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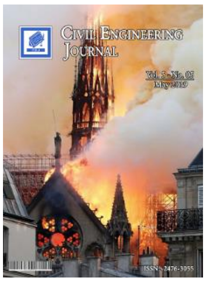

Wireless Video Monitoring of the Megacities Transport Infrastructure

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Abstract

The article discusses the development of megacities transport infrastructure. The problem of traffic congestion is touched upon, the task of optimal road design is justified. In the context of these issues gives a system of wireless video monitoring of traffic flows on base of digital panoramic video images. The main objective is to obtain a universal mathematical model for the description of a radio signal with any type of digital modulation. This will greatly facilitate the parametric calculation of the radio channel for image transmission and the design of the monitoring system. The objective is achieved by applying the Fourier method of separation of variables in combination with computer simulation methods. As result, a highly accurate universal mathematical model of radio signal with digital modulation is proposed. The scientific novelty of the model is that it allows to simulate the propagation of a radio signal with an arbitrary waveform. Thanks to this, the model covers almost all common types of digital modulation of the radio signal. In addition, the model takes into account the internal noise of the equipment and the external interference of the radio channel. The article describes in detail the process of solving the wave equation, underlying the model. Examples of modeling are given, the advantages and disadvantages of the model are indicated. Recommendations are made on its use for calculating radio channels and designing systems for analyzing and developing the transport infrastructure of a megacity.

Keywords: Metropolis; Transport Infrastructure; Development; Video Monitoring; Image Transmission; Wireless Communication; Radio Signal; Digital Modulation; Wave Equation; Fourier Method of Separation of Variables; Complex Time Basis.

1. Introduction

The problem of traffic congestion can be identified as one of the most pressing problems of megacities [1-5]. Traffic congestion is the main cause of the residents being late for work, they impede the work of the emergency services (fire brigade, first aid), and have a negative effect on the development of the city's infrastructure. Today, this problem is being solved, mainly due to the commissioning of new lanes and "interchanges". At the same time, as a rule, the road architecture develops "blindly", that is, without conducting a deep statistical analysis of the movement of traffic and the identification of patterns of their movement.

It is obvious that it is more profitable to design the transport infrastructure of the city purposefully (pre-analyze traffic at different times of the year, at different times of the day, on public holidays and on weekdays, peak times, and so on). Thus, the task of creating a system for monitoring traffic flows arises.

From a technical and economic point of view, aero video monitoring with using digital signal processing [6-12] and radio connection [13, 14] is the most promising direction. Quadcopters [15] can be used for panoramic aerial video images (Figure 1), video cameras on the roofs of high-rise buildings can also be installed, or special towers can be used

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(since the height of 30-40 m in total with wide-angle video cameras is already enough for statistical analysis of traffic flow).

Digital video images allow recognizing vehicle projections with a high degree of accuracy and automatically calculating traffic flow parameters such as the number of vehicles, their speeds, distances between them, and so on. However, to ensure high accuracy and reliability of the obtained statistical information, widescreen images of HD and Full HD formats are necessary, which require a high value of the carrier frequency of the radio signal for their wireless transmission.

Figure 1. The principle of panoramic video monitoring of traffic flows with using a quadrocopter

In other words, to transmit more digital data in time, it is necessary to significantly increase the value of the carrier frequency of the radio signal (especially when it comes to conducting measurements in real time). The complexity of the design of the radio channel increases. Consequently, the problem of modeling and preliminary estimation of radio signal parameters with digital modulation (amplitude or frequency) arises at the design stage of the measuring system.

These signals, used for organizing digital communications, usually have a rather complicated form [16, 17], therefore, the existing mathematical apparatus does not fit to describe their transmission, and the development of new mathematical models is required. So, the necessity of the proposed technical solution is due to the absent of universal mathematical models of signal with arbitrary waveform. This greatly complicates the process of calculating the digital radio channel. This is especially true in the case of designing monitoring systems, based on small-sized aircraft, for which the size and power of the transmitter are most important.

