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SIGNAL FADING IN LAND-SATELLITE COMMUNICATION LINKS

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Abstract. *Land–satellite communication (LSC) systems enable users of handle wireless pho¬nes, portable computers, or mobile phones to communicate with one another from any two points worldwide. Signal propagation for such systems has become an essential consideration. Path conditions may cause harmful impairments that severely corrupt the system availability and performance. Hence, propagation considerations are very important for successful operation.*

To design successful wireless LSC links, stationary or mobile, it is very important to predict all propagation phenomena occurring in such links, to give a satisfactory physical explanation of main parameters of the channel, such as path loss and slow and fast fading, and finally, to develop a link budget compared to total noise at the outputs of the terminals of the channel (called signal noise figures or maximum acceptable path loss

The work considers effects of fading phenomena on signal data transmitted through the land-satellite communication links, accounting mostly for LEO satellite, as most complicated configuration of the satellite links. Based on the selected, among other statistical and physical, model of fading effects prediction the probability of fading phenomena in land-satellite communication links is analyzed for three cities in Israel, small, medium and large, and is compared with the results obtained by other authors above the Copenhagen, Stockholm and in England.

Was developed a stable algorithm and the corresponding numerical code for predic-tion of fading phenomenon in the land-satellite communication links for various kinds of the built-up terraing, accounting for the buildings’ density and their overlap profile, the height of the antenna of arbitrary subscriber located in the urban scene. This ap-proach was compared with well-known and usually used in practice Saunders-Evans physical statistical model via experiments carried by them above the Stockholm, and finally, the proposed stochastic approach was approbated through the real experi-ments carried out for small, moderate and large cities of Israel.

Keyword*: fading phenomena, satellite communication, LEO, satellite links.*

ЗАГАСАНЯ СИГНАЛУ В СУПУТНИКОВІЙ ЛІНІЇ ЗВ’ЯЗКУ

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Анотація. *Системи наземного та супутникового зв'язку (LSC) дозволяють користувачам керувати бездротовими телефонами, портативними комп'ютерами або мобільними телефонами спілкуватися між собою з будь-яких двох точок по всьому світу. Поширення сигналу для таких систем стало важливим фактором. Умови на шляху можуть спричинити шкідливі порушення, які сильно погіршать доступність та продуктивність системи. Отже, міркування щодо поширення дуже важливі для успішної роботи.*

Для проектування успішних бездротових каналів LSC, стаціонарних або мобільних, дуже важливо передбачити всі явища поширення, що відбуваються в таких каналах, дати задовільне фізичне пояснення основних параметрів каналу, таких як втрата шляху та повільне та швидке згасання, і нарешті , розробити бюджет зв'язку порівняно із сумарним шумом на виходах кінцевих каналів (називаються цифрами сигнального шуму або максимальними втратами змінного струму.

В роботі розглянуто вплив явищ згасання на сигнал, що передаються в лінії супутникового зв'язку, здебільшого від супутника LEO, як по найскладнішій конфігурації супутникової ліній. На основі обраної серед інших статистичної та фізичної моделі прогнозування завмираючих ефектів, ймовірність явищ згасання у наземних супутникових каналах зв'язку аналізується для трьох міст Ізраїлю, малого, середнього та великого, та порівнюється з результатами, отриманими іншими автори для Копенгагена, Стокгольма та в міст Англії.

Був розроблений стабільний алгоритм та відповідний числовий код для прогнозування явища згасання наземних супутникових комунікаційних ліній для різних видів забудованого терасу, обліку щільності будівель та їх профілю перекриття, висоти антени довільного абонента, розташованого на міській арені. Цей підхід порівнювали з відомою і зазвичай застосовується на практиці фізичною статистичною моделлю Сондерса-Еванса за допомогою експериментів, проведених ними над Стокгольмом, і, нарешті, запропонований стохастичний підхід був апробований завдяки реальним досвідом, проведеним для малих, помірні та великі міста Ізраїлю.

