ДОКЛАДЫ АН ВШ РФ
2024 октябрь–декабрь № 4 (65)

УДК 621.396.94: 537.86.029: 52.65

MATHEMATICAL MODELS OF RADIO WAVE PROPAGATION IN HETEROGENEOUS ENVIRONMENTS FOR WIRELESS NETWORKS. REVIEW.

Part 2. MATHEMATICAL MODELS OF RADIO WAVE PROPAGATION IN FORESTS

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The paper proposes a classification of mathematical models of radio wave propagation (RWP) in forests in a wide frequency range, which summarizes the results of the works of the author and numerous researchers on the effective complex dielectric constant of forests, effective operating and linear attenuation coefficients, radio path losses, effective differential absorption cross sections and scattering, as well as the specific effective area of backscattering by forest vegetation.

The rather complex problem of the influence of forests on the propagation of radio waves of various ranges is still extremely relevant today due to the widespread use of mobile and space radio communication systems, as well as solving the problems of radio monitoring of the earth's surface and radio introscopy of objects in forests.

Keywords: propagation of radio waves in forests, mathematical models, effective complex dielectric constant of forests, effective attenuation coefficient, radio path losses, effective differential absorption and dispersion cross sections, effective backscattering areas of forest vegetations.

DOI: 10.17212/1727-2769-2024-4-26-47

Introduction

When solving electrodynamic problems of determining the levels of the electromagnetic field at the receiving point during the propagation of electromagnetic waves of various ranges in forests, various cases arise, for each of which it is necessary to build its own specific mathematical model, which allows us to give an approximate solution for determining the power of the radio signal at the receiving point (Rx).

The problem in this case is usually solved for the following main options (Fig. 1):

1) radio rays 1 – radio waves propagate from the transmitting station (Tx) from the forest in the direction of the receiver (or vice versa) – vertical end-to-end RWP,

2) radio rays 2 – radio waves propagate from a transmitting station located above a forest in the direction of the receiver – inclined RWP,

3) radio rays 3 – radio waves propagate from the transmitting station through the forest in the direction of the receiver (at different levels relative to the layers of the forest) – end-to-end RWP,

4) radio rays 4 – radio waves propagate from the transmitting station to the forest, are reflected from it in the direction of the receiver – vertical sensing.

When considering mathematical models of RWP in forests, the main attention is paid to RWP in wireless networks, especially in mobile communication networks.

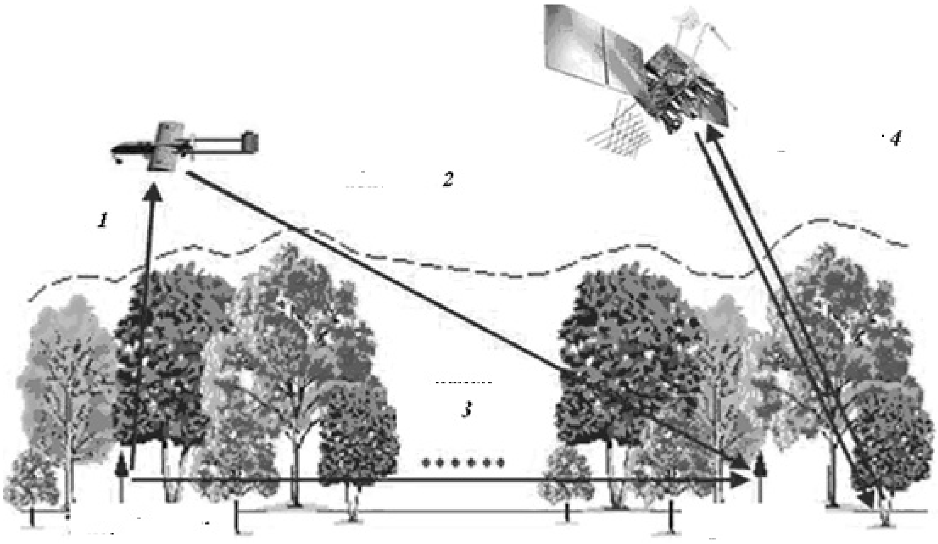


Fig. 1 – Radio wave propagation for four cases [1, 5, 36]:

1 – vertical end-to-end RWP (radio beams 1, bottom up or top down, Tx – aircraft Rx); *2* – inclined RWP (radio beams 2, from top to bottom, aircraft Tx – earth Rx); *3* – end-to-end RWP (radio beams 3, along of earth Tx-Rx); *4* – vertical sounding (radio rays 4, cosmic Tx or Rx – earth Rx or Tx)

Рис. 1 – Распространение радиоволн для четырех случаев [1, 5, 36]:

1 – вертикальная сквозная РВП (радиолучи 1, снизу вверх или сверху вниз, Tx – Rx самолета); *2* – наклонная РВП (2 радиолуча, сверху вниз, Tx самолета – Rx земли); *3* – сквозная РВП (радиолучи 3, вдоль земли Tx-Rx); *4* – вертикальное зондирование (радиолучи 4, космический Tx или Rx – земной Rx или Tx)

Before moving on to the classification of mathematical models of radio wave propagation (RWP) in forests, we present the main physical phenomena that arise in the process of RWP in forest vegetation. As follows from Fig. ,2 *a*, *b*, *c*.