Innovation of the technical solution is in mathematical model of propagation of arbitrary radio signal. It is a "linear" case of the wave equation, where it is assumed that the radio signal transmits along a straight line connecting the phase centers of the antennas of the source and receiver. The mathematical model is based on the partial differential wave equation, the solution of which was made possible by combination of Fourier method of separation of variables with computer simulation methods. The Fourier method allowed us to reduce the solution of the original partial differential equation to a set of ordinary differential equations. Computer methods have accelerated the process of finding a solution. The problem statement was given in the field of complex numbers.

2. Materials and Methods

The developed mathematical model was built on the basis of the well-known partial differential wave equation [18-20] with two terms with the second derivatives with respect to time and coordinate, solved by the Fourier method of separation of variables [20]. However, there are two beneficial differences in the proposed model from the standard wave equation and the standard method for its solution.

The first difference is that additionally introduces a term with the first derivative with respect to the coordinate, due to which the attenuation of the signal in space is taken into account. The second difference is the possibility of setting an arbitrary perturbing effect on the right-hand side, due to the transition to the mathematical apparatus of complex numbers (since only it allows to correctly combine even and odd harmonics of approximated functions in the Fourier method). Solution of the wave equation in partial derivatives (PDE) is reduced (Figure 2) to solving a set of ordinary differential equations (ODE).

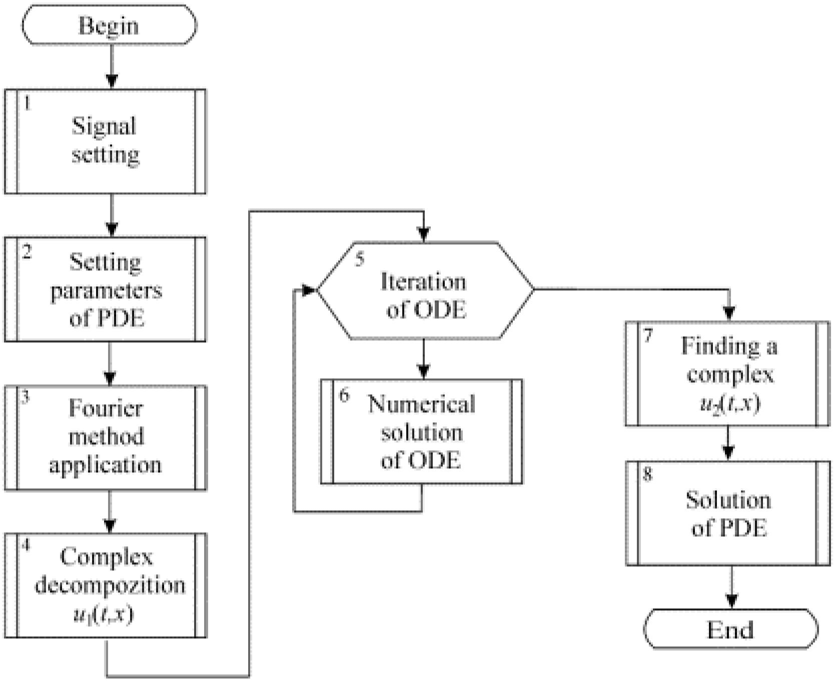


Figure 2. Explanation to the research methodology

For signals with digital modulation there is a certain ensemble of amplitudes in the case of amplitude modulation, and there is a certain ensemble of frequencies in the case of frequency modulation. The transition from one value of amplitude (frequency) to another value is carried out abruptly. The first kind of discontinuities are observed in the plots of amplitude and frequency changes in theory, which significantly complicates the mathematical model of the signal.