Ключові слова*: явища загасання, супутниковий зв'язок, стаціонарна орбіта, супутникова лінія.*

Introduction

Land–satellite communication (LSC) systems enable users of handle wireless phones, portable computers, or mobile phones to communicate with one another from any two points worldwide. Signal propagation for such systems has become an essential consideration. Path conditions may cause harmful impairments that severely corrupt the system availability and performance. Hence, propagation considerations are very important for successful operation.

To design successful wireless LSC links, stationary or mobile, it is very important to predict all propagation phenomena occurring in such links, to give a satisfactory physical explanation of main parameters of the channel, such as path loss and slow and fast fading, and finally, to develop a link budget compared to total noise at the outputs of the terminals of the channel (called signal noise figures or maximum acceptable path loss.

There are 3 main types of satellites, GEO, MEO and LEO. Geostationary satellites have a geostationary orbit (GEO), which is 36,000 kilometers from Earth's surface. It is called geo-stationary because, in relation to the Earth, it is stationary, since the satellite's orbital period is the same as the rotation rate of the Earth. MEO and LEO satellites are closer to Earth. MEO orbital altitudes range from 2,000 to 15,000 kilometers above Earth, and LEO satellites orbiting between 160 to 2,000 kilometers above Earth. MEO and LEO satellite's orbital rate is greater than the rotation rate of the Earth. For that reason, they are not stationary and appear to be at different relation to the Earth at different time points. However, due to their relatively small distance to the Earth their signals are stronger [1–3].

In a wireless channel, and in land-satellite link, particularly, the noise sources can be subdivided into additive and multiplicative effects. The additive noise is the noise generated in the receiver, such as thermal noise in passive and active elements of the electronic devices, and from external sources such as atmospheric effects, cosmic radiation, and man-made noise [4–8].

The multiplicative noise is a product of various processes inside the propagation channel and is influenced by the following: directional characteristics of the antennas, reflection, absorption, scattering, and diffraction phenomena caused by natural and artificial obstructions present between and around the transmitter and the receiver. Usually, the multiplicative process in the propagation channel is divided into three types: path loss, large-scale (or slow fading), and short-scale (or fast fading) [4–8].

Slow fading results in reflection and diffraction of the signal wave from objects surrounding the subscriber such as hills and corners and roofs of buildings. As shown by previous study and scanning of the corresponding literature [2–5], it is possible to define losses caused by slow fading by Gaussian distribution (PDF & CDF).

Fast fading results in situations where the receiver or the transmitter or the objects surrounding are in movement relatively to the others. So, the properties of the signal not only vary by the multipath, they vary also because of the movement, meaning changes in the paths in which the signal passes [9–12]. The effect of the fast fading on the signal can be seen clearly via the Doppler Effect [11–15]. The corresponding losses caused by fast fading can be described by Rayleigh distribution (PDF & CDF). Another more general form to describe those losses is using Rician distribution, involving parameter *K* of fast fading.

Experimentally approbated models

The main effect on the total path loss comes from the bottom part of the land-satellite channel, where effects of the terrain profile, which cause shadowing (or slow fading), become more appropriate. Furthermore, in the LSC a typical land built-up scenario, the line-of-sight (LOS) path between the satellite and the land terminal (stationary or mobile) can be affected by multipath mechanisms arising from reflection on rough ground surfaces and wall surfaces, multiple scattering from trees and obstacles.

As was mentioned in [1], in such very complicated environments, accounting high speed satellite movements, it is very complicated to differentiate slow fading and fast fading effects, as was done for land communication links analysis; they must be accounted for together. Therefore, we will try to show how to take into account effects of the terrain built-up profile and diffraction and scattering effects for fading description within the LSC channel.

We will analyze two main concepts on how to account for the terrain effects on land–satellite communications. The first is based on the statistical models, whereas another is based on the physical-statistical models. To unify these models and to use them together in our analysis, we assume that the radio signal is moving within a channel only between two states: good and bad, as is shown in Lutz model. As will be shown below, such model can be adapted by use of the Markov's chain, as a basic aspect of pure statistical model (see Fig. 1).

