# Wave propagation channel simulation by satellite-to-indoor radio link

LÓRÁNT FARKAS, LAJOS NAGY, ANDREA FARKASVÖLGYI

*Department of Infocommunication and Electromagnetic Theory, Budapest University of Technology and Economics,*

*lajos.nagy@mht.bme.hu*

***Keywords: propagation model, polarization, ray-launching, satellite communication***

*In our paper we present the simulation of the propagation characteristics of the satellite-to-indoor propagation channel. Our first aim has been to find a correct description of the polarization state of the received inside wave. The result of our first investigations is that the polarization state of the indoor wave signigicantly changes as we move further away from the windows that are the secondary source of radiation. First we examine how the polarization state of a complex harmonic field can be described, and then the results of our first simulations of the polarization state will be presented. A modified 3D ray-launching tool has been utilized for the coverage prediction. A detailed analysis of the dependence of the indoor wave on the elevation angle of the satellite is given, and the wideband characteristics of the channel: delay spread characteristics and Doppler spread, caused by satellite movement are dealt with. The applicability of MIMO systems in satellite communication is also investigated.*

## 1. Introduction

For mobile satellite systems a wide range applications can be foreseen. Indoor operation is one of the key problems in personal wireless communications. Without the possibility of indoor operation, application of satellite systems in personal communications networks would be unlikely. Users of personal communication networks will – sooner or later – force the operators to provide also this kind of service. Therefore, in our opinion, an elaborated tool for the prediction of the indoor penetration would be highly useful.

Due to extreme distances and extreme attenuation the propagation media may be considered a very hostile one. The waves arriving at the buildings do have significantly variable characteristics, but generally for tall buildings it can be assumed that plane waves have some kind of polarization state, mostly an elliptical one.

Once penetrated, the building adds its impact on the wave by multiple reflections, transmission through walls and diffraction through corners and inhomogeneities of building materials.

The field inside the building is a complex one, but it can be assumed to be harmonic and consequently it can be analyzed. As a general framework, we propose a complete simulation tool for the narrow-band and wideband characteristics of the satellite-to-indoor propagation channel.

In this paper we focus as a first step on the polarimetric description of the indoor waves and some conclusions regarding their general polarimetric characteristics in the case of elliptically and linearly polarized incident plane waves will be reached. This first step intends to clarify what kind of antennas would be needed for indoor receivers and what can be achieved using these antennas. The simulation at this stage takes into account multiple reflections and transmissions through walls and is based on a 3D ray-launching tool. Diffraction is intended to be taken into account as a next step.

## 2. Polarization

Every harmonic vector field can be characterized by its polarization property. Generally speaking we can define polarization as a local property of a harmonic vector field as the curve described by the field strength in a given location. According to [1] the polarization of a radiated wave is "that property of a radiated electromagnetic wave describing the time-varying direction and relative magnitude of the electric field vector; specifically, the figure traced as a function of time by the extremity of the vector at a fixed location in space, and the sense in which it is traced, as observed along the direction of propagation".

According to [2], polarization may be classified into three categories: linear, circular and elliptical, of which circular is a special case of the elliptical (in fact one extreme of it) and linear is also a special case of elliptical (the other extreme). Polarization in general, except the linear polarization, can be clockwise or counter-clockwise rotating one.

There are some differences between polarization phenomena viewed by optical specialists and antenna designers. In the theory of antennas, there exists horizontal and vertical polarization, meaning in fact a linear polarization with the end of the electric field in a horizontal plane (horizontal polarization) and along the vertical one (vertical polarization). There is also a difference between the clockwise and counter-clockwise rotating polarizations [3].

In the literature there are two main methods to characterize propagation: the so-called *Forward Scattering*

*Alignment* (FSA) and the so-called *Backward Scattering Alignment* (BSA). FSA is used to determine a change of polarization of a wave propagating to and from an observed target through the surrounding medium. The polarimetric scattering properties of the medium are described in this case by its Jones or Muller matrices. BSA is especially useful when analyzing transmission through a scattering object between antennas of various polarizations. Sinclair and Kennaugh matrices are in use to describe polarimetric properties in this case [5]. Polarization has a dual aspect: on the one hand, it describes the behavior of a complex harmonic vector field, on the other hand it serves as a way to describe scattering properties of different propagation media.