To take into account this feature of signals with digital modulation and to have the ability to specify an arbitrary disturbing action, a complex second-order partial differential equation with constant coefficients was chosen to describe the propagation of an arbitrary radio signal:

$$q_1\frac{\partial^2 u_2(t,x)}{\partial t^2}+q_2\frac{\partial^2 u_2(t,x)}{\partial x^2}+q_3\frac{\partial u_2(t,x)}{\partial x}=u_1(t,x) \tag{1}$$

With boundary and initial conditions:

$$u_2(t,0)=u_1(t,0),\ \ \frac{\partial u_2(t,0)}{\partial t}=\frac{\partial u_1(t,0)}{\partial t} \tag{2}$$

$$u_2(0,x)=0,\quad u_2(T,x)=0 \tag{3}$$

Where: $u_1(t,x)$ is a complex function of input actions (equivalent of perturbation voltage), $u_2(t,x)$ is the complex desired function (equivalent of propagation voltage), q_1,q_2,q_3 are constant complex coefficients with zero imaginary parts for taking into account the properties of the medium, T is the period of decomposition of functions in time, t is time, x is the coordinate.

The solution of this equation is based on the Fourier method of separation of variables, similar to the real case, but using the time-based complex decomposition of the input actions function $u_1(t,x)$ and the desired function $u_2(t,x)$:

$$u_1(t,x)=\sum_{k=0}^{K-1}c_{1,k}(x)e^{i\frac{2\pi kt}{T}},\quad u_2(t,x)=\sum_{k=0}^{K-1}c_{2,k}(x)e^{i\frac{2\pi kt}{T}} \tag{4}$$

Where: $c_{1,k}(x)$,$c_{2,k}(x)$ are the complex coefficients of the expansion of the function of input actions and the desired function, respectively, k is the index of decomposition coefficients (index of harmonics), K is the quantity of coefficients (harmonics) of the decomposition, i - imaginary unit.

After obtaining expressions for partial derivatives based on the last formulas and their substitution in the original equation, according to the algorithm of actions in the Fourier method, to find a separate coefficient $c_{2,k}(x)$, we have a complex differential equation:

$$q_2 c''_{2,k}(x) + q_3 c'_{2,k}(x) - q_1 \left(\frac{2\pi k}{T}\right)^2 c_{2,k}(x) = c_{1,k}(x) \quad (5)$$

In this case, the coefficients of decomposition of the input action $c_{1,k}(x)$ are assumed to be already known (obtained from the preliminary column-by-column decomposition of the signal function $u_1(t,x)$ during the simulation). The actual signal with digital modulation should be placed in the real part of $u_1(t,x)$.

Thus, the original partial differential equation splits into some set of ordinary differential equations, and the search for its general solution reduces to finding all solutions of the equations of a given set, that is, finding all coefficients $c_{2,k}(x)$ and then returning to the initial formula for the expansion functions $u_2(t,x)$.

Each real ordinary differential equation for $c_{2,k}(x)$is solved by an approximate method using difference ratios instead of derivatives. Finally, the solution is extracted from the real part $u_2(t,x)$, since the real part $u_1(t,x)$ is used to set the signal.

We emphasize that the model works correctly only for the linear case, when the source equation includes functions from two arguments (in this case, the arguments are time t and x coordinate). The propagation delay between two points of space is not taken into account.

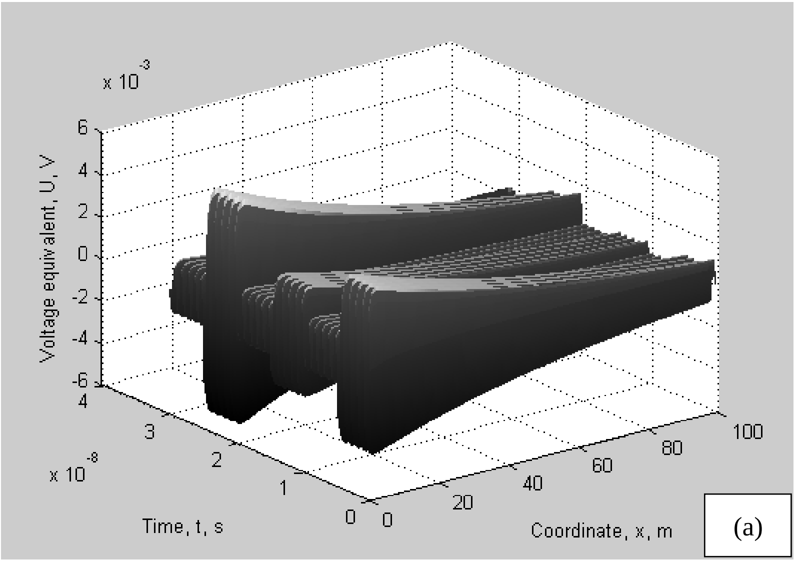
The efficiency of the mathematical model was confirmed by mathematical modeling, which was carried out using discrete programming methods and digital signal processing on a personal computer platform with Core 2 Duo processor and a clock frequency of 2 GHz system oscillator. The MATLAB environment of version R2009b, running under the Windows operating system, was used for writing and debugging software.