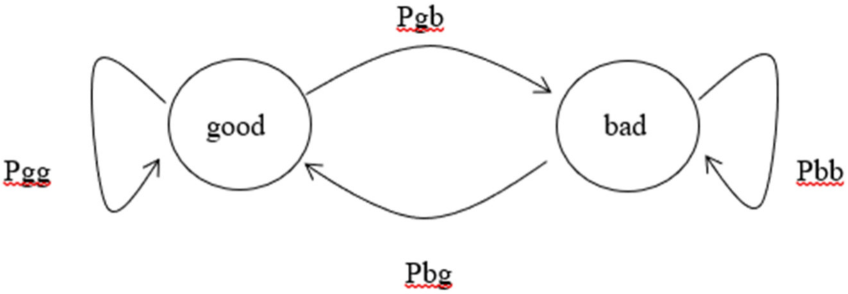

Fig. 1. Markov model of channel state

So, even though some researchers separate statistical and physical-statistical models and show them separately, we will show how to unify these approaches, using the statistical parameters of Markov's stochastic process, statistical distributions of the built-up terrain features and propagation phenomena.

Lutz Statistical Model. This model gives possibility to estimate effect of fading via parameter *A*, which gives information on how much time fading affects information data passing the channel [15]. It is based on Markovian chain. The simple statistics of LOS, is translated as "good" and NLOS, is translated as "bad" (see Fig. 1). In the good state, the signal is assumed to be Rician distributed with *K*-factor, which depends on the satellite elevation angle and the carrier frequency. In the bad state, the fading statistics of the signal amplitude are assumed to be Rayleigh. The transition probabilities, which summarize all mentioned models based on Markov chain are:

- Pgg — probability of transition from good state to good state.
- Pgb — probability of transition from good state to bad state.
- Pbb — probability of transition from bad state to bad state.
- Pbg — probability of transition from bad state to good state.

For a digital communication system, each state transition is taken to represent the transition of one symbol. The transition probabilities can then be found in terms of the mean number of symbol duration spent in each state [15]:

$$P_{gb} = \frac{1}{D_g}\ ;\ P_{bg} = \frac{1}{D_b} \tag{1}$$

Here *D*g is the mean number of symbol duration in the good state and Db is the mean number of symbol duration in the bad state. The time share of shadowing (the proportion of a symbol in the bad state) is:

$$A = \frac{P_{gb}}{P_{gb}+P_{bg}} \tag{2}$$

The sum of the probabilities leading from any state must be equal to the sum of the unit, therefore:

$$P_{gb} + P_{gg} = 1; P_{bg} + P_{bb} = 1 \tag{3}$$

In pure statistical models, the input data and computational effort are quite simple, as the model parameters are fitted to measured data. Because of the lack of physical background, such models only apply to environments that are very close to the one they have been inferred from.

Physical-Statistical Models. On the contrary, pure deterministic physical models provide high accuracy, but they require actual analytical path profiles and time-consuming computations. A combination of both approaches has been developed by the authors of this work. The general method relates any channel simulation to the statistical distribution of physical parameters, such as building height, width and spacing, street width or elevation and azimuth angles of the satellite link. This approach is henceforth referred to as the «Physical-Statistical’’ approach [1, 12, 13].

Physical-statistical models require only simple input data such as terrain distribution parameters. This model describes the geometry of mobile-satellite propagation in built-up areas and proposes statistical distributions of building heights, which are used in the subsequent analysis. We will consider only two of them, which have been fully proved by special experiments for land–land and land–satellite communication links:

- A model of shadowing based on the two-state channel

Lutz model created by Saunders and Evans [1, 2]

- A multi-parametric stochastic model created in [14]

Saunders-Evans Physical-Statistic Model. The geometry of the situation is illustrated in Figure 4. It describes a situation where a mobile is located on a long straight street and a direct ray from the satellite to the mobile from an arbitrary direction.