In order to characterize this aspect of the radio wave propagation, the role of precise wave propagation models is particularly important as through measurements is not possible to accurately measure the polarization because we are limited to certain types of antennas. In other words the radiation pattern of the antenna will influence our measurements and will not allow us to gain precise information regarding it. For the model that describes the polarization, a proper definition for the case of complex harmonic vector fields and an adequate set of graphical and numerical representation is needed. Our contribution addresses this problem.

## 3. The Stokes-parameters and the Poincaré-sphere

We can introduce the Stokes-parameters and the Poincaré-sphere [2,3] to characterize the polarization of an arbitrary plane wave. The Stokes-parameters are defined as follows:

$$s_0 = a_1^2 + a_2^2$$
$$s_1 = a_1^2 - a_2^2$$
$$s_2 = 2a_1 a_2 \cos\delta$$
$$s_3 = 2a_1 a_2 \sin\delta$$

where $a_1$ and $a_2$ represent the two perpendicular components of the field strength, one in the plane of the receiver and the other in the plane vertical to the receiver's plane and to the propagation direction. And only three of those four are independent because:

$$s_0^2 = s_1^2 + s_2^2 + s_3^2 .$$

The Stokes-parameters generally are defined by four element vectors: $S = [s_0 \ \ s_1 \ \ s_2 \ \ s_3]$.

For a horizontally polarized linear plane wave we have: S=[1100]

For a linear plane wave with circular polarization (45°): S=[1010]

For a linear plane wave with clockwise circular polarization: S=[1001]

For a linear plane wave with counter-clockwise circular polarization: S=[100-1]

For a non-polarized wave: S=[1000]

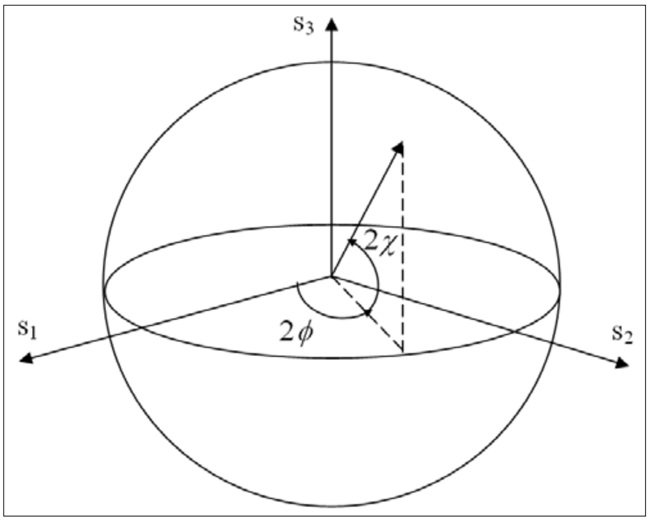



*Figure 1.*
*Characterization of the Stokes-parameters and the Poincaré-sphere*

We can define the triplet $\sqrt{s_0}, \chi, \phi$ called ellipsometric parameters. We can establish the following relationships between them and the Stokes-parameters:

$$s_1 = s_0 \cos 2\chi \cos 2\phi$$
$$s_2 = s_0 \cos 2\chi \sin 2\phi$$
$$s_1 = s_0 \sin 2\chi$$

## 4. Polarization ellipse distribution and the direction of the major semiaxis

The Poincaré-sphere gives a very good visual representation of the various polarization states of a wave: one point on the sphere corresponds to every possible state of a plane monochromatic wave of a given intensity $s_0$ and vice versa. However, in a complex indoor environment we do not have constant field intensity, neither monochromatic waves, but there are multipath components. So the Poincaré-sphere is not adequate for a proper description of such a complex harmonic vector field.