3. Results and Discussion

Results of modeling a «clear» radio signal are presented below (Figure 3). In the case of amplitude modulation, several levels of harmonic signal amplitude are used for transmitting digital symbols at the same frequency (information is transmitted by varying the amplitude of the signal by level). In the case of frequency modulation, on the contrary, several frequencies are used at a fixed signal amplitude (that is, information is transmitted due to the thickening and rarefaction of the harmonics).

The term equivalent of the propagation voltage is used for the voltage function on the graphs, since it is incorrect to speak of the “electromagnetic field voltage”. The equivalent of the propagation voltage is understood as the voltage value that would occur on the receiving antenna when it is placed “at a point” with a given x coordinate. In this case, the geometric dimensions of the antennas are neglected.

We also present the result of modeling a noisy radio signal with amplitude digital modulation as an example (Figure 4). This graph shows the effects of equipment noise and radio interference. The simulation was carried out in the MATLAB environment. The parameter of the propagation voltage equivalent, designated on the graphs as U, in the mathematical model corresponds to the function $u_2(t,x)$.



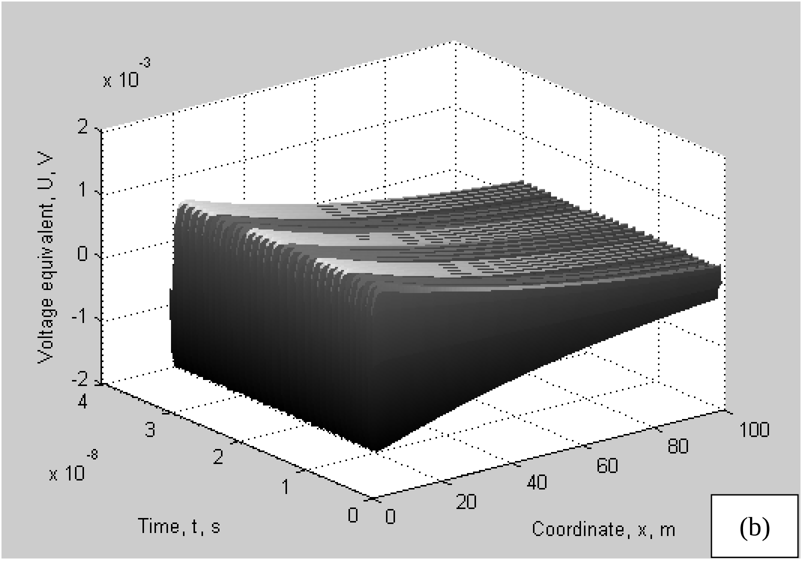


Figure 3. Equivalent of radio signal propagation voltage: (a) with amplitude digital modulation, (b) with frequency digital modulation

