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

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The issue of ensuring uniform radio coverage of service areas and the associated reliability of mobile radio systems in the 3G and 4G standards requires a lot of attention upon designing cellular mobile networks. One of the main tasks at the first stage of designing is the mathematical modeling of radio wave propagation under the influence of the environment.

This work provides classification of mathematical models of radio wave propagation in cellular mobile communication systems, the algorithm of calculating radio signal strength at the receiving point depending on the distance between the mobile and the base stations, as well as factors and conditions affecting radio wave propagation are specified.

Keywords: mathematical models, radio wave propagation, heterogeneous environment, wireless networks, cellular networks of mobile communication (CNMC).

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Introduction

Currently problems of radio wave propagation (RWP) in **cellular networks of mobile communications (CNMC)** are dealt with in many works [1–16]. Various methods of classification of mathematical models of RWP in the decimeter and centimeter wave band applied to CNMC are considered in them.

Depending on environmental influences, both deterministic and statistical models can be used for modeling RWP; often semi-deterministic, semi- empirical and empirical models are applied.

Deterministic mathematical models are based on the use of the physical laws of RWP. The calculation is based on single-ray, double-ray or multi-beam models of RWP. They take account of influencing factors of obstacles in the path of radio wave propagation and local conditions in the radio channel (Fig. 1): attenuation in free space, reflection from objects, diffraction due to obstacles, absorption, refraction and cross-polarization of electromagnetic waves (EMW).

Semi-empirical and empirical models are based on path loss formulas, including a number of empirical correction factors picked up by experiments. The accuracy of calculated results in such a case depends on the preciseness of the correction factor values and restrictions having significance within the chosen frequency range and for the specific environmental conditions only.

It is important to point out that results of experimental research for the real environmental conditions are often used to determine a path loss of EMW propagating along the terrain. Mathematical models of RWP in the heterogeneous environment, for example, have their own laws of attenuation for different surroundings and allow calculating median values of the received power depending on the distance to the receiver (consid-

The study was done in an initiative way.

ering ITU-R, CEPT recommendations). Combined methods represent a blend of deterministic and statistical models. RWP models based on these methods may be applied for more accurate measurements in specific situations.

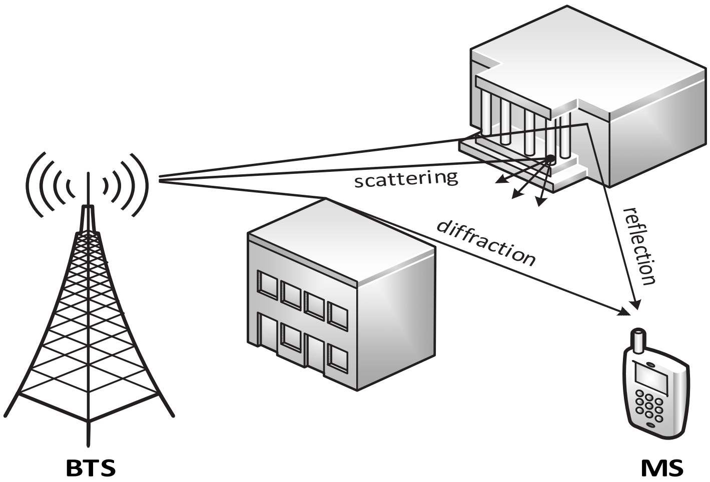


Fig. 1 – Impact of Obstacles on Radio Wave Propagation

Рис. 1 – Влияние препятствий на распространение радиоволн

Nowadays the majority of CNMC operators are using mobile network development and monitoring software products that are based on models listed above. Sadly, imperfections of digitized maps, approximation and averaging of path loss values lead to relatively large calculation and planning errors. Improvements in model simulation accuracy have been made possible lately by introducing geographic information systems (GIS), which use high-precision maps and geographical databases.

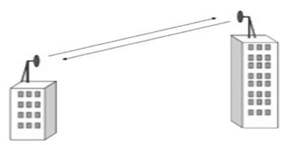
1. Classification of RWP Models in CNMC

Let's consider mathematical models of radio wave propagation in CNMC assuming standard conditions and propagation regimes are in place. Most characteristic regimes of wave propagation between the base transceiver station (BTS) and the mobile station (MS) in the real world conditions are generalized in Table 1 and serve as a basis for further mathematical model classification. The following abbreviations are used in the Table: R is reflection, EMW is an electromagnetic wave, NLOS is line-of-sight; NLOS is non-line-of-sight; D/EMW is diffraction of the electromagnetic wave, A/EMW is attenuation of the electromagnetic wave.

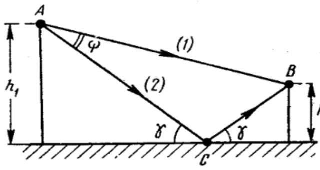
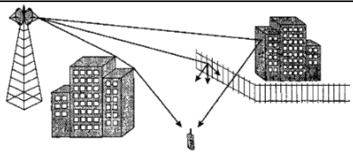
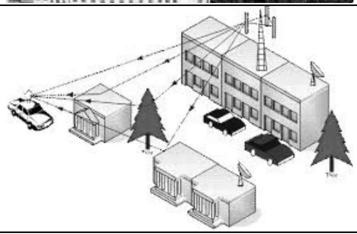
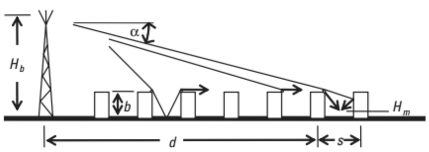
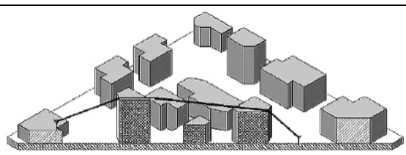
Table 1 / Таблица 1