Electromagnetic waves propagating in heterogeneous forest vegetation [1–81]:

1) attenuated in trunks, branches and leaves (needles) (with through propagation, may be arised fast and slow fading);

2) scattered (dispersed) on trunks, branches and leaves (needles);

3) diffracted at the edges of vegetation elements and at the tops of the forest canopy;

4) reflected from the forest floor [ground reflaction] and from the interfaces: the level of trunks – the base of the canopy, the upper level of the canopy – air, etc.;

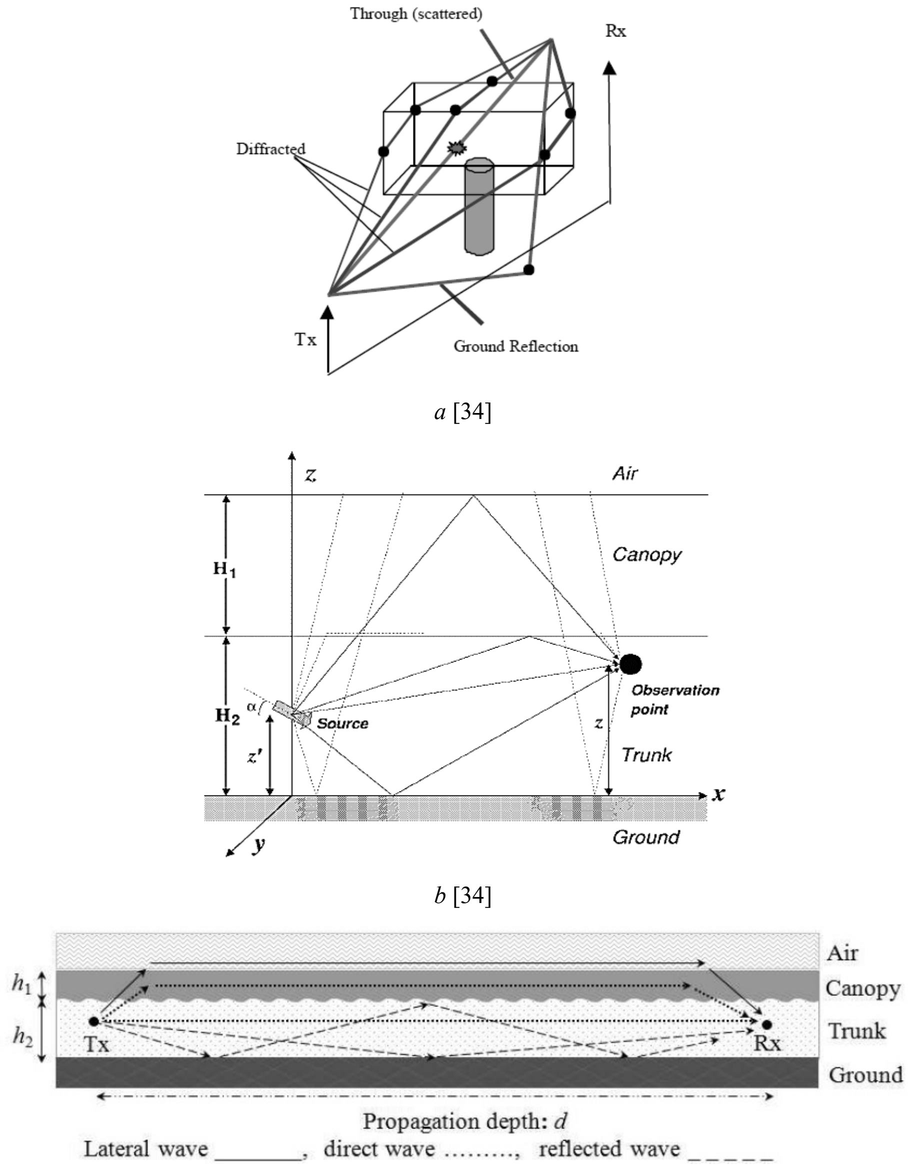
5) acquire the type of lateral wave, with electromagnetic waves propagating over short distances in the forest, then “emerging” from the forest and propagating as a lateral wave above the forest canopy in the air, and then “diving” in the forest towards the receiving antenna;

6) reflected from the forest (in the case of vertical and inclined sounding);

7) change the polarization of electromagnetic waves (cross-polarization of electromagnetic waves occurs);

8) in the general case EMW acquire a multimode propagation character.

It should be noted that it is almost impossible to construct a mathematical model of the propagation of radio waves in a forest, taking into account the above phenomena. Therefore, numerous scientific studies devoted to this problem, as a rule, were built on the basis of highlighting several characteristic phenomena while neglecting the rest.



a [34]

b [34]

c

Fig. 2 – Basic processes during RWP in the forest, [Tx – transceiver, Rx – receiver]

Рис. 2 – Основные процессы при РВП в лесу, [Tx – приемопередатчик, Rx – приемник]

1. Proposed scheme for classification of mathematical models of RWP in forests [5, 81]

Analysis of scientific literature [1-81] allows us to identify five main directions in mathematical modeling of radio wave propagation in forests and the development of the following mathematical models (Fig. 2):

1. Deterministic mathematical models (DMM).
2. Statistical mathematical models (SMM).

3. Semi-deterministic mathematical models (SDMM).
4. Semi-statistical mathematical models (SSMM).
5. Semi-empirical mathematical models (SEMM).
6. Empirical mathematical models (EMM).

In turn, these six directions, depending on the cases of propagation of a certain range of radio waves indicated in Fig. 1, are divided into a number of mathematical models most often used in practice (Fig. 3) [5, 81].