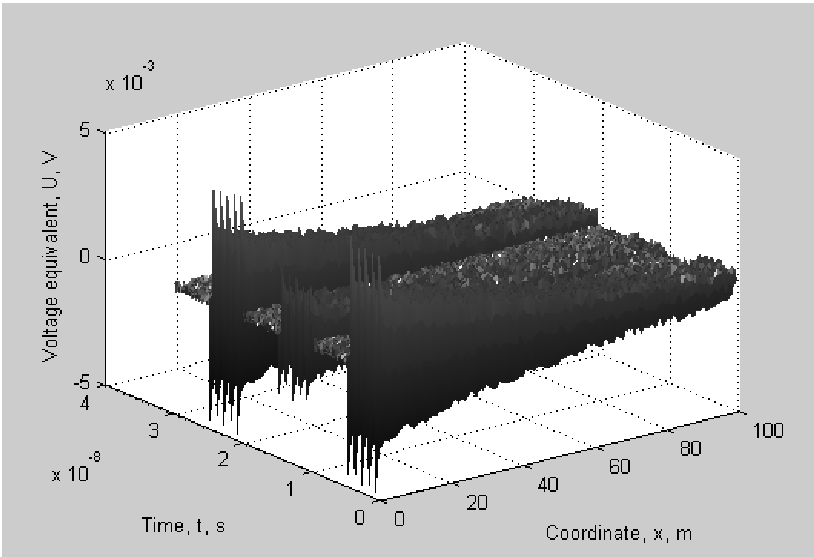
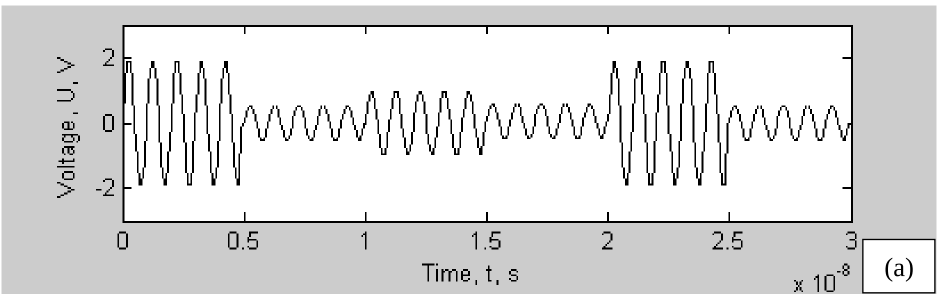


Figure 4. An example of a software implementation of a mathematical model for a signal with amplitude digital modulation (taking into account transmitter noise and external interference)

The radio signal in the model was transmitted at a distance of 100 m in the airspace. The amplitude of the voltage of the useful signal at the transmitting antenna was taken to be 1 V. The maximum noise level of the transmitting device was taken to be 10 μV, and the maximum voltage level of external interference was set to 100 μV. The carrier frequency used was 1 GHz. In this case, the total time interval for modeling was 30 ns. The figure below also shows the voltage in the receiver path (Figure 5).



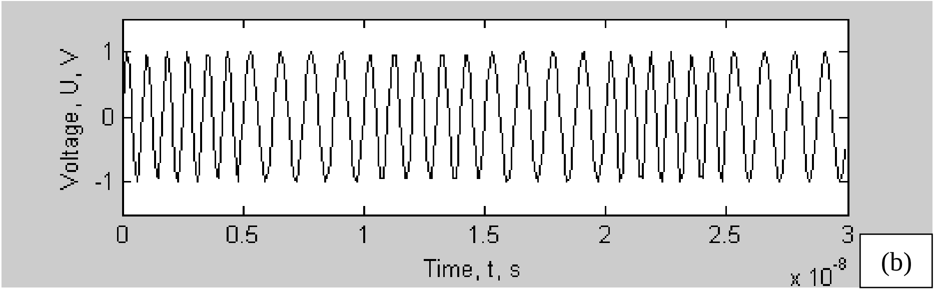


Figure 5. Voltage in receiver after filtering and amplifying:(a) amplitude digital modulation, (b) frequency digital modulation

According to the results of mathematical modeling, it is necessary to note the following important aspects regarding the proposed model. The intrinsic noise of the transmitting device at small values of their voltage level can be included in the model as an integral part of the full transmitted signal in the right-hand side. External interference with high voltage levels should be imposed after obtaining $u_2(t,x)$ and on the principle of superposition.