We use another approach [3] for a more detailed description, assuming that the electromagnetic field provided by a harmonic source that penetrates through a building, which suffers multiple reflections, transmissions and diffraction, remains harmonic. Therefore in every point of the space we have a harmonic vector, **V**, a three-dimensional function of the field intensity in that point:

$$V_x(r,t) = a_x(r)\cos(\omega t - \varphi_x(r))$$
$$V_y(r,t) = a_y(r)\cos(\omega t - \varphi_y(r))$$
$$V_z(r,t) = a_z(r)\cos(\omega t - \varphi_z(r))$$

where

for example $\varphi_x(r) = k \cdot r - \delta_x$ and so on meaning the initial phases of the scalar components of the vector field.

We can introduce the following vectors: $p(r)$ and $q(r)$, which depend on the position vector, as follows:

$$p_x(r) = a_x(r)\cos\varphi_x(r), p_y(r) = a_y(r)\cos\varphi_y(r)$$
$$p_z(r) = a_z(r)\cos\varphi_z(r), q_x(r) = a_x(r)\sin\varphi_x(r)$$
$$q_x(r) = a_y(r)\sin\varphi_y(r), q_x(r) = a_z(r)\sin\varphi_z(r)$$

Then we have:

$$V(r,t) = p(r)\cos\omega t + q(r)\sin\omega t$$

Between these two vectors there exists a relationship: they are conjugate semi-axes of the polarization ellipse. If we choose two other vectors, $s(r)$ and $u(r)$ with the following relations:

$$s = p\cos\alpha + q\sin\alpha$$
$$u = p\sin\alpha + q\cos\alpha$$

and we choose $\alpha$ such as $s$ and $u$ become perpendicular,

$$tg2\alpha = \frac{2pq}{p^2 - q^2}$$

then $s$ and $u$ will be the major and minor semi axes of the polarization ellipse. To see this, we can express $V$ in terms of $s$ and $u$ as:

$$V = s\cos(\omega t - \alpha) + u\sin(\omega t - \alpha)$$

Now that we have $s$ and $u$ perpendicular one to the other, we can choose a new coordinate system with the $x'$ and $y'$ axes along $s$ and $u$. In this new coordinate system the components of vector field $V$ will be the following:

$$V_{x'} = |s|\cos(\omega t - \alpha),\ V_{x'} = |u|\sin(\omega t - \alpha),\ V_{z'} = 0$$

Therefore we can conclude that:

$$\frac{V_{x'}^2}{s^2} + \frac{V_{y'}^2}{u^2} = 1$$

so $s=|s|$ and $u=|u|$ will be the major and minor semi-axes of an ellipse that describes the vector field in the rectangular coordinates defined by these vectors, which means that in fact it is the polarization ellipse itself.

So in the most general case in every point of the considered space the polarization is elliptic, but the plane of the ellipse, the direction of the greatest diameter within the plane and the eccentricity of the ellipse varies. That can be easily seen: as $\alpha$ varies, the direction of axes $x'$ and $y'$ also varies and so does the direction of the ellipse's support plane.

In conclusion we propose the following graphical representations for the polarization analysis:

– the distribution of the ellipse eccentricities, giving a description of how diffuse the field gets inside the building due to the obstacles and different propagation mechanisms;
– the two-dimensional histogram of the major semi-axis of the ellipses, varying $\varphi$ and $\theta$, it could give information related to the needed orientation of the receiver's antenna.

## 5. Simulation results and analysis

Using our ray-tracing tool [7,8], we simulated the radio waves generated by an external transmitter (LEO satellite) inside a building. Multiple reflections and transmission through objects were taken into account; diffraction is not included in our model so far. The transmitter generates waves with different polarizations, at 2.4 GHz (downlink band assigned for LEOS by WARC'92): circular (clockwise and counterclockwise) and linear.

