Educational Simulation Tools for Radio Wave Propagation Models

Anamaria Bjelopera, Matej Kajinić and Emil Dumić

***Abstract*—**Theory of electromagnetic waves is usually covered to a lesser extent within courses of physics for first year students of electrical engineering. Teaching higher education courses of more complex analysis of EM wave propagation which is meant for senior students, specially those of radio communications, imposes some challenges for professors because this subject is very difficult for students to understand. So, professors are faced with process of finding suitable tools for analysis and simulation of EM wave propagation which will complement their theoretical part of lectures. Various program tools such as MATLAB are useful applications for students in order to get a better insight of wireless network planning and design which will be a good preparation for their later work with real-life signals and industry systems worldwide. This paper describes basic properties and shows simulations results of COST 231-Hata, ITM (Irregular Terrain Model) and Ericsson used in the area of the city of Dubrovnik with frequencies of 800 MHz and 1.8 GHz used in Cloud RF tool.

***Keywords*—**propagation model, path loss, simulation, testing.

I. Introduction

Key step of designing and planning a new wireless network or analysis and improvement of existing one is modeling of the radio channel. Propagation models are designed in order to give acceptable accuracy level and computational complexity [1], [2]. For network operators it is important to define where each transmitter would be located so that the received signal level would be satisfactory and quality of service would be acceptable in all observed area [3].

During the propagation of radio signal from the transmitter to receiving stations in coverage area, it is important for students to know that the signal attenuates because of the interaction with different objects in the environment and it is crucial to predict path loss. So, in process of wireless network design a key figure is to gain data about the propagation environment which will be used as input values for models in order to find most suitable propagation model. Information about the transmitter and receiver is also very important.

The most common separation of propagation models is into two groups: empirical and deterministic models. Deterministic are more complex and require much more data about the environment than the empirical ones which are less complex and their computational time is also smaller. In urban environments usually different empirical models are used in order to calculate the value of electrical field in the observed area [1]. Depending on the type of radio network and type of the surrounding environment different models are going to be used. It is important for the students to learn that there is no universal solution for all kinds of networks and environments.

Experimentation and training are fundamentals of understanding EM wave propagation modeling but strong theoretical background is a must. With growth of numerous programming languages and computer technologies available on the internet, mostly in open source, today it is possible to simulate different complex EM propagation problems simply by using a computer [4].

In this paper we defined an example of using suitable CloudRF tool for better understanding of EM wave propagation analysis and simulation.

Okumura-Hata [5], [6] is often a starting point for understanding different models. In our paper we use three widespread propagation models: COST 231-Hata [7], ITM (Irregular Terrain Model) [8] and Ericsson model [9]. Detailed model analysis can be found in [10], [11] and [12].

The paper is organized as follows. Section II defines basic principles of the propagation of an electromagnetic wave. Propagation model analysis is given in Section III. Student simulation results for the location of University of Dubrovnik in the urban environment of city of Dubrovnik, Croatia used for studying within the course of Basic properties of electromagnetic waves are presented in Section IV. Section V brings the conclusion.

II. Basic Theory of Electromagnetic Wave Propagation

In theoretical part of EM wave propagation models education, first some basics of EM wave propagation should be covered. In wireless communications, the electromagnetic wave is used for the transmission of information. In order for this transmission to be possible it is necessary for the EM wave to have energy, and the energy of the wave is reduced through the space away from the source [13].

In the open space, the path between the transmitter and the receiver can be line-of-sight (LOS) or more complex where various obstacles can be found. When transmitting the wave, the greatest losses are achieved under the influence of diffraction, reflection and scattering, also there are fewer possible losses due to absorption, interference and refraction.

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Multipath propagation occurs in all types of radio communication. Radio wave does not only travel through direct path (line-of-sight) but the incoming radio waves arrive from different directions with different amplitudes, phases and time delays (different versions of same signal that travels from the transmitter). Even when a line-of-sight exists, multipath still occurs due to reflections from the ground and surrounding structures [14]. These multipath components combine at the receiver antenna and can constructively or destructively interfere with each other, and therefore can cause the received signal to distort or fade [14], [15].