Distinctive RWP Regimes in CNMC

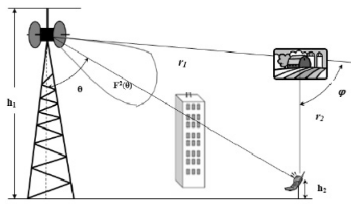
Отличительные режимы RWP в CNMC

No.	Conditions	RWP model, regime, cell type
1		Free space LOS macrocell

Continuation of the Table 1 / Продолжение табл. 1

No.	Conditions	RWP model, regime, cell type
2		A two-ray model LOS+R/EMW macrocell
3		A multiple ray model The Log-distance path loss model LOS+NLOS+D/EMW+ΣR$_i$/EMW$_i$ macrocell, microcell
4		A multiple ray model for urban conditions Lee model LOS+NLOS+ΣR$_i$/EMW$_i$ macrocell
5		A multiple ray model for urban conditions The Okumura model LOS+NLOS+ΣR$_i$/EMW$_i$ microcell
6		A multiple ray model for urban conditions TheOkumura-Hata model LOS+NLOS+ΣR$_i$/EMW$_i$ microcell, picocell
7		A multiple ray model for urban conditions TheCOST 231-Hata model LOS+NLOS+ΣR$_i$/EMW$_i$ microcell, picocell
8		Multiple ray model for urban conditions The Walfish-Ikegami model LOS+NLOS+ΣD$_i$/EMW$_i$ macrocell, microcell, picocell
9		Multiple ray model for urban conditions The Hata-Davidson model LOS+NLOS+ΣR$_i$/EMW$_i$ microcell, picocell

The End Table 1 / Окончание табл. 1

No.	Conditions	RWP model, regime, cell type
10		Radio wave propagation through the forest A semi-deterministic model LOS_1+A/LOS_F+Lateral/EMW+LOS_2 microcell, picocell
11		Radio wave propagation in free space with the reflection from the forest The deterministic model NLOS+$\Sigma R_i/EMW_i$ microcell, picocell

This paper, as it follows from table 1, examines 11 path loss mathematical models, which represent the approximation of the received signal strength in relationship to the distance between BTS and MS, taking into account environmental conditions, as well as transmitter and receiver antennas parameters. The determining of received signal strength for an array of distances allows finding the maximum radius of BTS cell coverage area $R_{\max}$ (fig. 2) for a downlink transmission when P_r is equal to the MS receiver sensitivity $P_{r\min}$, which is one of the main tasks in mobile cellular network area coverage planning.

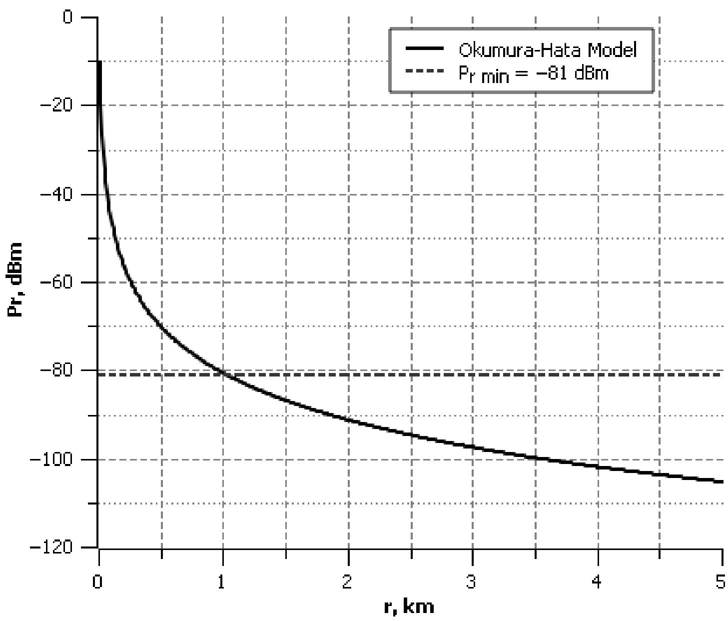


Fig. 2 – Finding Cell Tower Maximum Coverage Radius Using the Okumura-Hata Model ($P_{r\,\min}$ = −81 dBm, $R_{\max}$ = 1.021 km) [2]

Рис. 2 – Определение максимального радиуса покрытия вышки сотовой связи с использованием модели Окумура–Хата ($P_{r\,\min}$ = −81 дБм, $R_{\max}$ = 1,021 км) [2]

2. RWP Models in CNMC

Mathematical models, which determine the power of the harmonic electromagnetic wave (EMW) aired by the BTS antenna and received by MS, are shown in table 2 with the following set of parameters: P_t *is a* BTS transmitter power, dBm; f is an operational frequency, MHz; λ is an operational wavelength, m; G_t, G_r is BTS, MS antenna gain; h_t, h_r –BTS, MS antenna height, m; r is the distance between the BTS transmitter and the MS receiver, km; f_0 is a norming frequency, f_0 = 1 MHz; λ_0 is a norming wavelength, λ_0 = 1 m; h_0 is a norming height, h_0 = 1 m; r_0 is a norming distance between BTS and MS, r_0 = 1 km.