The geometry of the local situation occurring in the urban scene describes a situation where a mobile is located on a long straight street and a direct ray from the sa-tellite to the mobile from an arbitrary direction. The street is lined on both sides with buildings whose height varies randomly (see Fig. 2).

In the presented model, the statistics of the building height in typical built-up areas was used as input data. The PDFs that were selected to fit the data are the lognormal and/or Rayleigh distributions with unknown parameters of a mean value, *m*, and standard deviation, *σ*. The PDF for the lognormal distribution is:

$$p_b(h_b) = \frac{1}{h_b\sqrt{2\pi}\sigma_b}\exp\left\{-\frac{\ln^2(h_b/m)}{2\sigma_b^2}\right\} \tag{4}$$

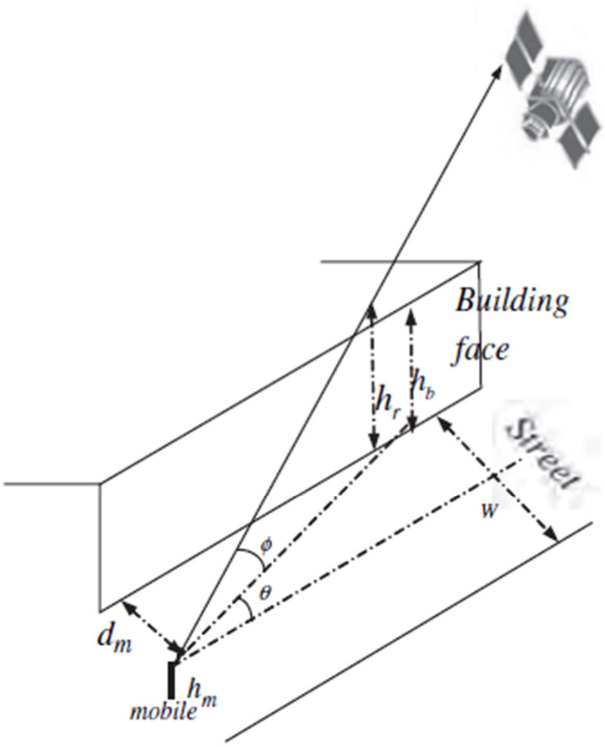

Fig 2. Geometry for mobile — satellite communication in built-up areas

The PDF for the Rayleigh distribution is:

$$p_b(h_b) = \frac{h_b}{\sigma_b^2}\exp\left\{-\frac{h_b^2}{2\sigma_b^2}\right\} \tag{5}$$

The direct ray is judged to be shadowed when the building height *hb* exceeds some threshold height *hT* relative to the direct ray height *hr* (see Fig. 2). The shadowing probability, *Ps*, can then be expressed in terms of the probability density function of the building height, *Pb* (*hb*) as in Ref. [1]:

$$P_s = \Pr(h_b > h_T) = \int_{h_T}^{\infty} p_b(h_b)\,dh_b \tag{6}$$

The definition of h_T is obtained by considering shadowing to occur exactly when the direct ray is geometrically blocked by the building face. Using a simple geometry, the following expression is extracted for h_T:

$$h_T = h_r = \begin{cases} h_m + \frac{d_m \tan\phi}{\sin\theta}, for\ 0 < \theta < \pi \\ h_m + \frac{(w-d_m)\tan\phi}{\sin\theta}, for\ 0 < \theta < \pi \end{cases} \tag{7}$$