Multipath propagation depends on antennas used for transmission and reception. Used antennas can be non-directive and radiate in all directions or directive ones which focus the power in one direction reducing the power of reflected signals away from main path [16]. But the main problem in planning of wireless networks is choosing the right location for transmitting antenna to be set up because of the various reflections from buildings, mountains or other reflective surfaces that make LOS communication hard.

Spreading over smooth terrain is an idealistic case, good for a simple explanation of the problem to students, but in reality we do not have cases of completely smooth surface, but variety of irregular surfaces. The method by which the roughness of a given surface is defined is known as Rayleigh's method which idealizes the real surface with the quasiperiodic surface shown in Fig. 1.

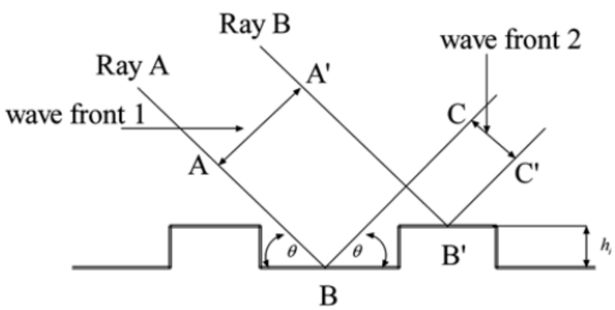


Fig. 1 Quasiperiodic surface [14]

Further analysis includes cases of reflection on uneven surface where due to energy spread, the scattering component will increase as the reflection component decreases. The total field on the receiving antenna will be reduced because only a small portion of transmitted power can be scattered in the direction of the receiving antenna.

The Rayleigh method takes into account two waves (ray A and B) reflected from the top and bottom of the uneven surface at points B and B'. These two rays will cross different paths and will have different phases in the receiving points C and C'. The difference in the phase and length of the path when they arrive at the points C and C ' can be defined as:

$$\Delta l = (\overline{AB} + \overline{BC}) - (\overline{A'B'} + \overline{B'C'}) = \frac{h_i}{sin\varphi}(1 - cos\,2\varphi)$$

$$\Delta l = 2h_i * sin\,\varphi \tag{1}$$

$$\Delta\varphi = k * \Delta l = \frac{2\pi}{\lambda}\Delta l = \frac{4\pi * sin\,\varphi * h_i}{\lambda} \tag{2}$$

where $\Delta\varphi$ is the phase difference and h_i is the height of terrain irregularity. If $\Delta\varphi \geq \pi/2$, $h_i \geq h_{R\max} \equiv \frac{\lambda}{8 sin\theta}$ and regard to (1) and (2), it can be seen that each surface, where the height of the terrain irregularity is greater than the critical height ($h_{R\max}$), can be classified as rough surface.

The theory of geometric optics can be very useful for many problems, but it is not enough for the shadowy surfaces behind the obstacle because it predicts that such fields do not exist. It is well known that in many cases energy portions also propagate in shady areas. This effect is known by diffraction and is explained by the Huygens principle. The principle suggests that each point in wave form acts as a secondary wave source and a combination of these waves creates a new wavefront in the direction of propagation. In other words, the sum of infinite secondary sources in the surface above the barrier causes the field to exist. In the case of more obstacles, models such as Deygout model, Bullington model, Epstein model, and Giovanelli model should be used [15].

During propagation in the built environment EM waves are in great interaction with the environment elements (buildings, hills, etc.) which cause attenuation of signal. Key conclusion for students is that the creation of a universal model is impossible because of the different characteristics of the environment and for each model it is important to define type of the terrain as precise as it is possible to get better results. There are various recommendations and templates of terrain type, among which is British Telecom where the classification is divided into 10 categories [15].