Table 2 / Таблица 2

RWP Mathematical Models

Математические модели RWP

No.	Model	Formulae
1	Le-of-sight LOS	in $$P_{r\,\text{LOS}} = P_t + 10\lg G_t + 10\lg G_t - 20\lg(4\pi) + +20\lg\left(\frac{\lambda}{\lambda_0}\right) - 20\lg\left(\frac{r\cdot 10^3}{r_0}\right) < 0,$$ where $P_{r\,\text{LOS}}$ is a received signal strength in the free space (LOS) environment, dBm;
2	The two-ray model LOS1 +R2/EMW (TR model)	$$P_r = P_{r\,\text{LOS}} + 10\lg\psi\ ;$$ $$\psi \approx 1 + R^2 + 2R\cdot\cos\left(\varphi + 4\pi\cdot\frac{h_t\cdot h_r}{\lambda\cdot r\cdot 10^3}\right),\ 0.8r > r > 18\frac{h_t h_r}{\lambda}\ ;$$ $$P_r \approx P_t + 10\lg G_t + 10\lg G_r + 20\lg\left(\frac{h_t}{h_0}\right) + 20\lg\left(\frac{h_r}{h_0}\right) - -40\lg\left(\frac{r\cdot 10^3}{r_0}\right),$$ where P_r is a median power level at the receiving point for point-to-point RWP, dBm; ψ is a value determined as a function of the terrain parameters, dBm; R is a coefficient of reflection, $R \le 1$; φ is a reflection angle, usually φ = 3.142 rad;
3	The Log-distance path loss model LOS+NLOS+ D/EMW+ +ΣR_i/ EMW$_i$ (TR model)	$$P_r = P_{r\,\text{LOS}} - 10n\lg\left(\frac{r}{r_0}\right) - (\pm X_g)\ ,$$ where n is an attenuation exponent, $n = 2$ for the free space (LOS), $n = 2.7 - 3.5$ for the suburban area (LOS/NLOS), and $n = 3 - 5$ for the urban area (NLOS); X_g is a random value for normal (Gaussian) distribution with a zero mean, representing a signal attenuation condition, which was caused by its fading (in case of no fading $X_g = 0$);
4	The Lee model LOS+ΣR_i/EMW$_i$	$$P_r = P_{r0} - 10\gamma\cdot\lg\left(\frac{r}{r_{n0}}\right) - 10n\cdot\lg\left(\frac{f}{f_{n0}}\right) + 10\lg(\alpha_0)\ ,$$ $$\alpha_0 = \left(\frac{h_t}{h_{tn0}}\right)^2\left(\frac{h_r}{h_{rn0}}\right)^v\left(\frac{P_{t\,mW}\cdot 10^3}{P_{tn0}}\right)\frac{G_t G_r}{4}\ ,$$

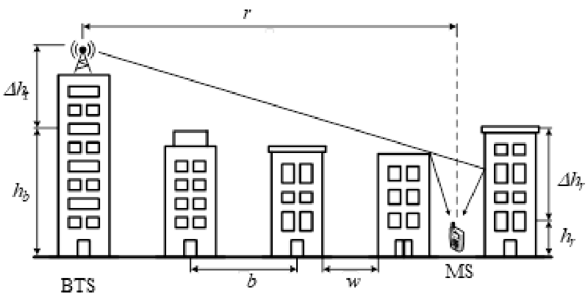
Continuation of the Table 2 / Продолжение табл. 2

No.	Model	Formulae
		$v = \begin{cases} 2, & if\ h_r > 10\,m; \\ 1, & if\ h_r < 3\,m, \end{cases}$ where α_0 is an adjustment factor; $P_{t\,mW}$ –is a BTS transmitter power, mW; P_{r0} is power at the r_{n0} point, dBm, $P_{r0} = -45$ dBm for free space, $P_{r0} = -49$ dBm for Rural area; $P_{r0} = -61.7$ dBm for the suburban area, $P_{r0} = -70$ dBm for the urban area, for the metropolitan center, γ is a path loss correction due to distance, $\gamma = 2$ for thefree space, $\gamma = 4.35$ for the rural area, $\gamma = 3.84$ for the suburban area, $\gamma = 3.68$ for urban area, $\gamma = 3.05$ for metropolitan area; n is a frequency correction factor, recommended values are $2 \le n \le 3$; $n = 2$ for the open, rural, suburban area, $f < 450$ MHz; $n = 2$ for the urban, metropolitan area, $f > 450$ MHz; v is a MS antenna height correction factor; f_{n0} is a nominal frequency, $f_{n0} = 900$ MHz; P_{tn0} isa nominal BTS transmitter power, $P_{tn0} = 10$ W; h_{tn0} is a nominal BTS antenna height, $h_{tn0} = 30.48\,m$; h_{rn0} is a nominal MS antenna height, $h_{rn0} = 3$ m; r_{n0} is a nominal distance between BTS and MS, $r_{n0} = 1.6$ km.
5	Okumura model LOS+ΣR_i/EMW$_i$	Limitations: frequency range f = 150–1920 MHz; BTS antenna height h_t = 30–1000 m; MS antenna height h_r = 1–10 m; distance between BTS and MS r = 1–100 km; $L_{rt} = L_{rt\,LOS} - A_{mu}(f,r) + H(h_t) + H(h_r) + G_{area}$, $P_r = P_{r\,LOS} - A_{mu}(f,r) + H(h_t) + H(h_r) + G_{area}$, $H(h_r) = \begin{cases} 10\lg\left(\dfrac{h_r}{h_{rn0}}\right), & if\ h_r \le 3\,m; \\ 20\lg\left(\dfrac{h_r}{h_{rn0}}\right), & if\ 3 < h_r < 10\,m. \end{cases}$ Here L_{rt} is path attenuation, dB; $A_{mu}(f,r)$ is median attenuation relative to free space (determined from the fig. 3), dB; $H(h_t)$ is a BTS antenna gain factor, dB; $H(h_r)$ is a MS antenna gain factor, dB; h_{tn0} is a nominal BTS antenna height, $h_{tn0} = 200$ m; h_{rn0} is a nominal MS antenna height, $h_{rn0} = 3$ m; G_{area} is s gain correction factor depending on the environment (see Fig. 4), dB.
	The Okumura-Hata model LOS+ΣR_i/EMW$_i$	Limitations: frequency range f = 150–1500 MHz; BTS antenna height h_t = 30–200 m; MS antenna height h_r = 1–10 m; distance between BTS and MS r = 1–20 km; $P_{r\,Hata} = P_t - 69.55 - 26.16\lg\left(\dfrac{f}{f_0}\right) -$

