposeful impact on it.

Thus, air pollution monitoring is a large-scale project that plays a key role in environmental issues. But in order to implement an information system for monitoring the environment, it is necessary to conduct a deliberate analysis of natural phenomena, to identify their direct impact on the state of the environment, in this case, the atmosphere. Then it is necessary to conduct a thorough analysis of the anthropogenic impact on the state of the surface air layer of this industrial center, that is, to identify the main stationary and mobile pollutants. In our case, we analyze the main stationary pollutants: plants, factories of various kinds, heat and power plants and similar industrial facilities that emit harmful pollutants into the atmosphere with a constant and continuous duration. To determine the level of pollution, it is necessary to measure emissions at certain intervals in certain places of the locality, depending on the chosen research method. To numerically implement the data obtained, it is necessary to apply a model for calculating the level of concentration of pollutants, which as a result will produce a numerical expression showing the state of the atmosphere in a given industrial area. The task of this work is to implement the actions listed above in software, i.e. to create software based on a specific adequate mathematical model that allows calculating the concentrations of pollutants and calculating the complex index of atmospheric pollution based on them. To perform analysis, identify characteristic features of concentrations for a certain time of year, make forecasts, and make certain decisions to reduce the level of pollution, it is necessary to track the dynamics of changes in the atmospheric pollution index over long periods of time. This means that you need to create a database for recording measurements, as well as the ability to view them visually at any time, for example, on a graph.

In Part I of this paper we presented the information system which is designed to monitor the state of the atmosphere of the settlement, by calculating the indices of atmospheric pollution [1]. Also, this information-analytical system stores recorded data in the database, which provides an overview of the complex index of air pollution for the last 6 and 12 months. This part of the paper presents Gaussian approximation for the solution of the semi-empirical equation of turbulent diffusion in the problems of transport of pollutants.

2. ANALYTICAL OVERVIEW OF EXISTING MATHEMATICAL MODELS

To obtain reliable characteristics about the level of air pollution from harmful vehicle emissions, it is necessary to conduct numerous and fairly large-scale sampling with the establishment of concentrations of gases and aerosol precipitation near industrial centers for several years, which is very expensive. Therefore, this problem is solved in practice by constructing mathematical, physical and analytical models of the processes of emission and dispersion of harmful substances in the atmosphere with assumptions that are adequate to the accuracy of specific practical problems. If the calculated estimates for the selected (justified) model coincide (with a certain accuracy) with the measurement results, the number of measurements can be significantly reduced, and for stylized schemes, for example, conditionally point or area sources of emissions, it can be avoided altogether. Three main aspects are considered when modeling the transport of substances in the atmosphere:

– source of pollution, its characteristics;

– the transfer process taking into account chemical reactions and transformations occurring in the atmosphere, the presence of natural and artificial obstacles, terrain, meteorological conditions, leaching of sediments, subsidence of soil, water surface and so on;

– the base of comparison of the impact of stationary sources on the urban environment (e.g., a human from the point of view of observance of the sanitary maximum allowable concentrations (Macs).

Methods for studying the meteorological regime and atmospheric pollution of cities are divided into:

- empirical-statistical;
- statistical;
- analog modeling;
- mathematical modeling.

Empirical-statistical and statistical methods relate different meteorological parameters and properties of the "underlying" surface. Statistical models include regression and autoregressive models. Statistical models are used, for example, to calculate average air pollution. To derive the regression equation, as a rule, the Gaussian formula is used ("Gaussian models"). Mathematical models fall into two categories: energy and hydrodynamic models. Energy models are designed to study the meteorological regime in the surface layer of air above the city. The method is based on the heat balance equation. The hydrodynamic modeling method is characterized as the most fruitful and promising. It is based on solving a system of equations describing the meteorological regime of air flow formation in an urban environment depending on the horizontal and vertical components of wind speed, temperature, specific humidity, horizontal and vertical pressure gradients, Coriolis force and other physical parameters. In general, there are four main directions in which the modeling of the distribution of gaseous impurities and particulate matter in the atmosphere of cities has been developed.

1. Using statistical propagation models based on the Gaussian distribution function. This direction consists in using propagation models designed for a flat underlying surface, modified by introducing empirical coefficients that take into account the possible redistribution of concentration in stagnant areas near buildings and structures.

2. Modeling of flows in street canyons based on solving transport-diffusion equations.

3. Physical modeling in wind tunnels. Such experiments make it possible to evaluate some features of the impurity distribution in building conditions for such meteorological conditions that

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can be reproduced with varying accuracy in a wind tunnel. At the same time, it is impossible to observe the similarity of the flow in pipes according to a sufficient set of criteria, for example, the Reynolds number simultaneously with the Rosby number. At the same time, this method allows you to determine some parameters necessary for modeling and allows you to compare model calculations with measurements, for example, to estimate the distribution of air flows along streets in different wind directions.