The shadowed model estimates the probability of shadowing for Lutz two-state model. The same Markov chain (as shown in Fig 1) is used, but parameters *A*, *Pbad* and *Pgood* are obtained from actual random distribution of the obstructions above the terrain. Parameter A is expressed:

$$A = \int_{h_1}^{h_2} p_b(h)dh \tag{8}$$

where *h* is different heights of obstacles, *h*1 and *h*2 are the minimum and maximum height of the built-up layer:

$$P_b = \begin{cases} lognormal + Rician \\ lognormal + Rayleigh \end{cases} \tag{9}$$

where a lognormal PDF is pure NLOS shadowing. The Rician's PDF describes both the LOS and the multipath component, and the Rayleigh's PDF describes the multipath component of the total signal, when the LOS component is absent:

$$p(S) = (1 - A) \cdot P_{good} + A \cdot P_{bad} \tag{10.1}$$

$$p(S) = (1 - A) \cdot P_{Rice}(S) + A \int_0^\infty P_{Ray}(S|S_0) \cdot P_{LN}(S_0)dS_0 \tag{10.2}$$

Then, we introduce the corresponding CCDF, which describes the signal stability, being the received signal with amplitude r that prevails upon the maximum accepted path loss (R) in the multipath channel, caused by fading phenomena. This can be presented in the following form:

$$CCDF = P_r(r > R) = \int_0^R p(S)dS \tag{11}$$

Multiparametric Stochastic Model. As an example of a physical–statistical model, we present now a stochastic approach, which was used successfully for land communication channels, rural, suburban, and urban description [8–12]. The reason for that is since the proposed physical–statistical model, as was shown in [1, 2, 12, 13], predicts more strictly the fading effects in different LSC links compared to the pure statistical models [6–12].

At the same time, as was mentioned in [15], the physical–statistical model, which is based on a deterministic distribution of the local built-up geometry, cannot strictly predict any situation when a satellite moving around the world has different elevation angles *θ,* with respect to a subscriber located at the ground surface (see Fig. 2). As the result, the radio path between the desired subscriber and the satellite crosses different overlay profiles of the buildings because of continuously changing elevation angle of the satellite during its rotation around the Earth, with respect to the ground-based subscriber antenna.

To predict continuously the outage probability of shadowing in real time, a huge amount of data is needed regarding each building, geometry of each radio path between desired user and the satellite during its rotation around the Earth, and finally, high-speed powerful computer. Most of these difficulties can be handled by using the multiparametric physical — statistical model [14]. Following [14], we consider both the buildings' distribution at the ground surface and their height profile changing in the vertical plane that is, accounting for the 3-D stochastic model of multiple scattering, reflection, and diffraction rearranging the corresponding equations in the case of the LSC link. For convenience, we will repeat some equations presented in [14], which are needed to introduce the main features of this model.

The LSC link is very sensitive to the overlay profile of the buildings as shown in Figure 3, because during its movement around the Earth, depending on the elevation angle ϕ, the buildings' profile will be continuously changed leading to different effects of shadowing in the current communication link (see Fig. 3).

Because real profiles of urban environment are randomly distributed, the probability function *Ph*(z), which describes the overlay profile of the buildings, can be presented in the following [14]:

$$P_b(z) = H(h_1 - z) + H(z - h_1)\cdot H(h_2 - z)\cdot\left[\frac{(h_2 - z)}{(h_2 - h_1)}\right]^n \qquad (12)$$

where: $n > 0, 0 < z < h_2$ and the function *H*(*x*) is the Heaviside step function, which is equal to 1, if *x* > 0, and is equal to 0, if *x* < 0.

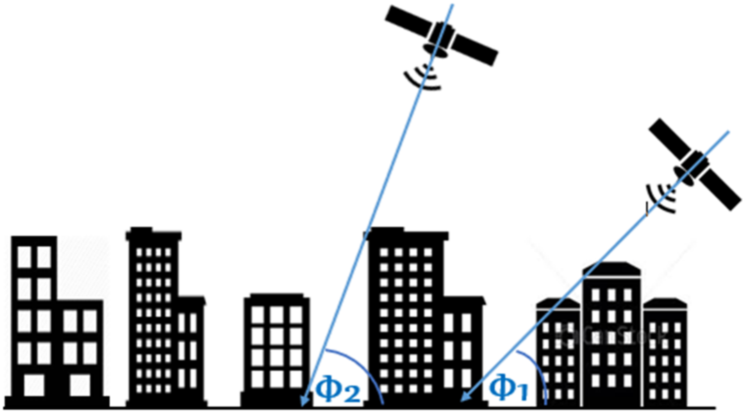

Fig. 3. Change of the profile function *F*(z1, z2), in the vertical plane during the movements of a satellite