Continuation of the Table 2 / Продолжение табл. 2

No.	Model	Formulae
6		$-\left(44.9-6.55\lg\left(\frac{h_t}{h_0}\right)\right)\lg\left(\frac{r}{r_0}\right)+$ $+13.82\lg\left(\frac{h_t}{h_0}\right)+a(f,h_r)+K(f);$ $a(f,h_r)=\begin{cases}\left(1.1\lg\left(\frac{f}{f_0}\right)-0.7\right)\cdot h_r-\left(1.56\lg\left(\frac{f}{f_0}\right)-0.8\right) \text{ for open, suburban, urban area,}\\ 8.29\left[\lg\left(1.54\frac{h_r}{h_{r0}}\right)\right]^2-1.1 \text{ for metropolitan area, } f<300\,\text{MHz},\\ 3.2\left[\lg\left(11.75\frac{h_r}{h_{r0}}\right)\right]^2-4.97 \text{ for metropolitan area, } f\geq 300\,\text{MHz};\end{cases}$ $K(f)=\begin{cases}4.78\left[\lg\left(\frac{f}{f_0}\right)\right]^2-18.33\lg\left(\frac{f}{f_0}\right)+40.94 \text{ for open area,}\\ 2\left[\lg\left(\frac{f}{28}\right)\right]^2+5.4 \text{ for suburban area,}\\ 0 \text{ for urban, metropolitan area;}\end{cases}$ where $a(f,h_r)$ is a correction factor for MS antenna height, dB; $K(f)$ is a correction factor that depends upon the environment, dB.
7	The COST 231-Hata model LOS+ΣR_i/EMW$_i$	Limitations: frequency range f = 150–2000 MHz; BTS antenna height h_t = 30–200 m; MS antenna height h_r = 1–10 m; distance between BTS and MS r = 1–20 km; $P_r=P_t-A-B\lg\left(\frac{f}{f_0}\right)+13.82\lg\left(\frac{h_t}{h_0}\right)+a(f,h_r)-$ $-\left[44.9-6.55\lg\left(\frac{h_t}{h_0}\right)\right]\lg\left(\frac{r}{r_0}\right)-C;$ $a(f,h_r)=\left(1.1\lg\left(\frac{f}{f_0}\right)-0.7\right)h_r-\left(1.56\lg\left(\frac{f}{f_0}\right)-0.8\right),$ where A is an attenuation component, dB ($A=69.55$ dB for $150\leq f\leq 1500$ MHz, $A=46.33$ dB for $1500\leq f\leq$ ≤ 2000 MHz); B is a frequency correction factor ($B=26.16$ for $150\leq f\leq 1500$ MHz, $B=33.9$ for $1500\leq f\leq 2000$ MHz); $a(f,h_r)$ is a correction factor for the MS antenna height, dB; C is an attenuation correction factor, dB. It depends on the environment ($C=0$ for open, suburban and urban area, $C=3$ for Metropolitan area), dB.

Continuation of the Table 2 / Продолжение табл. 2

<table>
<tr><th>No.</th><th>Model</th><th>Formulae</th></tr>
<tr><td>8</td><td>The Walfisch-Ikegami model
LOS/NLOS+ ΣD_i/EMW$_i$</td><td>Limitations: frequency range f = 800–2000 MHz; BTS antenna height h_t = 4–50 m; MS antenna height h_r = 1–3 m; distance between BTS and MS r = 0.02–5 km.


$$L_{rt} = \begin{cases} L_0 + L_{rts} + L_{mds}, & \text{if } L_{rts} + L_{mds} \le 0, \\ L_0, & \text{if } L_{rts} + L_{mds} > 0; \end{cases};$$
$$L_0 = -32.45 - 20\lg\left(\frac{r}{r_0}\right) - 20\lg\left(\frac{f}{f_0}\right);$$
$$L_{rts} = 16.9 + 10\lg\left(\frac{w}{w_0}\right) - 10\lg\left(\frac{f}{f_0}\right) - 20\lg\left(\frac{\Delta h_r}{h_0}\right) - L_{ori};$$
$$L_{ori} = \begin{cases} -10 + 0354\varphi, & \text{if } 0 \le \varphi < 35°, \\ 2.5 + 0.075(\varphi - 35), & \text{if } 35° \le \varphi < 55°, \\ 4 - 0.114(\varphi - 35), & \text{if } 55° \le \varphi < 90°; \end{cases}$$
$$L_{mds} = -L_{bsh} - k_a - k_d \lg\left(\frac{r}{r_0}\right) - k_f \lg\left(\frac{f}{f_0}\right) + 9\lg\left(\frac{b}{b_0}\right);$$
$$L_{bsh} = \begin{cases} -18\lg(1 + \Delta h_t), & \text{if } \Delta h_t > 0, \\ 0, & \text{if } \Delta h_t \le 0; \end{cases}$$
$$k_a = \begin{cases} 54, & \text{if } \Delta h_t > 0, \\ 54 - 0.8\Delta h_t, & \text{if } \Delta h_t \le 0 \wedge r \ge 0.5, \\ 54 - 1.6r \cdot \Delta h_t, & \text{if } \Delta h_t \le 0 \wedge r \ge 0.5; \end{cases}$$
$$k_d = \begin{cases} 18, & \text{if } \Delta h_t > 0, \\ 18 - 15\frac{\Delta h}{h_b}, & \text{if } \Delta h_t \le 0; \end{cases}$$
$$k_f = \begin{cases} -4 + 0.7\left(\frac{f}{925} - 1\right) & \text{for suburban, urban area,} \\ -4 + 1.5\left(\frac{f}{925} - 1\right) & \text{for metropolitan area;} \end{cases}$$
</td></tr>
</table>