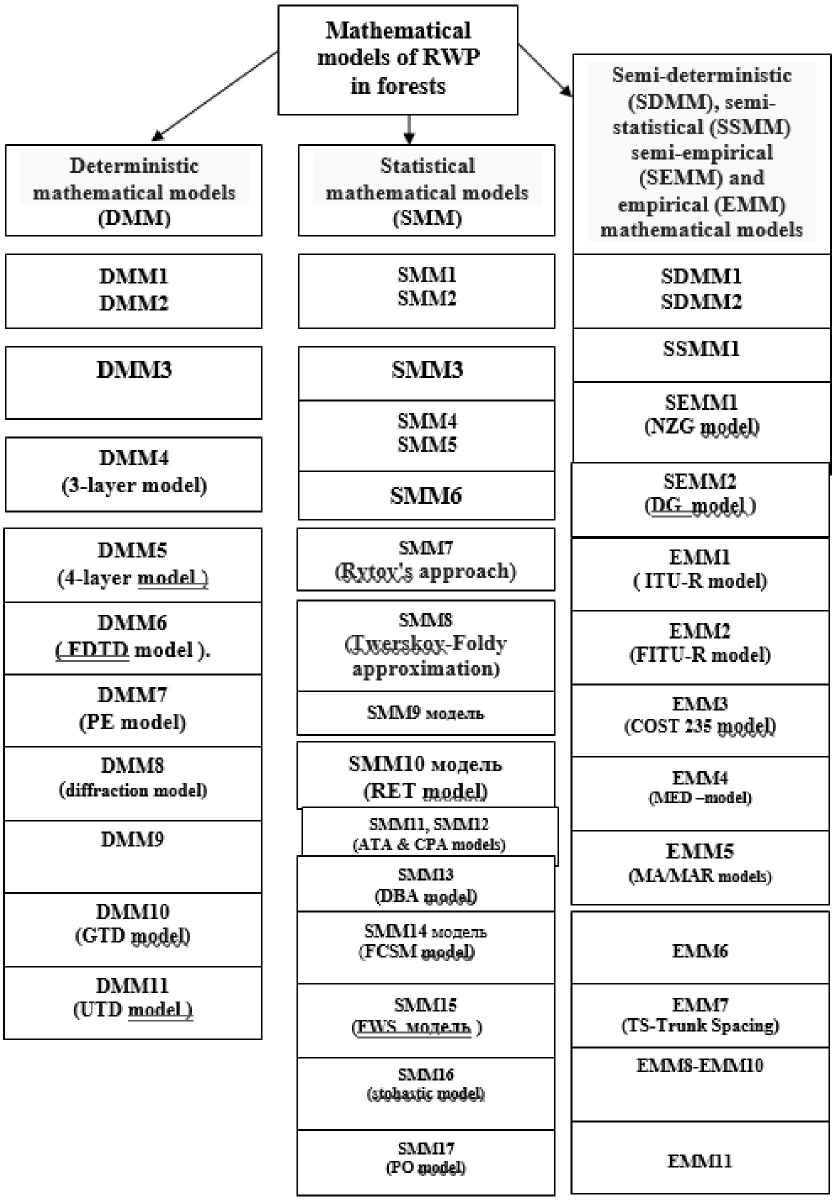


Fig. 3 – Mathematical models of radio wave propagation most often used in practice

Рис. 3 – Математические модели распространения радиоволн, наиболее часто используемые на практике

2. Brief description of the content of mathematical models

2.1. Deterministic mathematical models of radio wave propagation in forest environment

When constructing deterministic mathematical models (DMM – Determined Mathematical Models) of RWP in forest vegetation, Maxwell's equations are usually solved and the components of the electromagnetic field are determined under the conditions of monochromatic electromagnetic waves propagating in the forest, as in an inhomogeneous dielectric medium with losses. This makes it possible to evaluate the physical processes occurring during the propagation of radio waves and obtain approximate analytical expressions for the effective value of the attenuation coefficient or scattering area.

1. DMM1 model [1, 3] (deterministic mathematical model, which is based on the construction of an approximate mathematical model of end-to-end propagation of a vertically polarized monochromatic electromagnetic wave of the meter range in a forest area, representing a set of vertical weakly conducting cylinders of finite height, the influence of which on the resulting field at the receiving point comes down to the creation of secondary fields that interfere with the main field).

2. DMM2 model [4, 5] (a deterministic mathematical model, which is based on the assumption that the forest is a vertically oriented layered structure, while the wave equation is written for the averaged component of the electric field strength of a monochromatic vertically polarized electromagnetic wave (with end-to-end propagation of electromagnetic waves) and an expression is sought for the attenuation coefficient of EMW at a given operating wavelength).

3. DMM3 model [4, 5] (deterministic mathematical model, which is based on the assumption that the forest layer is a vertically oriented structure in space in the form of quasi-spherical trees (it is assumed that trees in spring and summer have a quasi-spherical shape) correctly located in space at the same time the wave equation is written for the averaged component of the electric field strength of a monochromatic vertically polarized electromagnetic wave (with end-to-end propagation of electromagnetic waves) and an expression is sought for the attenuation coefficient at a given operating wavelength).

4. DMM4 model [6–9] (a deterministic mathematical model, which is based on the assumption that the forest is a three-layer structure, while Maxwell's equations are solved for electromagnetic waves emitted by a dipole antenna located in the forest and propagating inside the forest in the direction of the receiving point, also located inside the forest (in this case, solutions to Maxwell's equations are sought using the dyadic method of the Green's function).