4. Construction of models based on an integrated approach: comparative analysis of the results of field experiments, the results of numerical modeling and physical modeling. At the same time, the analysis of the results of field experiments with the results of numerical and physical modeling is carried out, followed by the construction of parametric models of the distribution of impurities in street canyons depending on meteorological conditions: wind speed and direction, temperature stratification of the atmosphere, humidity, etc. Theoretical studies of large-scale motions in the atmosphere inside the so-called convective columns are based on fundamental ideas about the aerodynamics of the air. The first theoretical studies on free-ascending jets over point heat sources were theoretically considered by Ya.B. Zeldovich for laminar and turbulent jets. In a number of works, for a quantitative description of the dynamics of the development of convective flows in the atmosphere, both analytical dependences of the theory of free convective jets and non-one-dimensional mathematical models are used, which are implemented by numerical methods, for example, using the equations of an incompressible medium in the Boussinesq approximation. Models based on the Navier-Stokes equations for a viscous, compressible, and heat-conducting gas take into account the diffusion of aerosol particles and the influence of phase transitions due to the presence of moisture in the atmosphere, the dynamics of the rise and hovering of the convective column. The Navier-Stokes method involves the numerical solution of the equations of turbulent diffusion. An important advantage of these models is that the equation of turbulent diffusion is naturally linked to physical processes in the atmosphere. They make it possible to predict the spatio-temporal picture of atmospheric pollution, but only under normal meteorological conditions, which is not always observed and makes it impossible to consider the extreme, according to hydrometeorology, effects of stationary sources of pollution on the urban environment.

3. DEVELOPMENT OF A MATHEMATICAL MODEL

For modeling air pollution processes and plotting concentration fields at small and medium distances from the emission source (which most closely reflects the physical picture of atmospheric pollution with constant emissions), there are two approaches - based on scattering according to Gaussian formulas, which involves an estimate of the distribution of pollutant concentrations along the coordinate axes and based on the theory of mass transfer (the so-called "gradient" models or K-models based on solving the equations of turbulent diffusion. According to this method, the process of transport of harmful substances is described by the equations of turbulent diffusion in the atmosphere. Applying then averaging techniques pass from the diffusion equation for instantaneous concentrations to the equation of turbulent diffusion for average values of concentrations.

3.1 Gaussian Approximation For The Solution Of The Semi-Empirical Equation Of Turbulent Diffusion In The Problems Of Transport Of Pollutants

Let q (P, t) be a function whose value at time t at point P (x, y, z) coincides with the values of the instantaneous concentration of an impurity carried in the atmosphere by air flows. It is assumed that the function q (P, t) is continuously differentiable with respect to x, y, z, t. The semi-empirical equation of turbulent diffusion is written in the form:

$$\frac{\partial q}{\partial t} + V_x\frac{\partial q}{\partial x} + V_y\frac{\partial q}{\partial y} + V_z\frac{\partial q}{\partial z} = \frac{\partial}{\partial x}K_x\frac{\partial q}{\partial x} + \frac{\partial}{\partial y}K_y\frac{\partial q}{\partial y} + \frac{\partial}{\partial z}K_z\frac{\partial q}{\partial z} + S, \tag{3.1}$$

where S is an impurity source located at the point P_0 (x_0, y_0, z_0) and producing an instantaneous emission of pollutants at a time t_0 in an amount Q_0.

To calculate the average concentrations of impurities in the boundary layer of the atmosphere from an instantaneous point source, the solution to equation (3.1) is used:

$$q(x_0, y_0, z_0, t_0) = \frac{Q(x_0,y_0,z_0,t_0)}{[K_xK_yK_z]^{1/2}[4\pi(t-t_0)]^{\frac{3}{2}}} \times \exp\{\frac{[(x-x_0)-V_x(t-t_0)]^2}{4K_x(t-t_0)}\} \times \exp\{\frac{[(y-y_0)-V_y(t-t_0)]^2}{4K_y(t-t_0)}\} \times \exp\{\frac{[(z-z_0)-z(t-t_0)]^2}{4K_z(t-t_0)}\} \tag{3.2}$$

called the Gaussian distribution function of the impurity concentration. Solution (3.2) is obtained by the green's function method. To calculate the aerosol concentration at the observation point, it is necessary, first of all, to determine and set the values of the initial data and to normalize the main parameters and parameterize the problem. The initial data for equation (3.2) will be:

a) the moment in time when the source emits pollutants (EP) - t_0;

b) source coordinates $P_0(x_0, y_0, z_0)$(m);

c) distance from source to observation point R(m) - distance from point P_0- source of pollutant emissions to point P - observation point.

d) $Q_0(10^{-3}10^{-3}$ kg/s) - the amount of pollutants emitted by the source at the initial moment of time t_0;

e) turbulence of the atmosphere in the boundary layer, characterized by the coefficient of turbulent diffusion $K = \{K_x, K_y, K_z\}$ (m^2/*sec*);

f) wind speed $V = \{V_x, V_y, V_z\}$ (*m/sec*);

In addition to the initial data, it is also necessary to calculate the following parameters of the problem: coordinates of the observation point P, in which the concentration of pollutants coming from the source is measured:

$$x = \frac{1}{\sqrt{2}}R,\ y = \frac{1}{\sqrt{2}}R \quad (3.3)$$

Next, we normalize the variables of the problem. We put that

$$q(P_0, P, t_0, t) = Q_0 \times \tilde{q}(P_0, P, t_0, t), \quad (3.4)$$

where

$$\tilde{q}(P_0, P, t_0, t) = \widehat{q * \hat{q}}\,(\widehat{P_0}, \hat{P}, \hat{V}, \hat{K}, \widehat{t_0}, \hat{t}) \quad (3.5)$$