Continuation of the Table 2 / Продолжение табл. 2

No.	Model	Formulae
		$L_{\text{LOS}} = -42.6 - 26\lg\left(\frac{r}{r_0}\right) - 20\lg\left(\frac{f}{f_0}\right)$; $P_{r\text{LOS}} = P_r + L_{\text{LOS}} = P_t - 42.6 - 26\lg\left(\frac{r}{r_0}\right) - 20\lg\left(\frac{f}{f_0}\right)$; $P_{\text{rNLOS}} = P_t + L_{rt}$. Here $P_{r\text{LOS}}$ is the received signal strength in the line-of-sight (LOS) environment, dBm; $P_{r\text{NLOS}}$ is the received signal strength in the non-line-of-sight environment, dBm; L_{rt} is a path loss, dB; L_{LOS} is apath loss for thefree space environment, dB; L_0 is a free space loss, dB; L_{rts} is a diffraction and scatter loss, dB; L_{mds} is a multiscreen diffraction loss, dB; L_{ori} is an orientation loss, dB; L_{bsh} is a shadowing gain due to theBTS antenna location, dB; b is an average building separation, m; w is an average street width, usually $w = 0.5b$ m; h_b is an average building height, m; $\Delta h_t = h_t - h_b$ is the BTS antenna height above the rooftops, m; $\Delta h_r = h_b - h_r$ is the distance between MS antenna and rooftops, m; φ is a street orientation angle with respect to the direct radio path, $\varphi = 90°$ in the worst case; k_a is a correction factor, dB; k_d is a distance factor; k_f is a frequency factor.
9	TheHata-Davidson model LOS+ΣR_i/ EMW$_i$	Limitations: frequency range f = 150–1500 MHz; BTS antenna height h_t = 30–2500 m; MS antenna height h_r = 1–10 m; distance between BTS and MS r = 1–300 km. $P_r = P_{r\,Hata} - A(h_t, r) + S_1(r) + S_2(h_t, r) + S_3(f) + S_4(f, r)$; $P_{r\,Hata} = P_t - 69.55 - 26.16\lg\left(\frac{f}{f_0}\right) -$ $-\left(44.9 - 6.55\lg\left(\frac{h_t}{h_0}\right)\right)\lg\left(\frac{r}{r_0}\right) +$ $+13.82\lg\left(\frac{h_t}{h_0}\right) + a(f, h_r) + K(f)$; $A(h_t, r) = \begin{cases} 0, & \text{if } r < 20\ k\text{m}, \\ 0{,}62137(r-20)\times \\ \times\left[0.5 + 0.15\lg\left(\frac{h_t}{121.92}\right)\right] & \text{if } 20 \le r < 20\ k\text{m}; \end{cases}$

The End Table 1 / Окончание табл. 2

No.	Model	Formulae
		$S_1(r)=\begin{cases}0, & \text{if } r<64.38\ km,\\ 0.174(r-64.38) & \text{if } 64.38\le r<300\ km;\end{cases}$ $S_2(h_t,r)=\begin{cases}0.00784(h_t-300)\left\|\lg\left(\frac{9.98}{r}\right)\right\|, & \text{if } h_t\ge 300m,\\ 0 & \text{if } h_t<300m;\end{cases}$ $S_3(f)=\frac{f}{250\lg\left(\frac{1500}{f}\right)}$; $S_4(r)=\begin{cases}0, & \text{if } r<64.38\ km,\\ 0.112(r-64.38)\lg\left(\frac{1500}{f}\right) & \text{if } 64.38\le r<300\ km.\end{cases}$ Here $P_{r\,Hata}$ is thereceived signal strength for the Okumura-Hata model, dBm; $a(f,h_r)$ correction factor for the MS antenna height, dB (see the Okumura-Hata model); $A(h_t,r)$, $S_1(r)$ is distance correction factors, dB; $S_2(h_t,r)$ is a BTS antenna height correction factor, dB; $S_3(f)$ is a frequency correction factor, dB; $S_4(f,r)$ is a frequency and distance correction factor, dB.
10	RWP through the forest [1, 15] LOS_1+A/LOS_F+Lateral/EMW+ LOS_2	$P_r\approx P_{t\,LOS}-\alpha_{mF}r+10\lg[\varsigma(r)]$; $\alpha_{mF}=\begin{cases}0.185\text{ dB/m} & \text{for operational frequency } f=900\text{ MHz},\\ 0.36\text{ dB/m} & \text{for operational frequency } f=1800\text{ MHz};\end{cases}$ $\varsigma(r)=10^{0.1r}$.
11	RWP in a free space with the reflection from the forest [15] NLOS+ΣR_i/ EMW_i	$P_r=\frac{P_tG_tG_r\lambda^2}{(4\pi)^2}\int\limits_{V_F}\frac{F_t(\theta)^2\cdot\sigma(\phi)}{r_1^2\cdot r_2^2\cdot V_0}dV$, where P_r is a median power level at the receiving point for point-to-point RWP, W; $F_t(\theta)$ – BTS antenna radiation pattern, $F_t(\theta)=1$ for omnidirectional antennas; V_F is the volume of the forest, m^3; $V_0=1$ m^3 – norming volume, ϕ is an angle between the direction of the main wave and its reflection from the forest; $\sigma(\phi)$ is an effective scattering area of a volume unit, m^2; r – distance between BTS and forest, km; r_2 is the distance between the forest and MS, km