5. DMM5 model [10–14] (a deterministic mathematical model, which is based on the assumption that the forest is a four-layer structure, while Maxwell's equations are solved for electromagnetic waves emitted by a dipole antenna located in the forest and propagating inside the anisotropic forest in the direction of the receiving point, also located inside the forest (in this case, solutions to Maxwell's equations are sought using the dyadic method of the Green's function).

6. DMM6 model [15, 16] (a deterministic mathematical model using the well-known **FDTD – Finite Difference Time Domain method** – as a method for

numerically solving electrodynamics problems, based on non-standard discretization of Maxwell's equations in time and space).

7. DMM7 model [17–25] (a deterministic mathematical model that uses the **Parabolic Equation** (PE) Method) to simulate the propagation of electromagnetic waves in heterogeneous media, including vegetation).

8. DMM8 model [4, 23, 24] (deterministic mathematical model using the well-known Fresnel optical diffraction method on a wedge, Fig. 4).

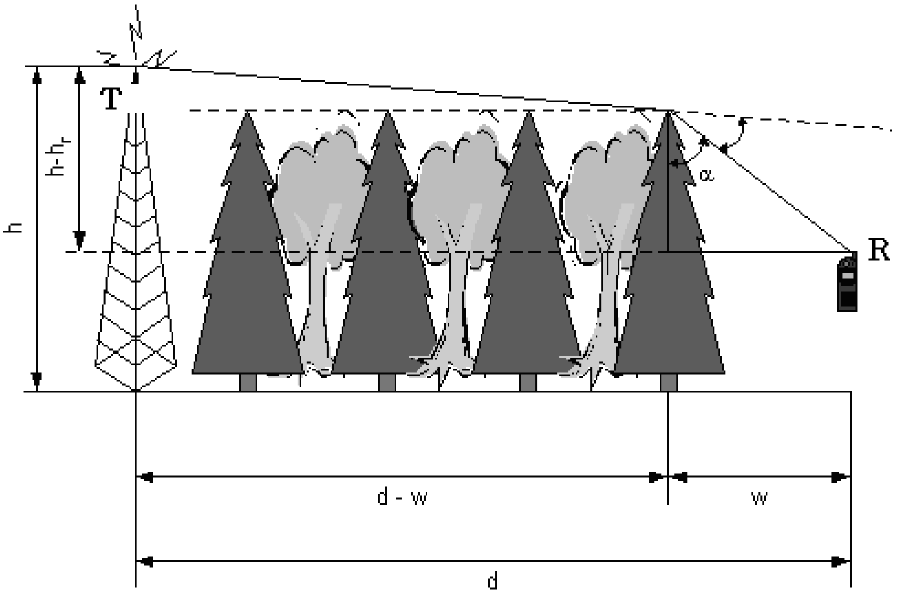


Fig. 4 – DMM8 model

Рис. 4 – Модель DMM8

9. DMM9 model [26, 27] (a deterministic mathematical model that uses the diffraction model of the RWP for a mixed path: from the transmitting base station to the receiving mobile station, taking into account the influence of two forests, Fig. 5).

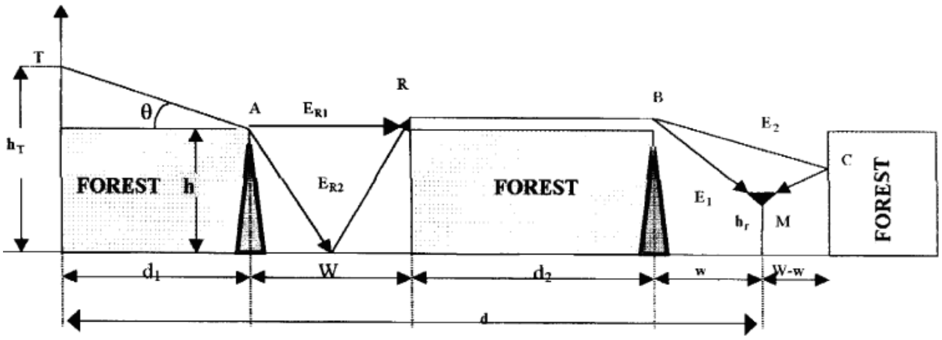


Fig. 5 – DMM9 model

Рис. 5 – Модель DMM9

10. DMM10 model [28–31] (deterministic mathematical diffraction model based on the GTD (**Geometrical Theory of Diffraction**) method – geometric theory of diffraction).

11. DMM11 model [32–34] (diffraction model based on the UTD (**Uniform Theory of Diffraction)** method – the unified theory of diffraction).

2.2. Statistical mathematical models of radio wave propagation in forest areas

In general, forests are heterogeneous environments with a random arrangement of plant elements of different shapes, sizes and parameters. Therefore, in the development of mathematical models of forests in recent years, various statistical approximations (statistical mathematical models – SMM – Statistical Mathematical Models) have been widely used.

1. SMM1 model [37] (Statistical mathematical model of radio wave scattering in forests for mobile communication systems (in the single scattering approximation)).

2. Statistical mathematical models of reflection and scattering of electromagnetic waves during radar sounding of the earth's surface):

SMM2 model [38] (Statistical mathematical model of a finely rough reflective surface).

SMM3 model [38] (Statistical mathematical model of a reflective surface with large-scale irregularities).

SMM4 model [38] (Statistical mathematical model of a reflective surface with complex roughness).

SMM5 model [38] (Statistical mathematical model of electromagnetic waves reflection from a set of multiple linear reflectors)

SMM6 model [38] (Statistical mathematical model of electromagnetic waves reflection from "multiple" reflectors).