$\hat{q}$, $\widehat{P_0}$, $\hat{P}$, $\hat{V}$, $\hat{K}$, $\widehat{t_0}$, $\hat{t}$ - normalized values taking values in the interval (0,1). Let's normalize the variables and distributions of the problem as follows: $\widehat{P_0}(\widehat{x_0}, \widehat{y_0}, \widehat{z_0})$ $\widehat{P_0}(\widehat{x_0}, \widehat{y_0}, \widehat{z_0})\widehat{P_0}(\widehat{x_0}, \widehat{y_0}, \widehat{z_0})$

where $\widehat{x_0} = x_0/R$, $\widehat{y_0} = y_0/R$, $\widehat{z_0} = z_0/R$. Similarly, we obtain $\hat{P}(\hat{x}, \hat{y}, \hat{z})$, where $\hat{x} = x/R$, $\hat{y} = y/R, \hat{z} = z/R$. The coefficients of turbulent diffusion and wind speed are normalized as usual:

$$\hat{K} = \{\widehat{K_x}, \widehat{K_y}, \widehat{K_z}\}, \widehat{K_x} = \frac{K_x}{K^*},$$
$$\widehat{K_y} = \frac{K_y}{K^*}, \widehat{K_z} = \frac{K_z}{K^*}, \quad (3.6)$$

where: $K^* = \max\{K_x, K_y, K_z\}$;

$$\hat{V} = \{\widehat{V_x}, \widehat{V_y}, \widehat{V_z}\}, \widehat{V_x} = \frac{V_x}{V^*},$$
$$\widehat{V_y} = \frac{V_y}{V^*}, \widehat{V_z} = \frac{V_z}{V^*}, \quad (3.7)$$

where: $V^* = \max\{V_x, V_y, V_z\}$.

Next, we normalize the variables:

$$\widehat{t_1} = \frac{t_1}{T}, \widehat{t_0} = \frac{t_0}{T}, \widehat{t_2} = \frac{t_2}{T},$$
$$\widehat{t_1} \le \hat{t} \le \widehat{t_2} \quad (3.8)$$

$T = t^* - t_0$ - time interval during which contamination will enter the observation point.

Taking into account the above, equation (3.4) can be written as follows:

$$\hat{q}(\widehat{P_0}, \hat{P}, \hat{V}, \hat{K}, \widehat{t_0}, \hat{t}) = \frac{1}{[4\pi(\hat{t} - \widehat{t_0})]^{3/2}[\widehat{K_x}\widehat{K_y}\widehat{K_z}]^{1/2}} \times$$
$$\exp\{-\frac{[(\hat{z} - \widehat{z_0}) - \widehat{V_z}(\hat{t} - \widehat{t_0})]^2}{4\widehat{K_z}(\hat{t} - \widehat{t_0})}\} \times$$
$$\text{EXP}\{-\frac{[(x - \widehat{x_0}) - \widehat{V_x}(t - \widehat{t_0})]^2}{4\widehat{K_x}(t - \widehat{t_0})}\}$$
$$\text{EXP}\{-\frac{[(y - \widehat{y_0}) - \widehat{V_y}(t - \widehat{t_0})]^2}{4\widehat{K_y}(t - \widehat{t_0})}\} \quad (3.9)$$

3.2 Estimation Of The Amount Of Aerosol Impurities

Let us consider the case when a source operates at the point $P_0(x_0, y_0, z_0)$ for a finite period of time $[\zeta, \zeta_0 + T]$ and the process of accumulation of pollutants occurs at the observation point P(x,y,z). It is assumed that the monitoring point is measuring (receiving) the concentration of incoming impurities from sources at time t $\in[t_1, t_2]$(Figure 1). The function $S(P_0, \zeta)$ has the meaning of the source intensity, while the function $S(P_0, \zeta)\ \Delta\zeta(10^{-3}$ kg/m^3) determines the amount of substance, eleased into the atmosphere over an elementary time interval $\Delta\zeta$ in the vicinity ζ. According to the considered theory, the perturbation pulse of pollutants $S(P_0, \zeta)$ will be taken at the point P in the interval $[t_\zeta^* - \tau_1, t_\zeta^* + \tau_2]$. Because of this, the initial perturbation $S(P_0, \zeta)$ will be taken at the point P at time $(t_0^* - \tau_1, t_0^* + \tau_2)$, and the last one at time $(t_T^* - \tau_1, t_T^* + \tau_2)$. The Union of these intervals gives an interval $(t_0^* - \tau_1, t_T^* + \tau_2)$. Thus, it becomes clear that the interval $[\zeta, \zeta_0 + T]$ corresponds to the interval $(t_0^* - \tau_1, t_T^* + \tau_2)$. Moments in time ζ and t_ζ^* are linked by a simple transformation:

$$t_\zeta^* = t^* + \zeta, \quad (3.10)$$

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and therefore the interval $[\zeta, \zeta_0 + T]$ corresponds to the interval $\zeta_0 + t^* - \tau_1 \le t \le \zeta_0 + T + t^* + \tau_2$. As a result, we have:

$$\zeta_0 + t^* - \tau_1 \le t \le \zeta_0 + T + t^* + \tau_2. \quad (3.11)$$

Inequality (3.11) determines the time of reception of pulse disturbance of contaminants or, in other words, the propagation time of a pulse perturbation of pollutants through point P – point of observation.