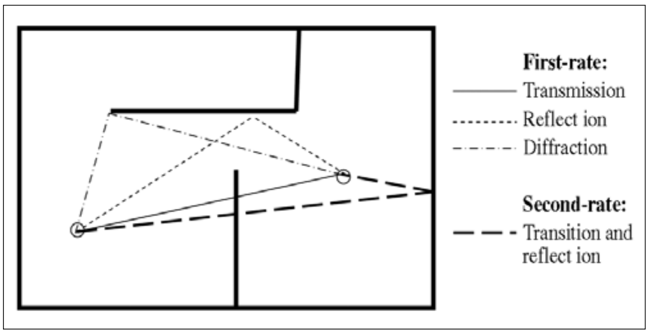



*Figure 2.*
*Some possible first- and second-rate component of the Ray Launching*

The ray launching wave propagation models are based on geometrical optics instead of the full space modeling. The propagated waves are divided into finite space angles and these components are treated independently. The model provides a complete result from point to point by the independent space components and the phenomena on the different surfaces (reflection, transmission, diffraction).

In practice the method of the ray-launching is extended for third-rate arbitrary propagation mechanism combination (in our simulation we took into account seventh-rate combination) or we follow the wave while the field strength of the followed wave decreases under a definite level. Our ray launcher is based on the ray launching concept; it has at its origin the Luneberg-Klein [2] series expansion, a high frequency approximation called geometrical optics.

| | Ray Launching |
|---|---|
| **Characteristics** | • Frequency domain method<br>• Narrow-band sinusoidal excitation |
| **Advantage** | • Easy partitioning |
| **Disadvantage** | • Programming is complicated<br>• Significant ray divergence for complex geometries |

*Table 1. Characteristics of ray launching*

The ray launching in our case has been applied in inverse direction: we launch rays from the receiver locations under 8 different angles,in which directions the rays propagating from the satellite could arrive. We follow the rays until a given number of intersection points is reached, which is 7 in our simulation. We took into account only those rays that propagate in the direction of the satellite position, so basically a plane wave, because the real wave, propagating from the satellite towards the building, can be considered as plane due to the great distance between the satellite and the building.

We present simulation results for these polarizations, in the near field of the building side, at different distances from the windows, for the case of satellites at various elevation angles.

The figures present simulated results of the polarization characteristics, for two regions of the building: one inside the rooms that were directly irradiated through windows and the next one for in-building regions not directly irradiated, inside the building, for low elevation angles and for clockwise, counterclockwise and linear polarization, respectively, of the wave source.

At high elevation angles (45° and above) the principal penetration mechanism is the diffraction through window frames, as transmitted rays would rapidly bounce between the ceiling and the floor, rapidly attenuating, therefore rather few rays arrive into remote regions, so generally valid conclusions cannot be drawn for these angles so far.

Low and medium elevation angles at which the penetration through windows is the principal mechanism, can also be taken into account. The results show that the wave, suffering specular multiple reflections and transmissions, changes its polarization state, in other words the polarization of the incident plane wave will be preserved only in the near-window region; otherwise, in all three examined cases, i.e. for linear, clockwise and counterclockwise polarizations of the incident wave, in distant regions the polarization ellipses become almost evenly distributed, so it seems that there is no direct connection between the polarization state of the incident waves and the polarization of ellipses in different points of the building. As for major semi-axis orientation of the polarization ellipse, it varies rather deeply. However, the distribution curves can be observed to be centered at the angles corresponding to those under which the satellite is seen, or those under which once or more than once the reflected waves reaching the satellite, generate from the source.

## 6. Simulation results for satellite-MIMO channel

In our work, we analyzed the MIMO – satellite channel in scatterer and non-scatterer environment. The transmitter was a three – element dipole antenna system and