It should also be emphasized that the proposed mathematical model most reliably describes the propagation of a powerful radio signal over short distances. The greater the voltage amplitude of the transmitted useful signal, and the smaller the transmission distance, the more reliable the mathematical model works at a fixed coordinate point. This aspect is connected (Figure 6) with the issues of convergence of Fourier series (insufficiently good convergence leads to sharp bursts of the signal amplitude at the moments of its change, such bursts are usually called “outliers” in the literature on mathematical statistics).To eliminate this disadvantage, it is necessary to increase the number of Fourier coefficients.

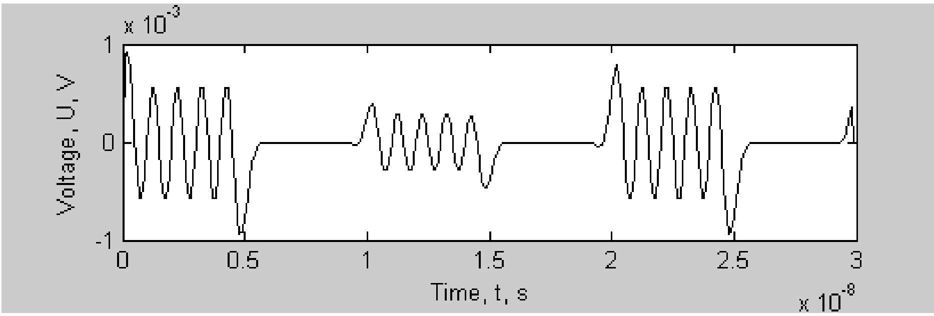


Figure 6. The disadvantage of the proposed model

We emphasize that the solution of the model should not be sought only by analytical methods, or only software (approximate methods). A joint approach is needed, since it may be necessary to solve several hundred ordinary differential equations to accurately reproduce the graph of the function sought (it is too laborious to do this “manually”).

In other words, the proposed mathematical model is the result of a combination of analytical (exact) and program (approximate) methods. It is based on the analytical Fourier method of separation of variables, but it is advisable to use computer simulation to find solutions of ordinary differential equations.

4. Conclusion

Based on the results of the research, first of all, we should highlight the following main advantages of the proposed mathematical model: the arbitrariness of the perturbing effect in the right side of the equation (which makes it possible to set a complex signal with digital modulation), the signal attenuation in space (which makes the model close to reality), as well as a convenient way to specify the properties of a particular medium or the boundary between several media (through the coefficients of the original equation).

The disadvantages of the proposed mathematical model include: significant computer time costs associated with the software solution of a set of ordinary differential equations (into which the original partial differential equation splits), partial loss of accuracy in describing functions with an insufficient number of Fourier expansion coefficients, and the theoretical complexity of the mathematical apparatus (complex basis of decomposition of functions).

In general, despite the indicated drawbacks, it should be noted that a promising complex mathematical model of radio signal propagation was developed. The model was obtained "at the junction" of analytical methods (Fourier method) and numerical methods for solving differential equations using difference schemes and computer simulation.

The theoretical foundations of the Fourier method of separation of variables and the mathematical apparatus of complex functions were widely used during the development.

As a result, the proposed model allowed setting an arbitrary useful signal of a complex shape, as well as taking into account external interference of the radio channel and attenuation of the signal in space depending on the properties of the specific environment, which opens up the possibility of modeling and preliminary assessment of the quality of receiving-transmitting devices with amplitude and frequency digital modulation of the signal. This is extremely important for design of measuring systems operating with widescreen video images.

The model is recommended to use for the selection of signal parameters with digital modulation and preliminary assessment of such important radio channel efficiency indicators as: required transmitter power (taking into account the working distance and signal attenuation index), radio channel capacity, signal-to-noise ratio at the receiver, calculated and mass-dimensional indicators of receiving and transmitting equipment.

Due to these advantages, the mathematical model can find the widest application in the design of wireless video monitoring systems of motor traffic flows to develop the transport infrastructure of the metropolis. In addition, the model can be used for wireless real-time traffic control, for example, by adjusting the switching time of traffic lights based on a statistical analysis of the transmitted video images.

5. Conflicts of Interest

The authors declare no conflict of interest.

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