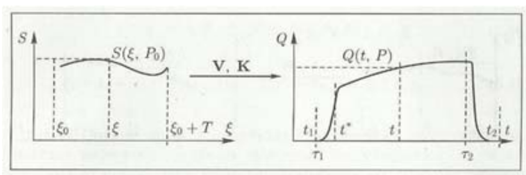

Figure 1: The process of converting "Pulse perturbation" of pollutants S(P_0, ζ), coming from a source operating during time [t_0,T] into a pulse Q(P,t)

Now it is necessary to construct an integral form Q(P_0,P,t), which determines the amount of pollutants accumulated during the operation of the source at point P. To do this, select on the interval $[\zeta_0, \zeta_0 + T]$ the point ζ_k and the interval $\Delta\zeta_k$ as follows:

$$\zeta_k = \zeta_0 + k\Delta\zeta,$$

where $k = \overline{0, m}$ and $\Delta\zeta_k = \zeta_{k+1} - \zeta_k$ (3.12)

Let's get the point $\zeta'_k = \frac{\zeta_k + \zeta_{k+1}}{2}$ and take an outlier at the point P_0:

$$Q(P_0, \zeta'_k) = S(P_0, \zeta'_k)\,\Delta\zeta_k. \quad (3.13)$$

Then at point P the reaction will be as follows:

$$Q(P,t) = Q(P_0, \zeta'_k)\tilde{q}(P_0, P, \zeta'_k, t). \quad (3.14)$$

As a result, you can write:

$$Q(P_0,P,t) = \sum_{k=0}^{m(t)} Q(P_0, \zeta'_k)\,\tilde{q}(P_0, P, \zeta'_k, t). \quad (3.15)$$

This is the integral sum, it remains to go to the limit at $\Delta\zeta \to 0$ and make the replacement $m(t) \to \zeta(t)$, we get:

$$Q(P_0,P,t) = \int_{\zeta_0}^{\zeta(t)} S(P_0, \zeta)\tilde{q}(P_0, P, \zeta, t)d\zeta, \quad (3.16)$$

where $\zeta_0 \le \zeta < \zeta_0 + T$, $\zeta_0 + t^* - \tau_1 \le t \le \zeta_0 + T + t^* + \tau_2$

or $t_1 \le t \le t_2$, if we equate

$$t_1 = \zeta_0 + t^* - \tau_1,\ t_2 = \zeta_0 + T + t^* + \tau_2,$$
$$\zeta(t) = t - t^*. \quad (3.17)$$

Next, we will consider the case when the source operates continuously, and the amount of pollutants is fixed at point P for a certain period of time $[t_1, t_2]$. We need to define:

$$\underline{Q}(P_0, P) = \frac{1}{(t_2 - t_1)}\int_{t_1}^{t_2} Q(P_0, P, t)dt. \quad (3.18)$$

Expression (3.13) sets the average value of the concentration of pollutants per cubic meter and accumulated over time $[t_1, t_2]$.

In this case, the interval $[t_1, t_2]$ is set and you need to define the corresponding interval $[\zeta_1, \zeta_2]$. According to (3.13) $t_1 = \zeta_0 + t^* - \tau_1$, $t_2 = \zeta_0 + T + t^* + \tau_2$. So we find $\zeta_0 = t_1 + \tau_1 - t^*$ и $\zeta_0 + T = t_2 - t^* - \tau_2$. Indicate that $\zeta_1 = \zeta_0$ и $\zeta_2 = \zeta_0 + T$. As a result, we get $\zeta_1 = t_1 + \tau_1 - t^*$ и $\zeta_2 = t_2 - t^* - \tau_2$. As a result, we have the following calculation formulas:

$$\underline{Q}(P_0, P, t_1, t_2) = \frac{1}{(t_2 - t_1)}\int_{t_1}^{t_2} Q(P_0, P, t)dt, \quad (3.19)$$

$$Q(P_0, P, t) = \int_{\zeta_1}^{\zeta_2(t)} S(P_0, \zeta)\tilde{q}(P_0, P, \zeta, t)d\zeta, \quad (3.20)$$

$$\zeta_1 = t_1 + \tau_1 - t^*,\ \zeta_2 = t_2 - t^* - \tau_2,$$
$$t_1 \le t \le t_2. \quad (3.21)$$