*Figure 3.*
*25°, 5°, near zone, clockwise,*
*50% of points clockwise*

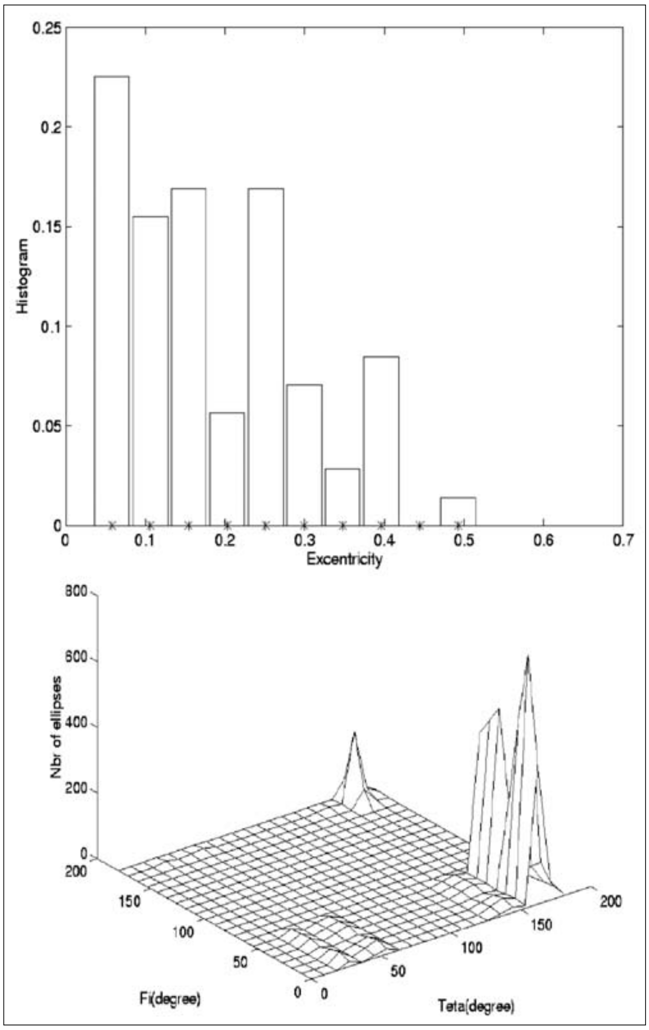
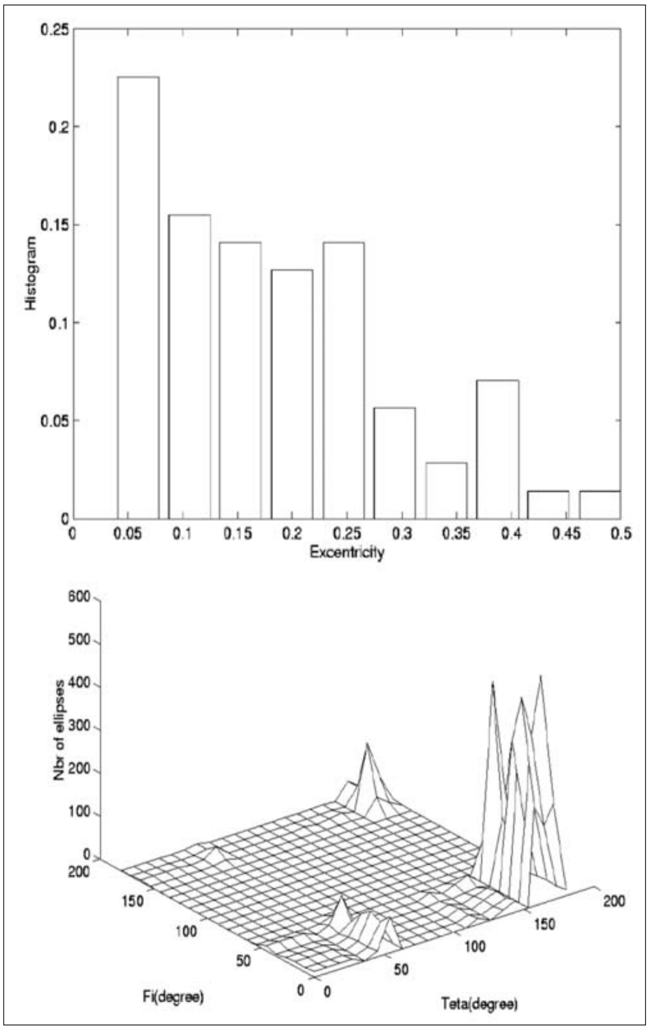