For *n* >>1 *Pb*(z) describes the case where buildings higher than *h*1 (minimum height level) very rarely exist. The case, where all buildings have heights close to *h*2 (maximum level of the built-up layer), is given by *n*<<1. For *n* close to zero, or *n* approaching infinity, most buildings have approximately the same level that equals *h*2 or *h*1, respectively. For n =1, we have the case of building height uniformly distributed in the range of *h*1 to *h*2. Parameter *n* can be calculated by the following expression:

$$n = \frac{h_2 - \bar{h}}{\bar{h} - h_1} \tag{13}$$

The average height is given by an investigation of a topographic map of the terrain. In an urban environment, measuring all (or at least, most) of the building's heights the average height can be found. Finally. We can obtain the built-up profile between two terminal antennas for the case when the antenna height is above the rooftop level. According to configuration of the land-satellite links, where $z_2 > h_2 > z_1$ we get:

$$F(z_1, z_2) = H(h_1 - z_1)\left[(h_1 - z_1) + \frac{(h_2 - h_1)}{(n+1)}\right] \tag{14}$$

$$+H(z_1 - h_1)H(h_2 - z_1)\frac{(h_1 - z_1)^{n+1}}{(n+1)(h_2 - h_1)^n}$$

Then, the CDF of the event that any subscriber located in the built-up layer is affected by obstructions due to shadowing effect can be presented as [14]:

$$CCDF(z_1, z_2, n) = \frac{1}{z_2 - z_1}\int_{z_1}^{z_2} P_h(z)dz \equiv \frac{1}{z_2 - z_1}F(z_1, z_2) \tag{15}$$

Numerical computations

To proof the assumptions presented above, we create a numerical experiment, and compute the equations presented in previous section. We use in our computations the following parameters of the built-up terrain and configuration of the link land satellite $h_2 = 100\,m\; h1 = 10m\; z_1 = 3\; z_2 = 100,\; n = 0.01, 0.1, 1, 10, 100$.

Distribution for a building's overlay profile as a function of the subscriber's height *h*1=10m and the satellite virtual height of *h*2=100m (we, as in Fig. 2,, take the height of the roof of higher building which can intersect the LOS trace) for various the terrain factors *n* =0.01 (sky-elevated buildings) to *n*=100 (small buildings) is shown in Fig. 4. It is seen that fore *n*>>1, profile limits to high-elevating buildings, and for *n*<<1 — to small buildings. For *n*=1, the amount of high and small buildings the same. This situation is illustrated by straight line.

Fig. 5 illustrate changes of function of the buildings' profile with change of the height of the receiving antenna. It is seen that with increase of *hr* the influence of the built-up profile becomes weaker; the effect depending on the parameter of the terrain *n*.

Similar property is found for CCDF describing diffraction effect on fading for various heights *hr* and parameters *n*: lower parameter *n*, that is, higher buildings heights much more influence of diffraction of signal from building roofs is observed; this tendency is weak for small-building topography of built-up terrain (see Fig. 6).

Comparison between saunders — evans model and the stochastic multiparametric model

We will prove the accuracy of the stochastic model. To achieve this goal, we will assist the Saunders — Evans model, and the results obtained by Saunders experimentally. Based on the corresponding models and formulas presented above, we will evaluate the *A* parameter, that is valuable in understanding the expected fading occurring in the land-satellite link.