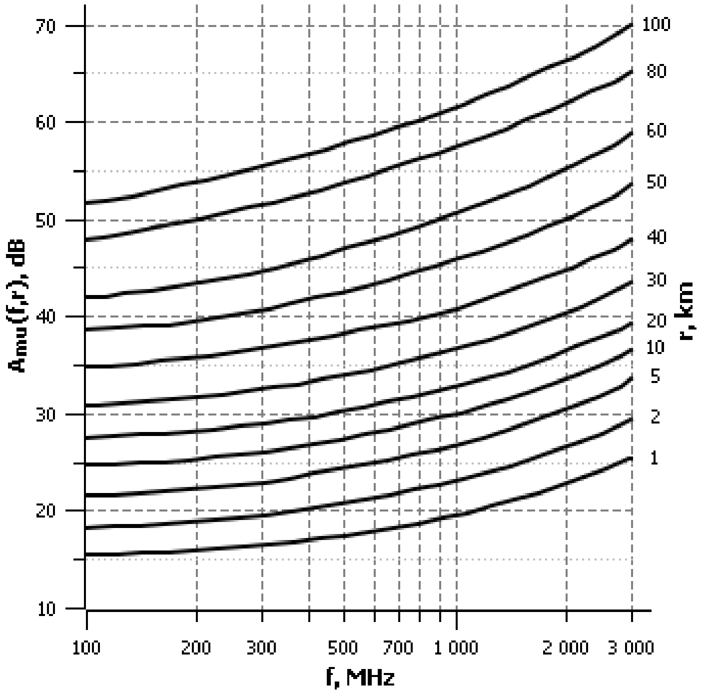


Fig. 3 – Attenuation Factor for Urban Areas

Рис. 3 – Коэффициент затухания для городских территорий

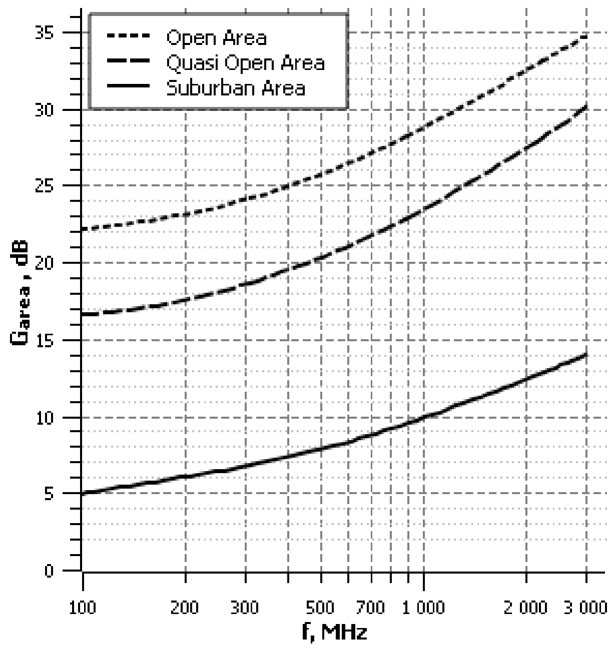


Fig. 4 – Gain Correction Factor

Рис. 4 – Поправочный коэффициент усиления

3. Calculation Algorithm for RWP Models

TheRWP numerical calculation algorithm based on the examined mathematical models is shown in Fig. 5. The values of received signal strength for every model are found by using formulas from Table 2 with appropriate standard BTS and MS parameters.

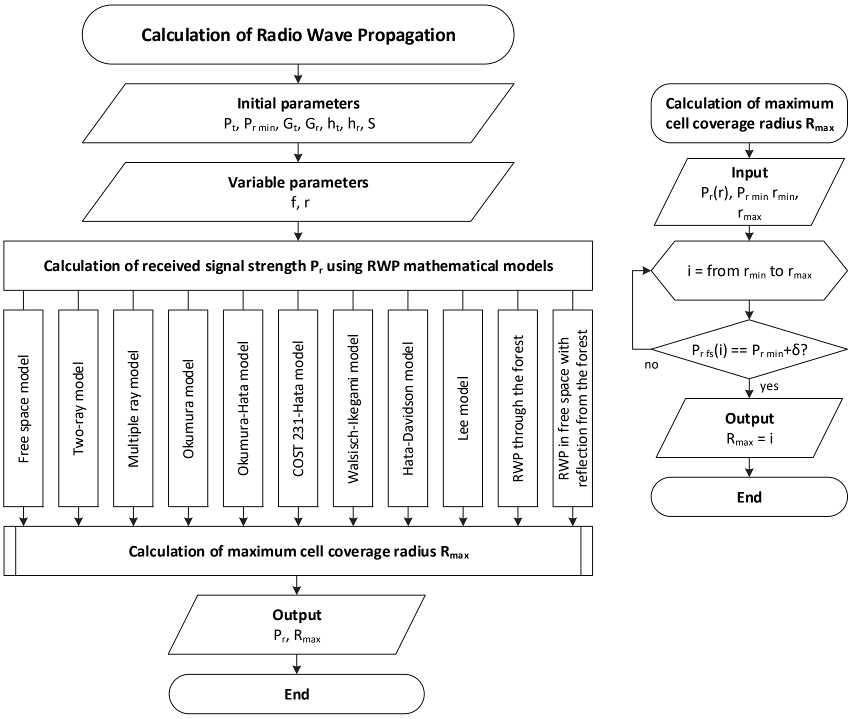


Fig. 5 – Algorithm for RWP Calculation Using Mathematical Models and Standard BTS and MS parameters

Рис. 5 – Алгоритм расчета РВП с использованием математических моделей и стандартных параметров БТС и МС

As it follows from the right part of the flowchart (Fig. 3), the maximum radius of BTS radio coverage area $R_{\max}$ depends on the values of MS receiver sensitivity $P_{r\,\min}$ and received signal strength $P_r(r)$ for corresponding RWP model.

Example of the R_{max} numerical calculation using the proposed algorithm (Fig. 5).