Let us calculate the concentration of impurities entering the observation point from the source according to the method (3.11), (3.12). For this, it is necessary, first of all, to set the initial data and to normalize the main variables and fields of the problem [13-14]. Then it is necessary to calculate the arrival of P – the maximum of pollutants coming from the source. Then, we set the partition of the segment $[t_1, t_2]$ and form the array $\{t_l\}$, $l = \overline{1, n}$, $t_{l+1} = t_l + hl, h = \frac{(t_2 - t_1)}{n}$. After normalizing the variables $\hat{t_1} = t_1/(T - t_0)$, $\hat{t}* = t^*/(T - t_0)$, $\hat{t_0} = t_0/(T - t_0)$, $\hat{t_2} = t_2/(T - t_0)$, $\hat{t_0} \le \hat{\zeta} \le \hat{t} - \hat{t}*, \hat{\zeta} = \zeta/(T - t_0)$, $d\zeta = (T - t_0)$, $d\zeta = (T - t_0)d\hat{\zeta}$ we have the following calculation formulas:

$$\hat{q}(\hat{P}, \hat{\zeta}, \hat{t}) = \frac{1}{[4\pi(\hat{t} - \hat{\zeta})]^{3/2}[\hat{K_x}, \hat{K_y}, \hat{K_z}]^{1/2}} \times \exp\{-\frac{[(\hat{z} - \hat{z_0}) - \hat{V_z}(\hat{t} - \hat{\zeta})]^2}{4\hat{K_z}(\hat{t} - \hat{\zeta})}\} \times \exp\{-\frac{[(\hat{x} - \hat{x_0}) - \hat{V_x}(\hat{t} - \hat{\zeta})]^2}{4\hat{K_x}(\hat{t} - \hat{\zeta})}\} \times$$

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$$\exp\{-\frac{[(\widehat{y}-\widehat{y_0})-\widehat{V_y}(\widehat{t}-\hat{\zeta})]^2}{4\widehat{K_y}(\hat{t}-\hat{\zeta})}\} \qquad (3.22)$$

Next, consider the source function. Let us assume that:

$$S(P_0,\zeta) = S_0\hat{S}(\widehat{P_0},\hat{\zeta}) = S_0 \times \eta(\widehat{x_0},\widehat{y_0},\widehat{z_0},\hat{\zeta}), \quad (3.23)$$

$\eta(\widehat{x_0},\widehat{y_0},\widehat{z_0},\hat{\zeta})$=(1 + a×$sin$ sin $(b \times \widehat{x_0} + c)$)× (1 + a×sin sin $(b \times \widehat{y_0} + c)$)× (1 + a×sin sin $(b \times \widehat{z_0} + c)$)× (1 + a×sin sin $(b \times \hat{\zeta} + c)$).

As a result, we have:

$$Q(P,t)=\tilde{Q}^*(P,t) \times \hat{\tilde{Q}}(\hat{P},\hat{t}), \qquad (3.24)$$

$$\hat{\tilde{Q}}(\hat{P},\hat{t}) = \int_{\widehat{t_0}}^{\hat{t}-\widehat{t*}} \hat{S}(\widehat{P_0},\hat{\zeta})\hat{q}(\widehat{P_0},\hat{P},\hat{t},\hat{\zeta},\hat{V},\hat{K})d\widehat{\zeta}, \quad (3.25)$$

$$\widehat{Q*} = T \times S_0 \times q^*, S_0 = Q_0 . \qquad (3.26)$$

Thus, the possibility of practical application of the developed computational and analytical technique for assessing the concentration of pollutants to applied problems of operational monitoring of the state of an industrial region is shown, which makes it possible to carry out its environmental forecast.

4. ANALYSIS AND EVALUATION OF THE DESIGNED HARDWARE AND SOFTWARE COMPLEX

Existing 4G mobile communication networks are represented by LTE Advanced networks, which provide several technologies that can be used to transmit data from stationary and mobile posts that collect basic indicators about the current environmental situation:

- LTE-M - as an evolution of LTE technology, which is optimized For IOT in the RAN network. The first version appeared in Release 12 in the fourth quarter of 2014, and was further optimized in Release 13. the Full LTE-M specification appeared in the first quarter of 2016. A 1.4 MHz wide channel is used;

- EC-GSM (with extended GSM coverage) - the technology is an evolutionary approach, standardized for the GERAN solution in Release 13. the Full specification appeared in the first quarter of 2016. uses a standard GSM channel with a width of 200 kHz;

- NB-IoT-this new narrow-band radio interface technology is being created as part of the development of RAN. Standardization started in the fourth quarter of 2015. This solution based on narrowband FDMA signals in the up line and narrowband OFDMA signal in the down line uses channels with a width of 180 kHz.The NB-IoT radio line budget was improved by 20 dB compared to LTE Advanced.

From the analysis of the data in Table 4.1, it can be seen that NB-IoT technology, due to low costs, increased coverage and prolonged battery life of connected devices, will allow connecting a very large number of sensors used in environmental monitoring networks based on IoT devices.

The ecosystem of subscriber devices NB-IoT today is the most developed and has more than 210 devices supporting either Cat-NB1 or NB-IoT [2]. Below are shown the economic and technical parameters (Table 1) that provide 3GPP technologies for Internet of Things services based on NB-IoT, LTE-M, EC-GSM technologies.