Depending on the system and its purpose, it is necessary to decide point-to-point or area planning and accordingly collect the necessary information. In the calculation itself and the model, diffraction and reflection which are particularly expressed in the surface planning should be taken into account which will increase the complexity of the calculation. In discussion about propagation models, students should consider five area of interest [8]:

- *design of the equipment* - Using of equipment need to be defined also as the reliability of it, i.e. it should be possible to predict the characteristics of the channel (e.g. values of path loss) for which the equipment must compensate. It should also be possible to predict how the new equipment will behave in various situations.
- *general system design* - This is an extension of the first area and in this area interaction of radio equipment need to be considered i.e. interference between elements of the same system and also between elements of one system with another one on the same or adjacent frequencies.
- *specific area of operation* - Similar as first two areas. Important issues are location of the radio systems and the control of communications traffic. Sometimes Monte Carlo simulations are taken into account.
- *coverage area* - In this case, one of the cells is set to a

specific location while the rest are placed nearby. The aim is to determine the surface on which communication is reliable and potentially detect interferences of other cells.

- *specific communication link* - In the latter case, both terminals are at specific locations, and the level of the received signal must be determined, i.e. the characteristics of the received signal at different times and conditions. These calculations are usually used for communication link design.

Point-to-point planning requires detailed information of the propagation path, while area planning requires less such information and there is no need for a specific link.

On the propagation path between the transmitter and the receiving antenna, because of the contact with the environment the electromagnetic wave partially "*loses*" the energy. This loss is called path loss (PL) and represents the ratio expressed in decibels (dB) between the transmitted power and the received power expressed according to:

$$PL = P_T + G_T + G_R - P_R - L_T - L_R \qquad (3)$$

where P_T and P_R are transmitted and received power, G_T and G_R are gains of the transmitter and receiver antenna and L_T and L_R are losses of connection between transmitter/receiver and antenna (feeder losses) shown in dB scale.

Free space path loss (*FSL*) can be shown as:

$$PL_{freespace} = 32.4 + 20 * log\, d + 20 * log\, f \ \text{[dB]} \qquad (4)$$

where d is the distance between the transmitting and receiving antenna in kilometers and f frequency in MHz. In point-to-point communication, the FSL model can be used only if there is a direct line between transmitters and receivers without any obstacles. In area communication, even in the case of direct lines, the diffraction and reflection affect the wave that comes to the receiver and further increase the complexity of the calculation [15].

III. PROPERTIES OF USED EMPIRICAL MODELS

Propagation model is a tool that is crucial in process of planning, designing and analyzing of radio communication networks. There is no general propagation model that can be applied to all situations and environments. The results of used model have to be carefully analysed and will depend on parameters available for the defined area of propagation and different parameters of the model.

Propagation models are divided into empirical models and deterministic ones. Deterministic models include huge amount of geometric data of the path of transmitting electromagnetic wave [3], [12]. These models usually include ray tracing techniques and physical optics theory. Deterministic models obtain a high level of accuracy on the expense of complex computation and high cost. Empirical models are based on measured data and give the estimation of path loss. These models are not computationally demanding models and give results of acceptable accuracy. This is the reason why they are usually used for designing and planning of wireless networks.

In the mid-20th century, the development of empirical models of propagation of radio waves for different spectra, which we used in this paper, began. The Okumura-Hata model was created by measuring in Tokyo and its surroundings in 1968. It is applicable to the frequency range of 150 MHz to 1500 MHz and is divided into open space, suburban area and urban area. For reference, the urban area is taken in the form of:

$$L_{dB} = A + B\, log_{10} R - E \qquad (5)$$

where:

$$A = 69.55 + 26.16\, log_{10} f_c - 13.82\, log_{10} h_b$$
$$B = 44.9 - 6.55\ log_{10} h_b$$
$$C = 2\ (log_{10}(f_c / 28))^2 + 5.4$$
$$D = 4.78\ (log_{10} f_c)^2 + 13.88\, log_{10} f_c + 40.94$$
$$E = (1.1\ log_{10} f_c - 0{,}7)h_m - (1.56\ log_{10} f_c - 0.8) \ \text{---}1$$
$$E = 3.2\ (log_{10}(11.7554 h_m))^2 - 4.97 \ \text{---}2$$
$$E = 8.29\ (log_{10}(1.54 h_m))^2 - 1.1 \ \text{---}3$$

1 – medium to small cities

2 – large cities, $f_c \geq 300$MHz

3 – large cities, $f_c < 300$MHz

h_m is mobile station antenna height above local terrain height in meters, f_c carrier frequency in MHz, h_b base station antenna height above local terrain height and R great circle distance between base station and mobile in kilometers.