3. SMM7 model [39, 40] (Statistical mathematical model of radio wave propagation in forests using the Rytov approximation).

4. SMM8 model [40] (Statistical mathematical model of radio wave propagation in forests using the Tversky-Foldy theory).

5. SMM9 model [41, 42] (Statistical mathematical models of the reflection of radio waves from forests during microwave radiometry of vegetation [continuum and discrete medium approximations]).

6. SMM10 model [43, 44] (Statistical mathematical model based on RET theory (The Radiative Energy Transfer Theory), in which the energy transfer equation is defined as a change in the intensity of a radio signal propagating through a statistically quasi-homogeneous medium filled with random small diffusers).

7. SMM11 model [45–49] (Statistical mathematical model of radio wave propagation in forests using ATA theory (Average T-matrix Approximation – approximation of the ensemble averaged T-matrix), which uses quasi-static approximation and material equations for inhomogeneous forest environment are averaged over an ensemble of scatterers).

8. SMM12 model [45–49] (Statistical mathematical model of radio wave propagation in forests using the CPA theory (Coherent Potential Approximation), which uses quasi-static approximation and introduces the assumption that the difference in the

electromagnetic field in an inhomogeneous medium is negligible and averaged EMF over ensembles).

9. SMM13 model [74–79] (Statistical mathematical model of radio wave propagation in forests using the DBA theory (Distorted Born Approximation (DBA)). The DBA model is based on wave theory (approximation of solutions to Maxwell's equations) and considers the case the incidence of electromagnetic waves with a relatively long wavelength on a forest and their coherent backscattering (taken into account by the surface-volume interaction terms [75]). This model does not take into account the interaction between various plant elements during multiple scattering of electromagnetic waves.

10. SMM14 model [51, 54–58] (Statistical mathematical model of radio wave propagation in forests based on FCSM (Fractal-based Coherent Scattering Model) model that uses fractal geometry to describe the real structure of trees, modeling the interaction of electromagnetic waves with vegetation, using DBA, which determines the coherent component of the electromagnetic field, its attenuation and phase change under the influence of forest vegetation, and the Monte Carlo method for determining the statistical distribution of electromagnetic fields with a large number of implementations.

11. SMM15 model [50, 51, 64] (Statistical mathematical model of radio wave propagation in forests using the theory of FWS (Full Wave Solutions) or Full Wave Analysis – full wave solutions or full wave analysis), in which, for example, according to [51], based on the Monte Carlo method, the effects of multiple scattering from a large number of forest scatterers with subsequent interference at the point of receiving scattered electromagnetic waves and a lateral electromagnetic wave are simulated.

12. SMM16 model [52–54] (Statistical mathematical models of radio wave propagation in forests using 3D-Stochastic model of wave scattering in mixed areas with vegetation – 3D-stochastic model of wave scattering on a mixed path with vegetation, in which, for example [52], a forest model is used for a mixed route in a rural area, representing buildings and trees, while the buildings are represented as blocks, and trees are in the form of cylinders, and the entire propagation medium is assumed to be a medium with randomly oriented roughnesses on the earth's surface, while this model allows us to give approximate estimates of the total intensity of the electromagnetic field at the receiving point, scattered on inhomogeneities of the environment such as trees and buildings.

13. SDMM17 model [33, 36, 59, 60] (Statistical mathematical model based on the Physical Optics method, which is based on the Fresnel-Kirchhoff theory. As shown in [59], for mobile communication systems, in addition to calculating coherent component of the EMF at the point of reception, for a more accurate accounting of permissible losses in forest vegetation, include an incoherent component).

14. SDMM18 model [61] (Statistical mathematical model based on the MoM (Method of Moment) or BEM (Boundary Element Method). The MoM method uses numerical solutions of integral equations in boundary form).

2.3. Semi-deterministic mathematical models of radio wave propagation in forest areas

When constructing semi-deterministic mathematical models SDMM (Semi-Determined Mathematics Model) using RWP, which describe the end-to-end propagation of radio waves (in the range from 100 MHz to 100 GHz) in forest vegetation, the concept of electromagnetic energy losses in the path (path loss) or losses during transmission loss in the form:

$$L_{rt} = 10 \cdot \lg \frac{P_r}{P_t} < 0$$

or

$$L_{tr} = 10 \cdot \lg \frac{P_t}{P_r} > 0,$$

where, respectively, Pt is the radiation power of the transmitter antenna and Pr is the signal power at the receiver input (very often, assuming that the efficiency of the transmitter, feeder path and antenna is close to unity, the radiation power of the Pt antenna is equal to the transmitter power).

The main semi-deterministic mathematical models that describe the end-to-end propagation of radio waves in forest vegetation include (Fig. 2):

1. SDMM1 model is a semi-deterministic mathematical model (similar to the well-known exponential model (EXD – EXponential Model) [1.59]), based on a single-beam model of RWP in free space plus energy losses in forest vegetation $\boldsymbol{L=L_0+\alpha_{mF}\cdot l_F}$ [dB], with In this case, the effective value of the linear attenuation coefficient in a forest $\boldsymbol{\alpha_{mF}}$ **[dB/m]<0** for the semi-deterministic model is assumed to be constant for the corresponding operating frequency and type of forest vegetation.

2. SDMM2 model - a semi-deterministic mathematical model based on a two-beam model of RWP in a forest plus energy losses in forest vegetation for direct and reflected rays from the forest floor (at a constant effective value of the linear attenuation coefficient and the reflection coefficient from the forest floor for the corresponding operating frequency and type of forest vegetation).