To estimate the influence of the environment on the received signal strength (for downlink transmission), calculations of the proposed algorithm were made using the Mathcad engineering software. Comparison of the results, visible in Fig. 3, are true for the following parameters:

– BTS transmitter power: P_r = 50 W (47 dBm);

– Operational frequency: f = 900 MHz (λ = 0.33 m);

– BTS, MS antenna gain: G_t = 10, G_r = 1.

Environmental conditions, specific for every mathematical model (Tab. 2), were also taken into account.

The received signal strength is heavily dependent on wave propagation conditions, and it changes drastically with an increase in distance between BTS and MS (as it is shown in Fig. 6). For example, when distance $r = 3$ km, signal strength $P_r = -44$ dBm for the LOS model, but in dense urban area conditions (the Walfisch-Ikegami model) – $P_r = -95$ dBm. The stability of the radio communication link depends on the MS receiver sensitivity level ($P_{r\,\min}$). If $P_{r\,\min} = -93$ dBm and the real path loss is equal to the calculated one (using the Walfisch-Ikegami model), then a signal from BTS couldn't be received by MS already at a 3 km distance.

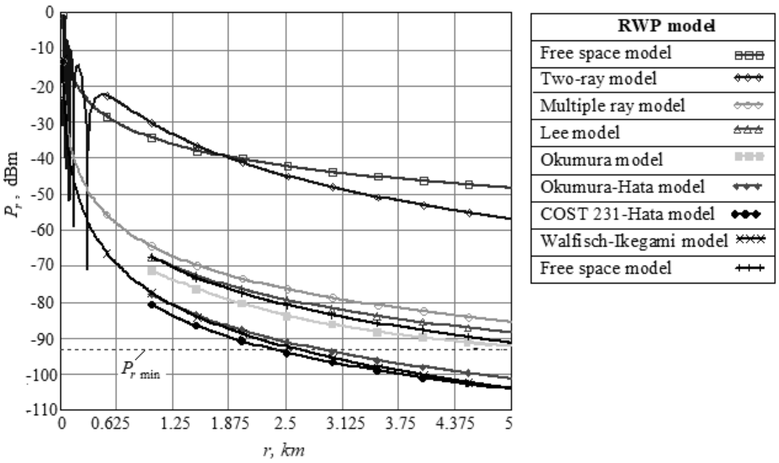


Fig. 6 – Comparison of the Received Signal Strength for 9 RWP models

Рис. 6 – Сравнение мощности принимаемого сигнала для 9 моделей RWP

Experimentally gathered RWP data for Philadelphia, New York and Tokyo are shown in Fig. 7 to compare the real signal attenuation slopes with the calculated results (Fig. 6).

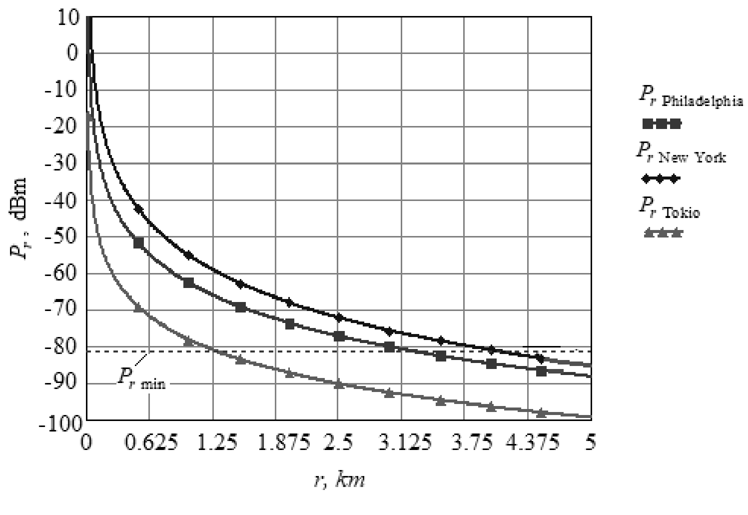


Fig. 7 – Received Signal Strength Relation to the Distance between BTS and MS (r, km) for Selected Urban Areas [9]

Рис. 7 – Зависимость мощности принимаемого сигнала от расстояния между BTS и MS (r, км) для выбранных городских территорий [9]

As it can be seen in Fig. 3, the Lee model is most suitable for environmental conditions in Philadelphia, while the COST 231-Hata model gives the best results for Tokyo.

Maximum cell coverage radiuses of the calculated path loss models for two different MS receiver sensitivity settings ($P_{r\,\min}$ = [–81; –100] dBm) are visible in Tab. 3.

Table 3 / Таблица 3

Maximum Cell Coverage Radius $R_{\max}$ for Given MS Receiver Sensitivity $P_{r\,\min}$

Максимальный радиус покрытия соты $R_{\max}$ для заданной чувствительности приемника MS $P_{r\,\min}$

RWP model	$R_{\max}$, km $P_{r\,\min} = -81$ dBm	$R_{\max}$, km $P_{r\,\min} = -100$ dBm
Free space model	210.253	1873.883
Two-ray model	19.911	59.452
Multiple ray model	3.536	15.202
Lee model	2.818	11.827
Okumura model	2.077	9.141
Okumura-Hata model	1.255	4.584
COST 231-Hata model	1.026	3.748
Walfisch-Ikegami model	1.253	3.962
Free space model	2.526	8.837
Hata-Davidson model	2.526	8.837

Conclusions

1. This work discusses relatively simple RWP models for CNMC, which, using a proposed algorithm along with appropriate software (such as Mathcad), allows determining the maximum coverage area of BTS cells based on environment characteristics.