Since 1999 the COST 231-Hata model is an addition to the Okumura-Hata model that extends the frequency range of 1500 to 2000 MHz for medium to small cities. It is expressed with [7]:

$$L_{dB} = F + B\, log_{10} R - E + G \qquad (6)$$

where:

$$F = 46.3 + 33.9\ log_{10} f_c - 13.82\ log_{10} h_b$$
$$E = (1.1\ log_{10} f_c - 0.7)h_m - (1.56\ log_{10} f_c - 0.8)$$

$G = 0$ [dB] - middle-sized cities and suburbs

$G = 3$ [dB] - city areas

The Ericsson model is Ericsson's Hata model implementation. For this model it has to be explained that it is possible to modify the parameters according to the propagation environment. Path loss is expressed with:

$$L_{Ericsson} = a_0 + a_1 * log\, d + a_2 * log\, h_b + $$
$$+ a_3 * log\, h_b * log\, d - 3.2 * (log(11.75 * h_m))^2 + g(f) \qquad (7)$$

where $g(f)$ is : $g(f) = 44.99 * lg\, f - 4.78 * (lg\, f)^2$.

Parameters a_0, a_1, a_2 and a_3 are constants that can be changed for specific propagation environments. Default sizes are: $a_0 = 36.2$, $a_1 = 30.2$, $a_2 = -12.0$ and $a_3 = 0.1$[15].

The ITM model or Longley-Rice is a model made specifically for computer use to solve various engineering problems, also defined in 1968. It is flexible in its application and can be operated as area prediction model or as a point-to-point model. It is applicable to the frequency range of 20 MHz to 20 GHz. The model, based on electromagnetic theory and statistical analysis of terrain and radio measurements, predicts the medium attenuation of a radio signal as a function of distance and signal variability in time and space. It is designed for wide variety of distances and antenna heights and as a solution for problems where terrain plays important role [15]. The total number of parameters is 5, which are the following: frequency, system parameters, environmental parameters, scheduling parameters and statistical parameters [8].

COST 231-Hata, Ericsson and Longley-Rice are empirical models and they mostly depend on measured data of received signal level but also depend on the theory of electromagnetism.

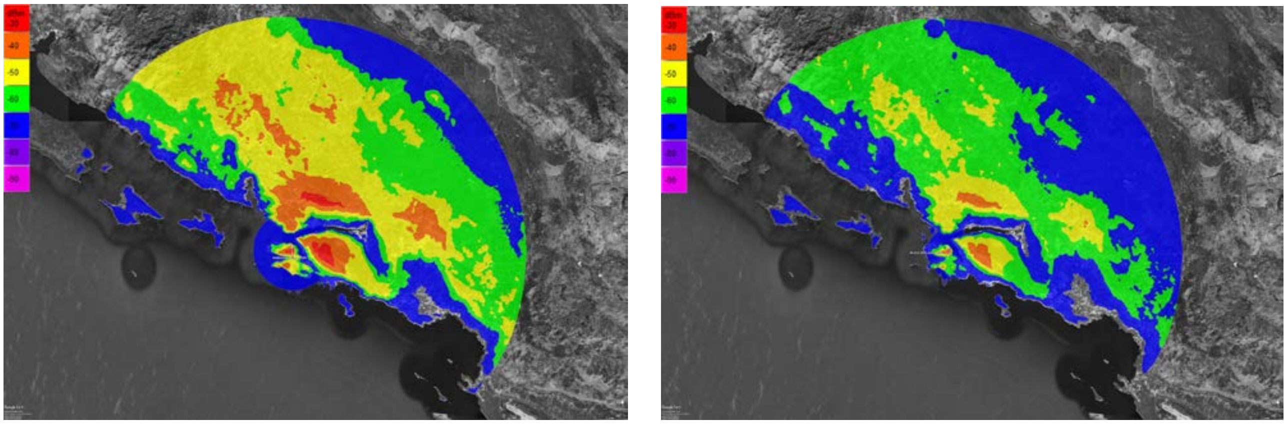
IV. Simulation results of COST-231 Hata, ITM and Ericsson models

For the empirical models we mentioned and the others we have not mentioned, there are different computer applications that can perform computing functions. We used cloud-based CloudRF which is available as open source software [17]. The results are displayed in Google Earth Pro.