2.4. Semi-statistical mathematical models of radio wave propagation in forests

Model **SSMM1 (Semi-Statistical Mathematics Model)** [5, 62] – semi-statistical mathematical model based on the assumption that at short distances between radio stations the coherent component predominates and power losses in the path are determined by the model **SDMM1,** and at large distances, the incoherent component of the electromagnetic field predominates, and to take it into account, expansion terms are introduced into the functional of power losses in the path, which determine additional losses in forest vegetation, while they are, in turn, functions of the operating wavelength, the average height of trees, the elevation heights of the transmitting and receiving antennas, etc.

2.5. Semi-empirical mathematical models for end-to-end propagation of radio waves in forests

When constructing semi-empirical mathematical models SEMM (Semi-Empirical Mathematics Model), describing end-to-end propagation of radio waves (in the range from 100 MHz to 40 MHz) in forest vegetation, as well as for deterministic models, the concept of electromagnetic energy losses in the path is usually or transmission loss obtained from experimental data.

The main semi-empirical mathematical models that describe the end-to-end propagation of radio waves in forest vegetation include (Fig. 2):

1) SEMM1 model [63,64] - a semi-empirical mathematical model based on the NZG model (**Non Zero Gradient Model)**, in which (in the range of millimeter waves) energy losses in the path are considered due to changes in the linear attenuation coefficient α_{mF} in forest area from the initial α_{mF1} to the final α_{mF2} values, i.e. in the model assumes the existence of a gradient $\partial\alpha_{mF}/\partial l \neq 0$ in heterogeneous forest vegetation (with the effective value of the initial and final values of the linear attenuation coefficient found from experiments).

2) SEMM2 model [64] is a semi-empirical mathematical model based on the DG model (**Dual Gradient Model**), into which a number of parameters are introduced in the millimeter wave range that correct the NZG model, i.e. the existence of a gradient $\partial\alpha_{mF}/\partial l \neq 0$ in heterogeneous forest vegetation is also allowed (with the effective values of the initial and final values of the linear attenuation coefficient and correction parameters found from experiments).

2.6. Empirical mathematical models of radio wave propagation in forest areas

As the name suggests, empirical mathematical models **EMM (Empirical Mathematics Model**) of RWP in forests are based on the results of experimental studies of losses during the propagation of electromagnetic energy in paths passing through forest vegetation, they take into account the statistical characteristics of received signals, while requirements for the influence of geometry elements of the forest are weakened, and the analytical expressions themselves are significantly simplified. According to the **ITU-R** Recommendations [67], the following empirical mathematical models (used in the range from 200 MHz to 95 GHz) have found the greatest application in practice.

1. EMM1 model [1], based on the **ITU-R** empirical mathematical model, in which path losses are defined as a function:

$$L = L(f,r) = a \cdot \left(\frac{f}{f_0}\right)^b \cdot \left(\frac{r}{r_0}\right)^c \text{, dB,} \tag{1}$$

where $-f$ is the operating frequency, f_0 = 1 GHz is the normalizing frequency, *r* is the distance between the transmitting and receiving antennas, (at < 400 m), r_0 = 1 m is the normalizing distance, coefficients a and power values *b* and *c* are selected during experiments, and for the ITU-R model they are equal**:** ***a = 0.2*** dB, ***b = 0.3*** and ***c = 0.6***.

2. EMM2 model [64], based on the empirical mathematical model **FITU-R (Fitted ITU-R – refined ITU-R)**, in which path losses are also defined as a function: (6.1) $L = L(f,r)$ similar to the ITU-R model, but in the frequency range from 11.2 to 20 GHz (with a distance between the transmitting and receiving radio stations d < 120 m) with excellent coefficients and power-law values outside the foliage (***a = 0.37*** dB, ***b = 0.18***, ***c = 0.59***) and inside the foliage (***a = 0.39*** dB, ***b = 0.39, c = 0.25***) of forest plants.

3. EMM3 model [64], based on the empirical mathematical model **COST235**, in which path losses are also defined as a function: (6.1) $L = L(f, r)$ similar to the ITU-R model (for the frequency range from 9.6 GHz to 57.6 GHz), but with different coefficients and power values outside the foliage ***(a = 26.6*** dB***, b = –0.2***, ***c = 0.5***) and inside the foliage (***a = 15.6*** dB, ***b = –0.009***, ***c = 0.26***) of forest plants.

4. EMM4 model [64,65], based on the empirical mathematical **MED (Modified Exponential Model**) model, in which path losses are also defined as a function: (6.1) similar to the ITU-R model, but with different coefficients and power values in the range of distances between the transmitting and receiving radio stations: at 0 < r < 14 m (***a = 0.45*** dB, ***b = 0.284, c = 1***), and at – **14 m. < r < 400** m. (***a = 1.33*** dB, ***b = 0.284, c = 0.588***) at normalizing frequency f_0= 1GHz.

5. EMM5 model [66], based on the empirical mathematical model **ITU-R P.833-2** (this model is called the **MA (Maximum Attenuation) MAR (Maximum Attenuation Rate**) model).

6. EMM6 model [42], based on an empirical mathematical model that determines the frequency dependence (in the frequency range from 100 to 1000 MHz) of the linear attenuation coefficient.

7. EMM7 model [67], based on the well-known empirical mathematical model **TS (Trunk Spacing -** channel distance) which is a modification of the MED model, which takes into account the density of forest vegetation.

8. The EMM8 model [70] is based on an empirical model used to calculate the amount of power loss due to the shadow effect for mobile communication systems in the UHF range.