Table 1: Economic And Technical Parameters Of NB-Iot, LTE-M, EC-GSM Technologies

Characteristics	LTE-M (1.4 MHz)	NB-IoT (200 kHz)	EC-GSM (200 kHz)
Improved coverage, including inside buildings	156 dB MCL (improvement +15 dB)	164 dB MCL (+20dB improvement)	164 dB MCL (+ 20dB improvement)
Radius (line of sight)	< 11 km	< 15 km	< 15 km
Capacity for mass use	> 52 thous. AT / cell / 180 kHz	52 thous. AT / cell / 180 kHz	52 thous. AT / cell / 180 kHz
Data Transfer Rate	<1 Mbps	< 200 kbps	< 70 kbps
Battery life	> 10 years	> 10 years	> 10 years
IoT module price	5.0$ (2016)/3.3$ (2020)	4.0$ (2016)/2-3$ (2020)	5.5$ (2016)/2.9$ (2020)
Spectrum usage scenario	In the 3GPP licensed frequency band (In-band)	Three scenarios (In-band, Stand alone, Guard-band)	In the 3GPP licensed frequency reforming band (Stand alone)
Need to update the network	Will be determined	Yes (HW/SW)	Yes (HW/SW)
*Note: MCL – MinimalCouplingLoss (minimum attenuation loss)			

The features of technological solutions incorporated in NB-IoT solutions are as follows:

• selection of the radio channel width equal to the width of the radio block of the LTE technology - 180 kHz for the user equipment UE both in the downlink and uplink [3].

• use of OFDMA-access downlink with 15 kHz subcarrier spacing (for normal CP), or 3.75 kHz spacing (for MBB mode).

• use of two modes in the uplink: FDMA access with GMSK modulation, and SC-FDMA access with a single frequency carrier (including single-tone transmission as a special form of SC-FDMA).

• the use of one reference carrier for synchronization in various modes of operation, including a solution for convergence with traditional LTE signals.

• use for NB-IoT technology existing procedures and protocols of the LTE standard: MAC, RLC, PDCP and RRC and optimization procedures that support the selected physical layer.

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• application of the enhanced S1 interface to the CN core network and associated radio protocols that define system aspects such as reducing signaling traffic when transferring small amounts of data from NB-IoT devices.

• the use of channel estimates based on power consumption, latency and throughput, these estimates are intended to be used in the Gb interface to the core network.

The physical resources of the LTE radio access network in the uplink are allocated between subscriber terminals in the form of time-frequency PRBs (Physical Resource Block) [4].

The resources of one such time-frequency block, whose frequency width for NB-IoT technology is equal to the corresponding channel width, contain:

- frequency domain of 12 radio frequency subcarriers, each 15 kHz wide in the frequency domain with QPSK or 16QAM or 64QAM modulation, separated by 15 kHz; total PRB width is 12x15 kHz = 180 kHz;
- the time domain, divided into subframes 1 ms long, including two slots of 0.5 ms each; the slots are formed by 6 or 7 SC-FDMA symbols (NULsimbl = 6 or 7) in the time domain, depending on the type of the CP;
- a set of signals: LTECRS - cell – specificreferencesignal, LTECSI-RS – ChannelStateInformationReferenceSignal (Channel state reference), LTEPDCCH - DownlinkControlChannel (Physical downlink control channel), NB-IoTRE - NarrowBandInternetquipmentThings (subscriber equipment).

As with LTE, NB-IoT uses two basic states of the RRC radio resource control protocol: RRC_Idle (idle) and RRC_Connected (connected). In RRC Idle mode, devices save energy, as well as radio resources, which will be used to transmit measurement reports and reference (reference) signals in the uplink, and in RRC_Connected mode (Figure 2) subscriber devices receive or transmit data directly [5].

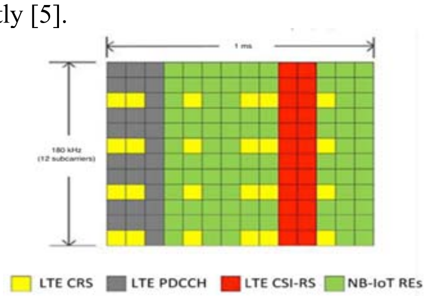

Figure 2: An Example Of The Formation Of Time-Frequency Blocks NB-Iot

NB-IoT technology will support 3 different RFS use cases in 3GPP bands:

- stand-alone use case (‘Stand-alone’), when the permitted spectrum for NB-IoT devices is selected in the permitted channels of 3GPP networks on the principles of refarming, and in fact substitution (for example, for LTE and GSM);
- the 'Guard band' scenario, when the excess spectrum of the frequency channel is used for the operation of NB-IoT devices within the dedicated LTE channel on its unused part;
- the scenario of shared spectrum use (‘In-band’), when resource radio blocks are used for NB-IoT devices within the radio channel already allocated to the LTE network (Figure 3).

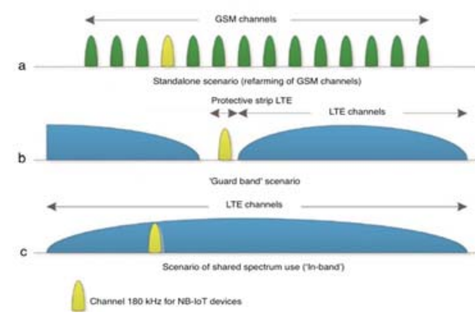

Figure 3: RFS Use Cases For NB-Iot In 3GPP Bands

Based on these scenarios, for the organization of IoT / M2M access networks in NB-IoT technologies, the bands of GSM networks can be used, since the width of the NB-IoT channel coincides with the standard GSM channel [5].