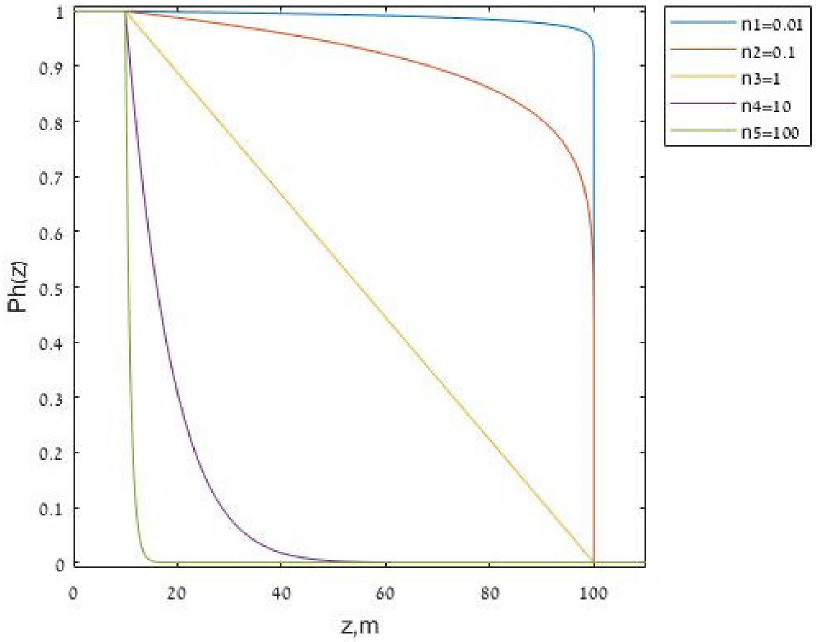

Fig. 4. Distribution for a building's overlay profile presence as a function of the subscriber's height and the terrain factor *n*=0.01, 0.1, 1, 10, 10, for *h*1=10m and *h*2=100m

According to Saunders — Evans model, above the Stockholm was found that *A*=0.24. Working with the topographic map of Stockholm (see Fig. 7), was found that the highest building in Stockholm is 120m. We putted it as *h*2. The lowest building was taken *h*1=3m. By examining the map of Stockholm, was found that the average height of the building was near 30m. By examining the topographic map of Stockholm deeper, we obtained that *n*=3, and that the parameter of fading A=0.25, that is, very close to that found by Saunders and Evans.

At the same manner, working with topographic maps of Ofakim (small town, *n*=10), Be'er Sheva (medium city, *n*=1), and Ramat Gan (large city, *n*=0.1), we can predict the parameter of fading for these three cities of Israel (see Table 1):

It is clearly seen from data computed according to the stochastic multiparametric model that it can be used as a stable and correct predictor of fading phenomena occurring in land-satellite communication links and proves results obtained by

Saunders and Evans experimentally above England and Scandinavian countries: with increase of the height of buildings and decrease of their built-up terrain profile parameter *n*, the effect of fading becomes more significant and can achieve the probability of this phenomenon close to unit. In other words, the probability of fading and its relative duration (via parameter *A*) limits to unit. Thus, for small town Ofakim *A*=0.091, whereas for big city Ramat Gan *A*=0.909, and for medium city, as Beer Sheva, *A*=0.5.

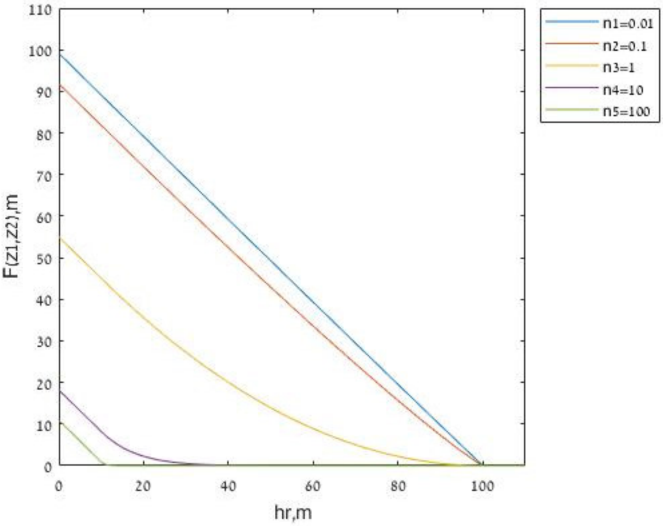

Fig. 5. Distribution of buildings' profile vs, *hr* for various values of the terrain factor *n*