9. EMM9 model [71] is based on an empirical model used to calculate the amount of power loss for the forest canopy for space mobile communication systems in the UHF range (870 MHz) and in the frequency ranges – L (1.6 GHz) and K (19.6 GHz).

10. The EMM10 model [72] is based on an empirical model used to calculate the amount of power loss for the forest canopy for space mobile communication systems in the frequency bands – L (1.6 GHz) and K (19.6 GHz).

11. EMM11 model [73] is based on an empirical model used to calculate the operating attenuation of electromagnetic waves in forests in the L(1.6 GHz) frequency range.

Conclusions

1. The classification scheme in Fig. 3 shows the main mathematical models that are most often used in approximate estimates of the effective complex dielectric constant of scaffolding, effective operating and linear attenuation coefficients, radio path losses, effective differential absorption and scattering cross sections, as well as specific effective area backscattering by forest vegetation during the propagation of radio waves of various ranges in forests.

2. The classifications of mathematical models of RRR in vegetation given in [34, 69, 68] (respectively, Fig. 6–8) are special cases of the classification scheme Fig. 3 proposed in [5].

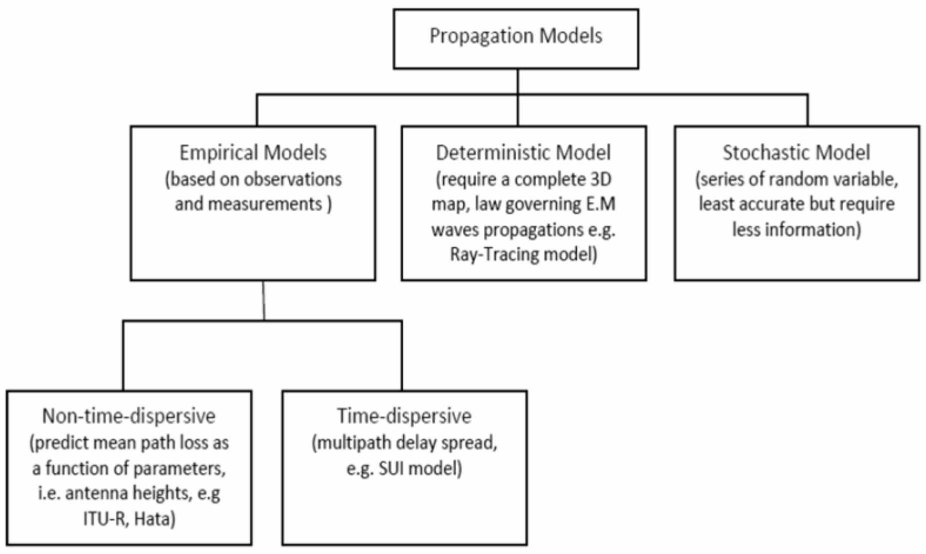


Fig. 6 – Generic vegetation model development from [69]

Рис. 6 – Разработка типовой модели растительности [69]

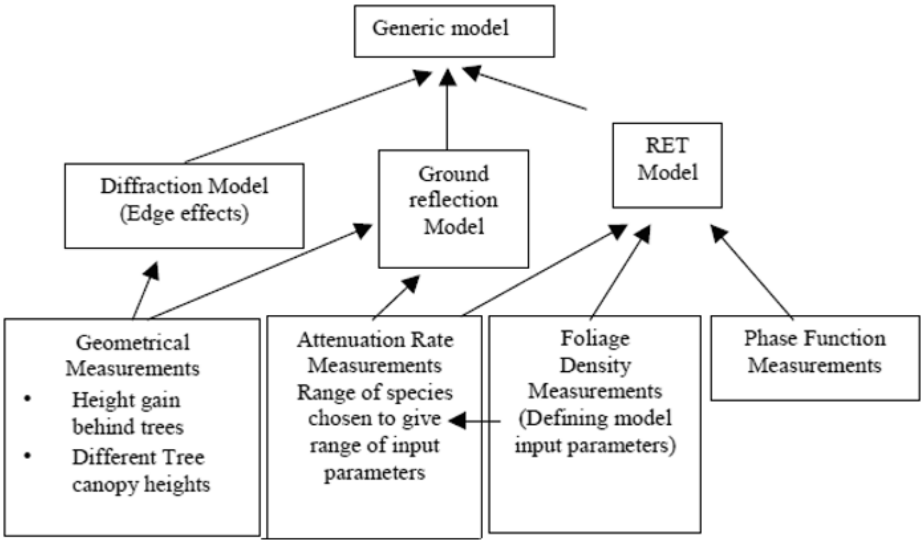


Fig. 7 – Generic vegetation model development from [34]

Рис. 7 – Разработка типовой модели растительности [34]