As seen in Fig. 6, when using an LTE channel with a width of 10 MHz, the occupied effective channel width, determined by the number of 50 resource radio blocks used (Table 2), is 9 MHz, and to the left and right of the main signal spectrum, Guardbands 500 kHz wide appear (Figure 4). Thus, in these guard bands with LTE channel widths of 5 and 10 MHz, at least two NB-IoT channels can be transmitted, and with channel widths of 15 and 20 MHz, two or more.

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Table 2: Parameters And Guard Bands Of LTE Frequency Channels

Parameters	The ratio between the width of the frequency channel and the number of resource blocks for LTE-signals					
LTE channel bandwidth (BW), MHz	1,4	3	5	10	15	20
The structure of the transmitted LTE signals - the number of NRB resource blocks in the LTE channel	6	15	25	50	75	100
Effective channel width by resource blocks, MHz	1,08	2,7	4,5	9,0	13,5	18
Guard stripes for NB-IoT channels	No	No	2x0,25	2x0,5	2x0,75	2x1,0

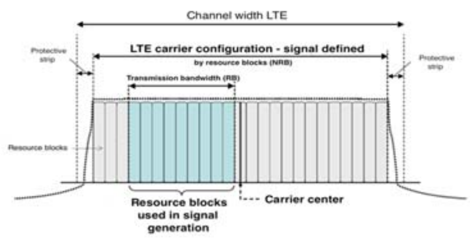

Figure 4: LTE Channel Width And Effective Channel Width Determined By The Number Of Resource Blocks Used

The 3GP requirements for the NB-IoT access network architecture imply improvements that can be made at the hardware and software level. LTE hardware developers consider two types of solutions when implementing NB-IoT technology: with an IOT/M2M controller outside the network architecture, and with centralized management based on an existing LTE solution (Figure 5) [6].

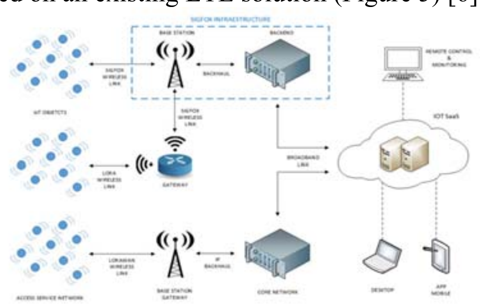

Figure 5: Variants of the NB-IoT technology access network architecture

Existing use cases (business cases) are traditionally designed for two segments of NB-IoT technology application. This is primarily the industrial segment and the consumer segment of the IoT / M2M market, including IoT solutions for environmental monitoring, as well as public (public) needs (IoT Public), industrial IoT solutions (IoT Industry). Thus, business models for NB-IoT currently cover more than 50 options for implementing various categories of services, including environmental monitoring [7].

According to the technical specifications, coverage for NB-IoT devices will be a 164 dB radio link budget, versus 144 dB GPRS radio link budget (TR 45.820 [10]) and an LTE radio link budget of 142.7 dB (TR 36.888 [8]). Thus, the NB-IoT technology will have improved coverage (the budget of the radio link is 20 dB higher than the budget for cellular networks of GPRS and LTE standards).

In addition to improved coverage, the LTE base station for NB-IoT devices will have more capacity due to the devices' low data rates. According to the calculations of Neul and Huawei [9], as well as the partner project 3GPP [10], one LTE macro base station with a range of 1 km will be able to serve more than 50 thousand NB-IoT devices. The capacity of such a base station is sufficient to serve consumers in dense urban conditions, when there are about 1500 households per 1 sq. Km, each of which has 40 IoT devices [11].

However, it should be noted that such a large number of serviced devices does not mean simultaneously serviced devices, but devices serviced by the BS for 1 hour in one 180-kHz channel, provided that each device transmits 100 bytes of information. Dependence of the number of serviced devices in a cell on the cell radius for different levels of additional building penetration losses (Figure 6) [12].

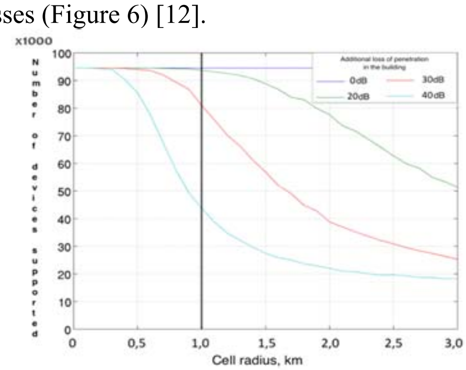

Figure 6: The number of served NB-IoT subscriber devices in a cell per hour in a 180 kHz channel

Figure 6 shows that even with high building penetration losses, up to 40 dB, one LTE base station with a range of 1 km can serve up to 45 thousand IoT devices per hour.

Below are the dependences of the percentage of available NB-IoT subscriber devices in a cell, provided they are evenly distributed, on the cell radius for different levels of additional building penetration loss. Devices are considered unavailable if they cannot support the minimum baud rate of 250 bps. As can be seen from the graph, building penetration losses of less than 20 dB practically do not affect the availability of NB-IoT subscriber devices in a cell with a radius of up to 2 km. With higher building penetration losses for a cell with a radius of more than 1 km, the percentage of available devices decreases sharply (Figure 7).