The parameters used for testing models are shown in the Table I. In simulations, frequencies of 800 MHz and 1.8 GHz and propagation models: COST 231-Hata, Ericsson and ITM were used. We used transmitter power of 25 W through the isotropic antenna with 2.14 dBi gain and azimuth 0° and tilt 0° [17]. Testing location was set to building of University of Dubrovnik, with address Ćira Carića 4, Dubrovnik, Croatia. Results of simulations shown on Fig. 2, Fig. 3 and Fig. 4 obtained big differences in area coverage so we did not go into a deeper comparison between the models. We believe that for the given area the most appropriate model is ITM propagation model while the worst results were attained using the COST 231-Hata model. The reason why the results are so different is because of different parameters used for each model which are more or less adjusted to the target environment. Each of parameter could be more efficient if there would be more collected data about the area. For further research, field measurements should be made and the models should be adapted to the real situation i.e. more detailed data about the environment should be used. For students, simulation models should be complemented with measurements in laboratory and real-life environment.

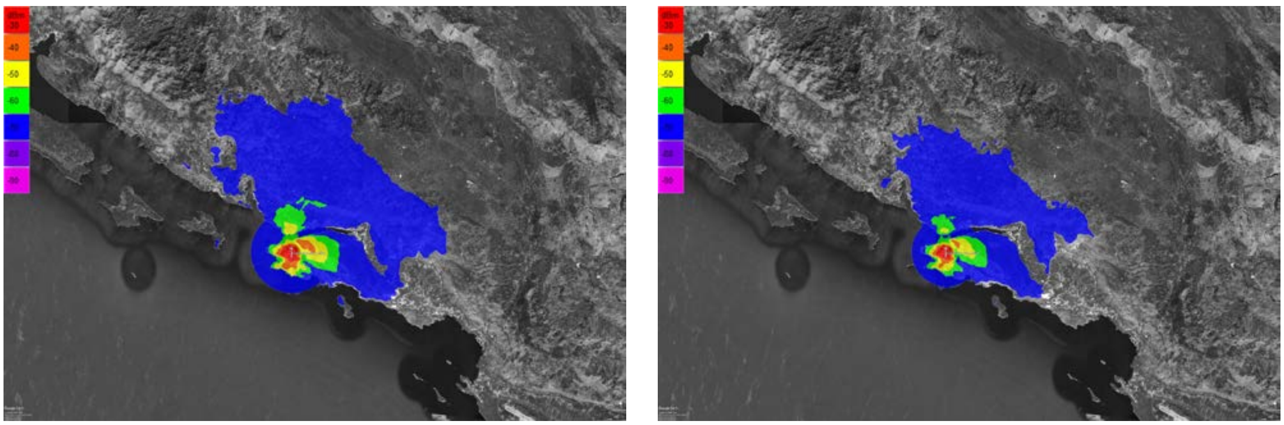
Table I Simulation parameters

TRANSMITTER	
Frequency	800/1800 MHz
RF Power	25 W
Radius	15 km
Tx Gain	2.14 dBi
Antenna pattern	Isotropic radiator
Antenna polarisation	Vertical
Azimuth	0°
Tilt	0°
Tx Latitude	42.659339
Tx Longitude	18.077294
Tx Height	30 m
RECEIVERS	
Rx Height	1.5 m
Rx Gain	2.14 dBi
Unit of measurement	Received Power (dBm)
RF model	- COST231-Hata - Ericsson - ITM
Rx Sensitivity	-90 dBm
OUTPUT	
Terrain Resolution	30 m
ENVIRONMENT	
Random clutter	0 m
Terrain conductivity	Average ground
Radio climate	Maritime Temperate (sea)