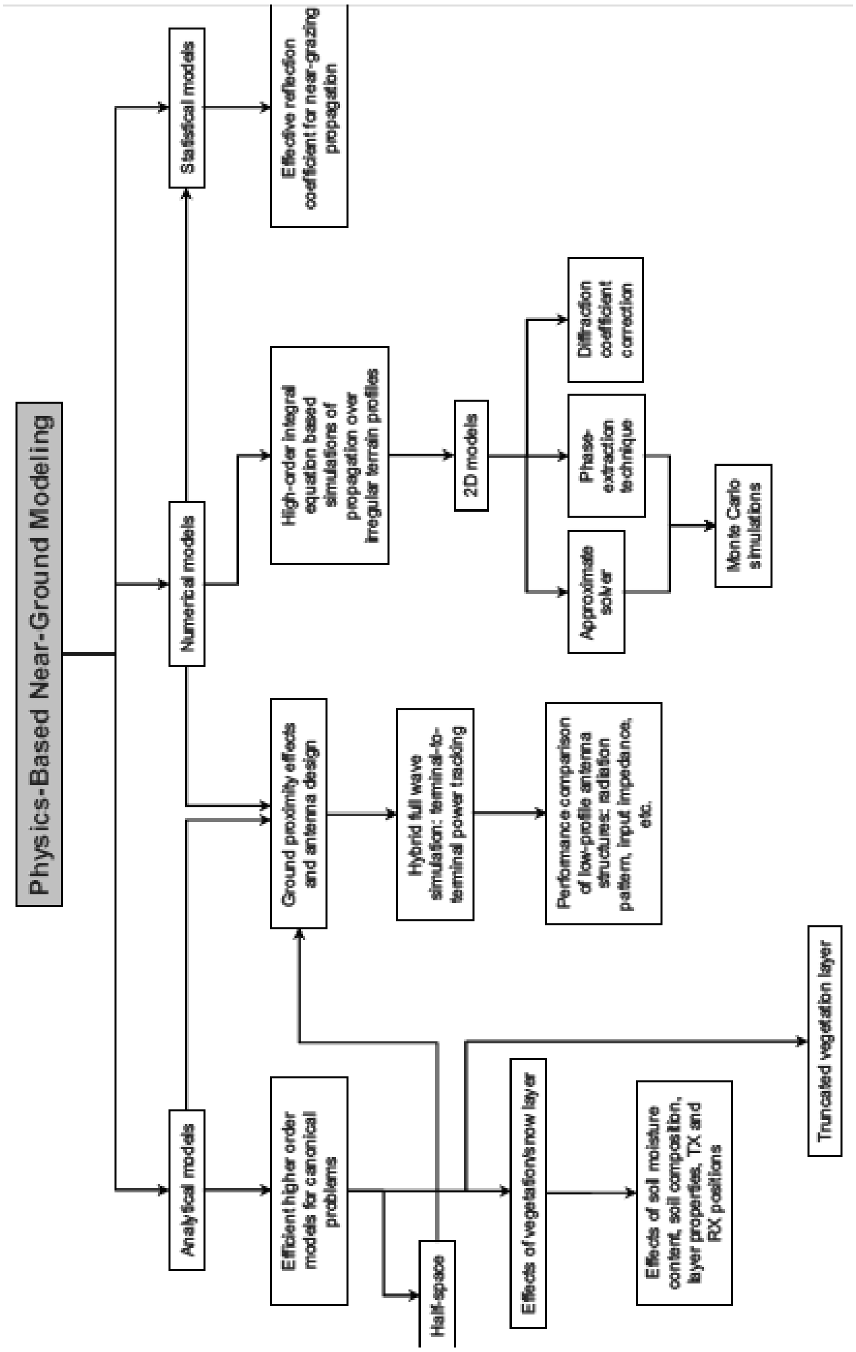


Fig. 8 – Generic vegetation model development from [68]

Рис. 8 – Разработка типовой модели растительности [68]

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МАТЕМАТИЧЕСКИЕ МОДЕЛИ РАСПРОСТРАНЕНИЯ РАДИОВОЛН В ГЕТЕРОГЕННЫХ СРЕДАХ ДЛЯ БЕСПРОВОДНЫХ СЕТЕЙ

ОБЗОР

Часть 2. МАТЕМАТИЧЕСКИЕ МОДЕЛИ РАСПРОСТРАНЕНИЯ РАДИОВОЛН В ЛЕСАХ

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В статье предложена классификация математических моделей распространения радиоволн (РРВ) в лесах в широком диапазоне частот, которая обобщает результаты работ автора и многочисленных исследователей по эффективной комплексной диэлектрической проницаемости лесов, эффективным рабочим и линейным коэффициентам затухания, потерям на трассе радиоизлучения, эффективным дифференциальным сечениям поглощения и рассеяния, а также удельной эффективной площади обратного рассеяния лесной растительностью.

Достаточно сложная проблема влияния лесов на распространение радиоволн различных диапазонов остается чрезвычайно актуальной и в наши дни в связи с широким распространением систем мобильной и космической радиосвязи, а также решением задач радиомониторинга земной поверхности и радиоинтроскопии объектов в лесах.

Ключевые слова: распространение радиоволн в лесах, математические модели, эффективная комплексная диэлектрическая проницаемость лесов, эффективный коэффициент затухания, потери на трассе радиоизлучения, эффективные дифференциальные сечения поглощения и рассеивания, эффективные площади обратного рассеяния лесной растительности.

DOI: 10.17212/1727-2769-2024-4-26-47

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Статья поступила 18 октября 2024 г.
Received October 16, 2024

To Reference:

Popov V.I. Matematicheskie modeli rasprostraneniya radiovoln v geterogennykh sredakh dlya besprovodnykh setei. Obzor. Chast' 2. Matematicheskie modeli rasprostraneniya radiovoln v lesakh [Mathematical models of radio wave propagation in heterogeneous environments for wireless networks. Review. Part 2. Mathematical models of radio wave propagation in forests]. *Doklady Akademii nauk vysshei shkoly Rossiiskoi Federatsii = Proceedings of the Russian higher school Academy of sciences*, 2024, no. 4 (65), pp. 26–47. DOI: 10.17212/1727-2769-2024-4-26-47.