*Figure 4.*
*25°, 5°, near zone, counterclockwise,*
*48.5% of points clockwise*



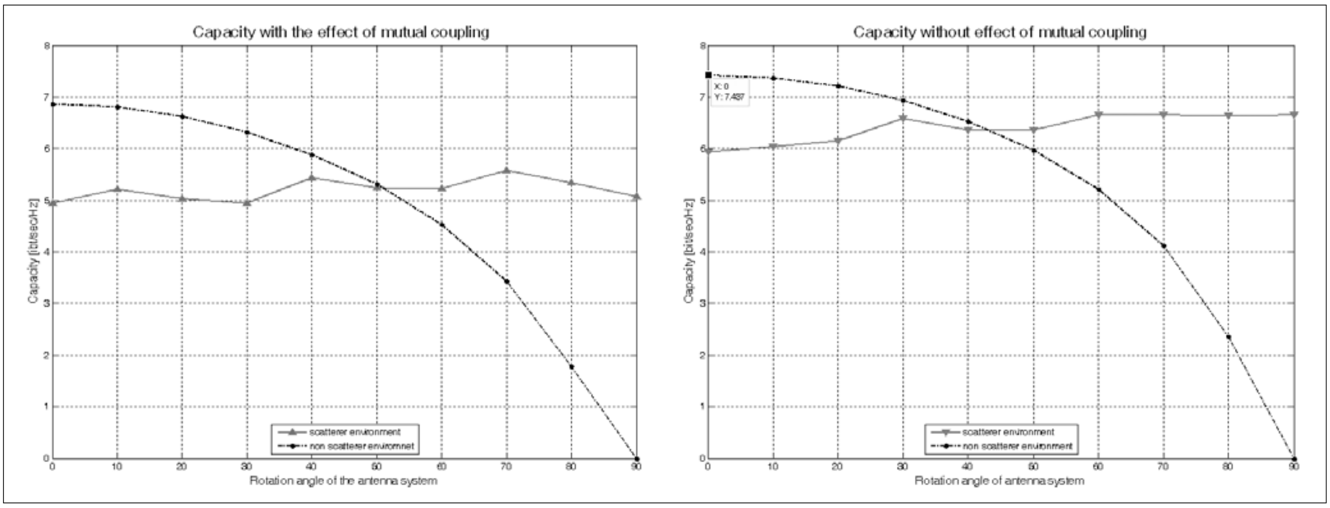



*Figure 7. The capacity for scatterer and non-scatterer environment*

the receiver was the satellite. This is why the simulated system was a SIMO structure. In the course of the simulation the receiver antennas were rotated. At first the tree antennas are in line with the axel-Z (rotation angle 0°). Then we opened the antennas like an umbrella the end position was the plane X–Y (rotation angle 90°). There was 120° between the projections of the antennas on the X–Y plane.

The scattered environment is an inside place where object can reflect and scatter the waves which came