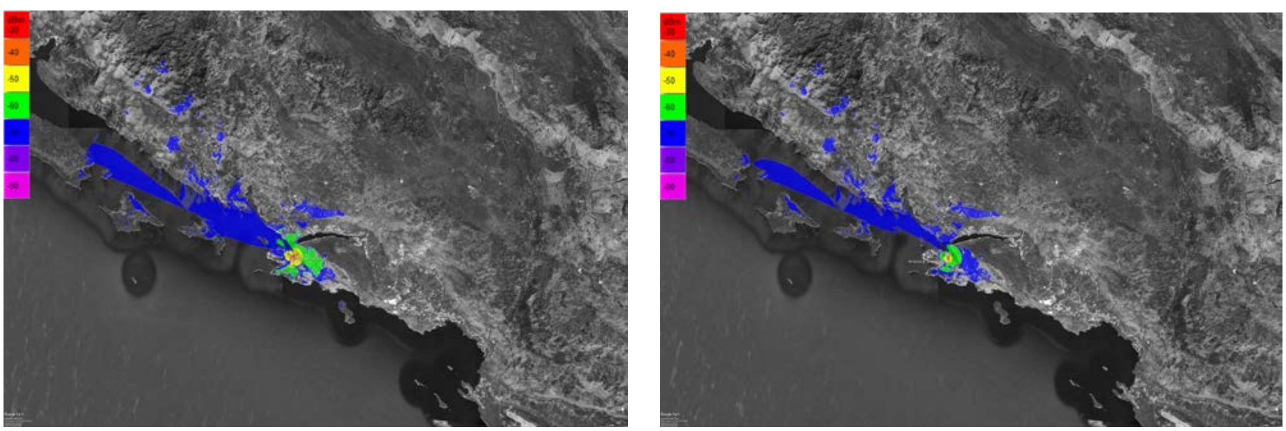
(a) (b)

Fig. 2. Simulation results COST231-Hata model with transmitter power of 25 W
(a) 800 MHz, coverage 333.696 km², (b) 1.8 GHz, coverage 427.928 km²



(a) (b)

Fig. 3. Simulation results of Ericsson model with transmitter power of 25 W
(a) 800 MHz, coverage 136.628 km², (b) 1.8 GHz, coverage 88.425 km²



(a) (b)

Fig. 4. Simulation results of ITM model with transmitter power of 25 W
(a) 800 MHz, coverage 37.781 km², (b) 1.8 GHz, coverage 31.554 km

V. Conclusion

Various program tools can be used for teaching students the EM wave propagation theory in different high education courses in order to see the whole perspective of planning and designing wireless networks. Not only theoretical knowledge but also simulation and analysis of different radio propagation models will be a good preparation for their future work after finishing their studies and facing with real-life signals and problems of designing and implementation of new radio networks and also fixing problems with existing ones.

In this paper, after an overview of basic principles of electromagnetic wave propagation and propagation models, results of simulation for the city of Dubrovnik for three empirical models and two commonly used radio frequencies are presented. It is useful for students to know that the use of empirical models is simple and it is possible to do a large number of simulations in a relatively short time, which means small costs. Depending on the area, it is necessary to choose a model that will be more appropriate and take the results with a reserve, as it was shown with graphic simulation results. We concluded that for the specific area of Dubrovnik the best model for both most commonly used frequencies of 800 MHz and 1.8 GHz in mobile communication networks is the ITM propagation model while the COST 231-Hata showed the worst results.

By development of technologies that enable more precise spatial data capture in the area meaning centimeter or millimeter precision, such as LiDAR (Light Detection and Ranging), it will be possible to include better description of the space around us in a computer-model manner. So, it will be easier to get much more necessary spatial data that should be included in models, such as natural and artificial obstacles that will disturb propagation of the waves. With this, it will be possible to plan the spread of radio waves even more efficiently in the shortest possible time. This will lead to further development of empirical models that will become deterministic.

Next step and challenge for professors in EM wave theory courses is for the students to complement their simulations knowledge with hardware implementation e.g. some quality laboratory exercises that turn simulations to real signals. Also, some extensive field measurements should be considered.

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