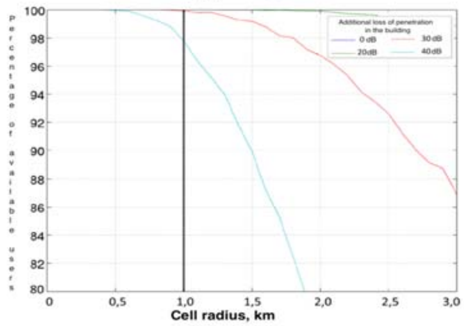

Figure 7: Percentage of available devices in a cell

Another important advantage of NB-IoT subscriber devices over conventional GSM / UMTS / LTE mobile devices will be a significantly longer battery life. According to 3GPP, the battery life of NB-IoT subscriber devices from a 2500 mAh battery under ideal theoretical conditions will reach 36 years. This indicator is calculated on the assumption that the NB-IoT module will communicate once a day to transmit no more than 50 bytes of data, and the signal attenuation between the antenna of the base station and the antenna of the IoT device does not exceed 144 dB (Figure 8).

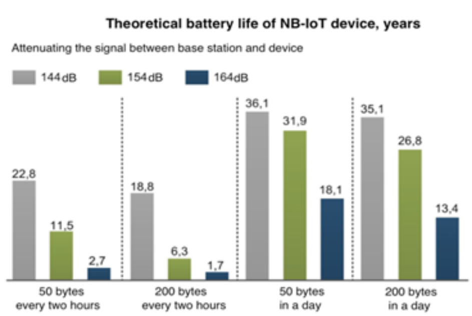

Figure 8: Theoretical battery life of an NB-IoT device

With more frequent data transmission by the NB-IoT subscriber device up to 200 bytes every two hours and with a stronger signal attenuation in the radio channel up to 164 dB, the battery life of the NB-IoT modules will be less than 2 years. On average, NB-IoT modules can operate independently from a single battery for about 10 years.

It should be noted that these calculations do not take into account the effect of self-discharge of batteries, which can significantly reduce the battery life of the NB-IoT device. The cost of batteries with a low self-reflection coefficient can be many times higher than the cost of the IoT device itself.

Assessment of the capabilities of 5g mobile communication networks to transmit data from fixed and mobile posts that collect key environmental monitoring indicators.

The most appropriate business model for environmental monitoring is the business model for using 5G devices in the key scenario of mass use of 5GIoT devices (mIoT). The implementation of this business scenario is preferred for 5G devices operating in the 700 MHz band with a minimum channel width of 5 MHz with an NG-RAN radio interface:

1. Higher data transfer speed, reliability, and lower latency than eMTC and NB-IoT;
2. Lower cost/complexity and longer battery life than NR eMBB devices;
3. Wider coverage area than devices with NR URLLC.

When solving environmental monitoring tasks for 5G networks, it is necessary to know the density of subscriber and base stations of the NG-RAN radio access network [10].

Analysis of the created database of standards and Technical specifications in the field of 5G showed that the two main developers of 5g network RES deployment scenarios are the 3GPP Partner project and the ITU-R radio Sector (WG 5D[8]).

Taking into account the data on the characteristics of the scenario of creating large cells in rural areas (Table 3), it is possible to calculate the site area for dense urban development, the specific number of base stations, and the number of as for environmental monitoring per 1 sq.km based on the DBS parameter (Distance between sites). This will be equal to 0.384/0.307 BS per 1 sq. km and 10 as per TRxP.

Table 3: Scenario of placement of autonomous stations for the range of 700 MHz

Characteristics of the base station scenario in rural areas	
Characteristics	**Values and assumptions**
Ranges used *Note 1*	700 MHz or 4 GHz range (for ISD 1) 700 MHz or 2 GHz range combined (for ISD 2)
Aggregated system lane *Note 2*	700 MHz range: up to 20 MHz (DL + UL) *(Note 3)* 4 GHz range: up to 200 MHz (DL + UL)
Location	One level of accommodation: - Hexagonal grids
Distance between sites (DBS)	ISD 1: 1732 m (0.384 BS per 1 sq. Km) ISD 2: 5000 m (0.307 BS per 1 sq. Km)
Number of BS antenna elements *(Note 3)*	4 GHz range: up to 256 Tx and Rx antenna elements 700 MHz range: up to 64 Tx and Rx antenna elements
The number of antenna elements of autonomous stations *(Note 3)*	4 GHz range: up to 8 Tx and Rx antenna elements 700 MHz range: up to 4 Tx and Rx antenna elements
Distribution of subscribers and speed of movement of autonomous stations	50% of subscribers in vehicles (at a speed of 120 km / h) and 50% of subscribers inside buildings (at a speed of 3 km / h), Density: 10 subscribers per TRxP

Note 1: The described 5G network deployment options are intended to be evaluated by research and do not imply a commitment to deploy the network

under these parameters and do not preclude the study of other spectrum use cases.
Note 2: The maximum number of antenna elements is a working assumption.

5. CONCLUSION

This study examined the problems of modeling environmental situations, as well as calculating a complex indicator of atmospheric pollution.

The next article will be about how an information system that calculates the concentration of pollutants in the city's atmosphere coming from stationary sources of pollution.

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