*Figure 5.*
*25°, 5°, far zone, counterclockwise,*
*45.1% of points clockwise*

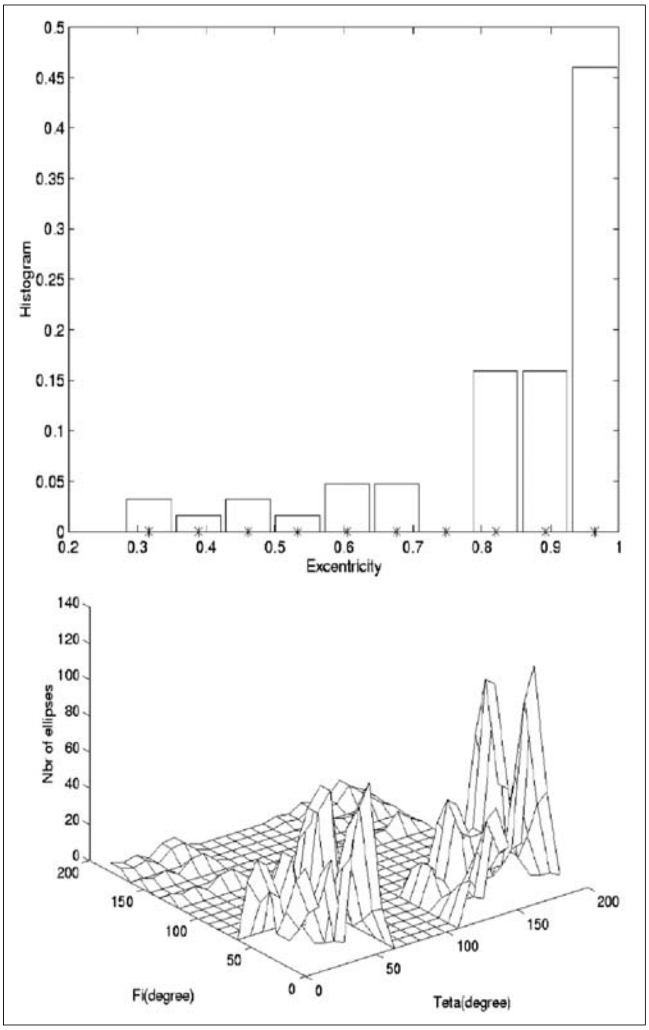
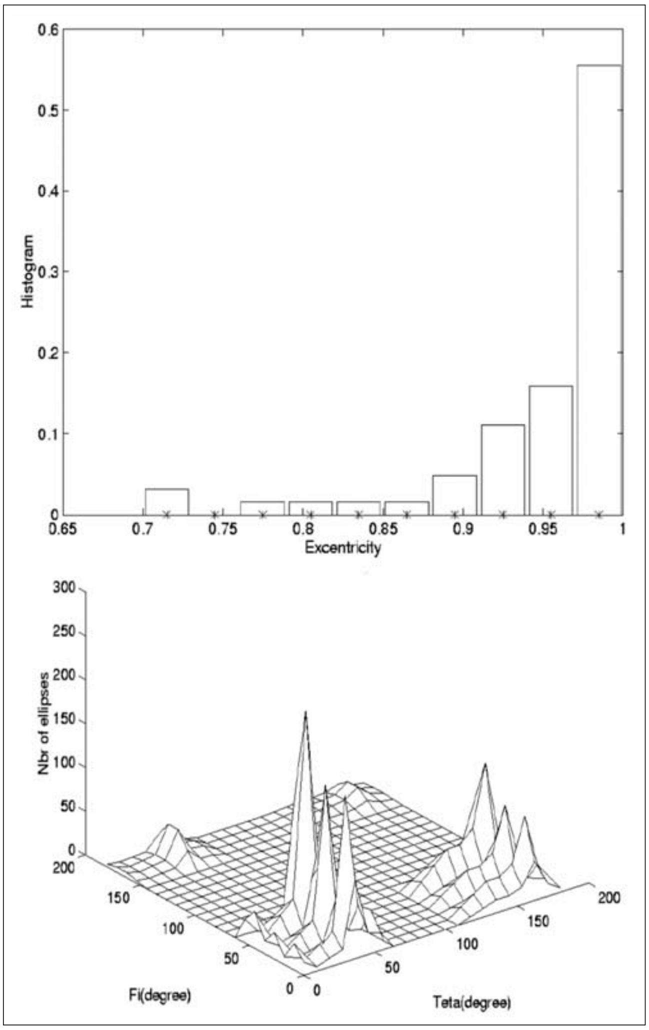



*Figure 6.*
*25°, 5°, far zone, linear,*
*54.8% of points clockwise*



from the satellite. The non-scattered environment is a so special reference inside place in where there is not scattered object. Consequently there is not reflection or scattering between the transmitter and the receiver unit.

*Figure 7* shows the result of the simulation. The broken line denotes the channel capacity in a non-scattered environment, and the continuous line is the channel capacity for standard environment. Without reference to the result of the mutual coupling it is evident that the channel capacity is about moderate in scatterer environment and dynamically fluctuates in non-scatterer environment. Consequently the scatterer environment causes increase in the channel capacity by n×m channel.