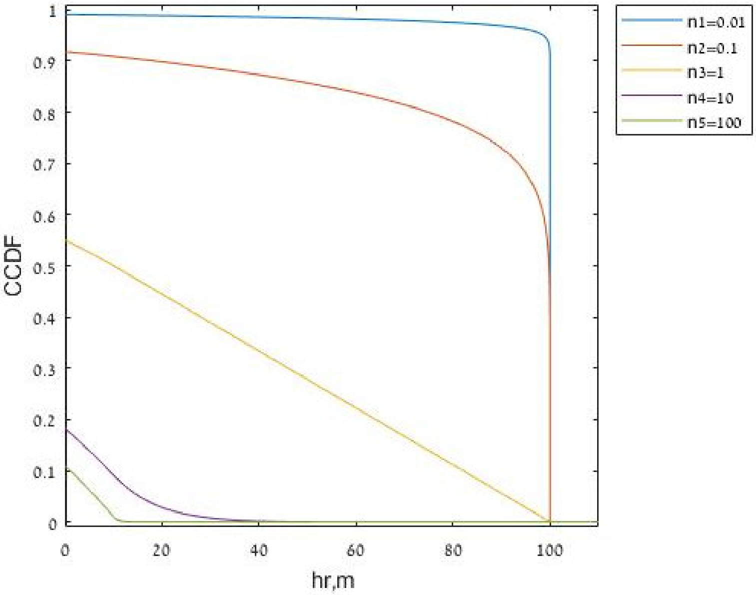

Fig. 6. CCDF as a function of the height of the receiver antenna and the terrain factor *n*

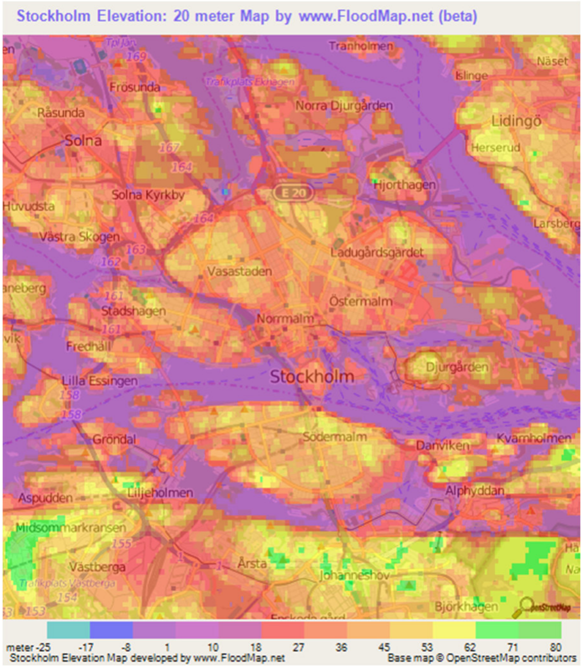

Fig. 7. 2-D topographic map of Stockholm

Table 1

Buildings' overlay parameters for three kinds of cities: small, moderate and large

Cities	n	λ0, km^(-1)		h_1, z_1, m	h_2, z_2, m	A
Ofakim	10	4		3	15	0.091
Be'er Sheva	1	7		3	35	0.5
Ramat-Gan	0.1	11		3	100	0.909

Summary. Was developed a stable algorithm and the corresponding numerical code for prediction of fading phenomenon in the land-satellite communication links for various kinds of the built-up terraing, accounting for the buildings' density and their overlap profile, the height of the antenna of arbitrary subscriber located in the urban scene. This approach was compared with well-known and usually used in practice Saunders-Evans physical statistical model via experiments carried by them above the Stockholm, and finally, the proposed stochastic approach was approbated through the real experiments carried out for small, moderate and large cities of Israel.

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