2. Every mathematical model is presented as a function of the received signal strength P_r (P_t, G_t, G_r, f, h_t, h_r, r). Unlike in most of the models recommended by ITU-R и CEPT, formulas in tab. 2 comply with the strict mathematical laws. Expressions with common logarithms are reduced to dimensionless forms by introduction of the norming parameters. For instance, the received path loss formula for the COST 231-Hata model in the book [6] looks like this:

$$L_{\mathrm{COST\,231}} = 46.3 + 33.9\lg(f) - 13.82\lg(h_t) - a(h_r) + \left[44.9 - 6.55\lg(h_t)\right]\lg(r) + C. \quad (1)$$

That path loss $L_{tr} = 10\lg(P_r / P_t) > 0$ doesn't match the actual reduction in the signal level when the distance between BTS and MS increases, and expression (1), in overall, is mathematically incorrect, because quantities with dimensions are used as an logarithm arguments. This work proposes the following formula:

$$P_{r\,\mathrm{COST\,231}} = P_t - 46.3 - 33.9\cdot\lg\left(\frac{f}{f_0}\right) + 13.82\cdot\lg\left(\frac{h_t}{h_0}\right) + a(f, h_r) - \left[44.9 - 6.55\cdot\lg\left(\frac{h_t}{h_0}\right)\right]\cdot\lg\left(\frac{r}{r_0}\right) - C, \quad (2)$$

which corresponds to the path loss $L_{tr} = 10\lg(P_r / P_t) < 0$ and shows the real attenuation of the radio signal.

3. Path loss in Philadelphia, as shown in Fig. 8, where experimental (Fig. 7) and calculated (Fig. 6) data are compared, can be expressed using the Lee model, whereas the COST 231-Hata model is a match to the measured path attenuation in Tokyo. Visible errors are possible due to the choice of parameters (BTS and MS antenna height, antenna gain, urban parameters, etc.).

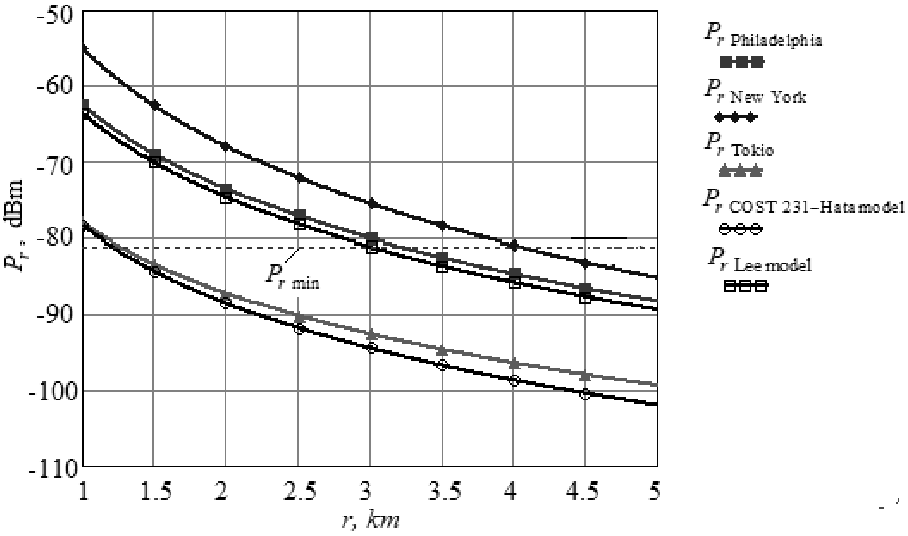


Fig. 8 – Comparison of the Experimental and Calculated Values of Received Signal Strength in Selected Cities

Рис. 8 – Сравнение экспериментальных и расчетных значений мощности принимаемого сигнала в выбранных городах

4. As a first approximation, calculations of the median received power $P_r(r)$ (for downlink regime) can be made using estimated engineering formula (3):

$$P_r = P_{r\,LOS} - 10n\lg\left(\frac{r}{r_0}\right), \tag{3}$$

where $r_0 = 1$ km is a norming distance, n is an attenuation exponent which depends on the environment (Tab. 4).

Table 4 / Таблица 4

Dependence of the attenuation exponent on the environment features

Зависимость показателя затухания от особенностей окружающей среды

Environment	Attenuation exponent n
Free space (LOS)	2
Suburban area (LOS/NLOS)	2.7–3.5
Urban area (NLOS)	3–5

For example, if the received power in the LOS environment $P_{r\ \mathrm{LOS}} = -60$ dBm at the distance r = 1 km from the BTS, and $P_{r\ \mathrm{LOS}} = -75$ dBm when the distance is $r = 3$ km, then the slope of experimentally acquired data for RWP in New York (fig. 3.3) can be roughly expressed using (3) with the coefficient $n = (-75 + 60) / (-10 \cdot 0{,}48) = 3{,}125$.

5. The developed algorithm (Fig. 2), which was implemented using Mathcad software, allows not only calculating maximum coverage area of BTS cell towers, but also performing network clustering and designing the coverage map afterwards [1, 2, 11].

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МАТЕМАТИЧЕСКИЕ МОДЕЛИ РАСПРОСТРАНЕНИЯ РАДИОВОЛН В НЕОДНОРОДНЫХ СРЕДАХ ДЛЯ БЕСПРОВОДНЫХ СЕТЕЙ ОБЗОР

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Вопрос обеспечения равномерного радиопокрытия зон обслуживания и связанной с этим надежности систем мобильной радиосвязи в стандартах 3G и 4G требует большого внимания при проектировании сотовых мобильных сетей. Одной из основных задач на первом этапе проектирования является математическое моделирование распространения радиоволн под воздействием окружающей среды. В данной работе представлена классификация математических моделей распространения радиоволн в системах сотовой мобильной связи, алгоритм расчета мощности радиосигнала в точке приема в зависимости от расстояния между мобильной и базовой станциями, а также факторы и условия, влияющие на радиосвязь. Распространение волн указано.

Ключевые слова: математические модели, распространение радиоволн, гетерогенная среда, беспроводные сети, сотовые сети мобильной связи (ССМС).

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