## 7. Conclusions

In our work we presented a method for describing the polarization state of a complex harmonic electromagnetic field inside a building. The presented graphical representations can be used to get an insight into the complex polarization phenomena of the radio waves in the case of multipath propagation environments, with application for the satellite-to-indoor radio propagation channel.

A generic conclusion is that, for an office type building, the polarization state of an incident plane wave does not have a major effect on the complex indoor harmonic field. Its polarization is not preserved in the far-window regions. In other words a circularly or linearly polarized plane wave generates a circularly or linearly polarized complex harmonic field inside the building only in a rather close proximity of the penetration regions, otherwise the field is diffuse.

**Acknowledgement**

We would like to thank MIK (Mobil Innovation Center) for its support.

**Authors**

**LÓRÁNT FARKAS** received his MSc degree from the Technical University of Timisoara, Romania in 1996, and his MBA degree from the Budapest University of Technology and Economics in 2005. Currently he is a Senior Researcher at Nokia Siemens Networks Hungary. His interests include streaming solutions, distributed multimedia systems and web technologies.

**LAJOS NAGY** has finished his studies at the Budapest University of Technology and Economics, specialization telecommunications in 1986 and his post-graduate engineering studies in 1988, obtaining a diploma with distinction. He has a Dr. Univ. degree (1990) and a Ph.D. degree (1995). At present he is Assoc. Professor and Head of the Department of Broadband Infocommunications and Electromagnetic Theory at the Budapest University of Technology and Economics. His research interests include applied electrodynamics, mainly antenna design, optimization and radio frequency propagation models. Dr. Nagy is Secretary of the Hungarian National Committee of URSI and the Hungarian delegate to the Section C of URSI. He is leading the Hungarian research teams in COST 248 and ACE2 EU projects. He has published over 100 papers.

**ANDREA FARKASVÖLGYI** graduated from the Budapest University of Technology and Economics, Faculty of Electrical Engineering, in 2002. She finished the Ph. D. school at the Department of Broadband Infocommunications and Electromagnetic Theory in 2006. Her research interests include satellite systems and MIMO antenna systems.

**References**

[1] IEEE Standard 145-1983, IEEE Standard Definitions of Terms for Antennas.

[2] C. E. Balanis, "Advanced Engineering, Electromagnetics", Wiley & Sons, 1989., pp.154–173; 748–760.

[3] M .Born, E. Wolf, "Principles of Optics", Pergamon Press, 1975., pp.28–36.

[4] G. R. Hoeft, "Ground Penetrating Radar", (1998), http://www.g-p-r.com

[5] Z. H. Czyz, "Polarimetric Bistatic Scattering Transformations as seen from Two Different Points of View: Optical (Propagation) and Radar (Transmission) – The Poincaré Sphere Analysis", U.R.S.I. General Assembly, 1999., p.359.

[6] D. J. de Smet, "A Closer Look at Nulling Ellipsometry", 1995., http://www.tusc.net/~ddesmet

[7] Z. Sándor, L. Nagy, Z. Szabó, T. Csaba, "Propagation Modeling", Microwave and Optics Conference, MIOP'97, Sindelfingen, Germany, 1997., pp.213–215.

[8] Z. Sándor, L. Nagy, Z. Szabó, T. Csaba: "3D Ray-Launching and Moment Method for indoor Radio Propagation Purposes", The 8 International Symposium on Personal Indoor and Mobile Radio Communications, PIMRC'97, Helsinki, Finland, 1997., Vol. I., pp.130–134.

[9] Adrián K. Fung, "Microwave Scattering and Emission Models and their Applications", Artech House, 1994., pp.14–26.

[10] B.G. Molnár, I. Frigyes et al, "Characterization of the Satellite-to-Indoor Channel based on Narrow-Band Scalar Measurements", PIMRC'97, Helsinki, Finland, Vol. 3., pp.1015–1018.

[11] Raymond L. Pickholz, "Communications by means of Low Earth Orbiting Satellites", Modern Radio Science, Oxford University Press, 1996. pp.133–151.