Ana Katalinić Mucalo,Radovan Zentner, Nikola Mataga

Benefits and Challenges of Deterministic Reference Channel Models

The paper introduces a new paradigm for reference channel models. Current reference channel models are designed as platforms that generate radio channels for testing using random values for their parameters. These parameters follow some pre-established distribution based on process called parameterization, i.e. statistical processing of previous real measurements or accurate ray tracing simulations. The paper argues that random generated channels give either no new insight or even delusive information and should be replaced with the initial set of radio channels that was used for parameterization. Therefore a deterministic reference channel model, as an emulator of previously recorded real radio channels, is proposed and its potential elaborated.

Key words: COST 259, COST 273, Reference radio channel models, MIMO

Pogodnosti i izazovi determinističkog referentnog modela radijskog kanala. U radu se uvodi nova paradigma za referentni model radijaskog kanala. Postojeći referentni modeli radijskog kanala dizajnirani su kao platforma koja generira radio kanale za testiranje pomoću slučajnih vrijednosti za svoje parametre. Ovi parametri prate neke unaprijed utvrđene raspodjele koje potječu iz procesa parametrizacije, odnosno statističke obrade prethodnih mjerenja ili točnih simulacija metodom slijeđenja zrake. U radu se tvrdi da slučajno generirani kanali ili ne daju nove uvide ili čak daju obmanjujuće informacije i valja ih zamijeniti s početnim skupom radijskih kanala koji je korišten za parametrizaciju. Stoga je predložen deterministički referentni model radijskog kanala, kao emulator prethodno snimljenih stvarnih radio kanala, te je njegov potencijal razrađen.

Ključne riječi: COST 259, COST 273, referentni model radijskog kanala, MIMO

1 INTRODUCTION

There has been a repeating need for Reference Channel Models (RCM), platforms that would enable realistic performance comparison and testing for advanced digital wireless communication systems with MIMO air interfaces, both fixed and mobile. Historically, these reference channel models would in essence look like random radio-channel generators that would generate random radio-channel characteristics, based upon some previously calculated parameters [1-5]. These parameters themselves were calculated from statistical analysis of available sets of measured radio-channels (data with desired geographical similarities, like sets for indoor scenario, urban scenario, suburban scenario etc.).

Therefore, reference channel models are also called "stochastic" or "stochastic based" since their output are channel transfer functions or matrices (static or dynamic, for mobile channels) which come as an result of stochastic process. Often the term "reference" is even omitted from their description or their title, assuming stochasticity as an exclusive approach for reference channel models.

The stochastic process in stochastic RCM is controlled by parameters of propagation extracted through different methods, such as parameterization using cluster assumption (e.g. [1-2]), all build upon a set of channel measurements or advanced numerical full wave channel simulations like ray-tracing method. The process of creating a reference channel simulation model is depicted in Fig. 1. Upper part (Fig 1.a) depicts a process of obtaining information about representative channels (statistically sufficient number of cases per environment class, i.e. macro, micro, pico, urban, sub-urban environments), either numerically (blue) or by measurements (red); lower part (Fig. 1.b) is a scheme of building a reference channel model, using a set of vector channel models either by direct use of already determined set of vector channel models, as it will be proposed in this paper (upper branch in green), or by building stochastic model through complex process of parameterization, followed by generating arbitrary number of random realizations of the model (lower branch in orange).

It is worth noting that stochastic based channel model realisations do not necessarily resemble any real physical

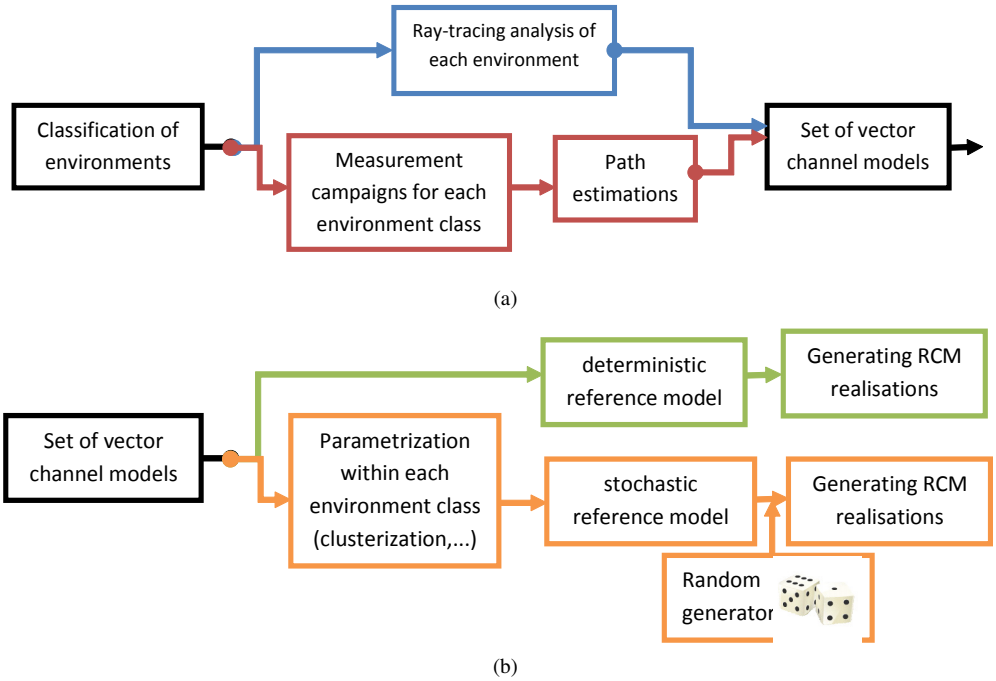

Fig. 1. Process of gathering set of vector channel models as a basis for RCMs (a) and process of obtaining reference channel models (b)

situation in some concrete geographic location or area.

It is however assumed, that these model realisations enable insight for various possible real-world geographical situations since they originate from real-world channels, which were fed to stochastic reference channel model. However, this assumption is only vaguely correct, since these realisations could, due to their random nature, represent various unrealistic, awkward "geographical" situations as well.

The main advantage of stochastic RCMs is that they are defined with limited, small number of parameters, typically a table on one sheet of paper or less, which can then be easily implemented on every modest computer. However, with increase in computer speed and availability of RAM and hard disk memory in large quantities, it is worth considering an alternative approach for reference channel modelling.

The alternative approach would be a "deterministic" reference channel model, which would directly encompass only measured and/or ray-tracing analyzed channels from real world geometries, the ones that would otherwise be used for feeding the stochastic channel models before parameterization.

Should double directional geometry based reference channel models in the future be stochastic or deterministic? The paper gives some thoughts on this question, starting with our experiences that motivated this enquiry, followed by briefly illustrating how stochastic models work, than listing the major advantages of prospective deterministic RCMs, including the implementation challenges and work ahead and finalizing with concluding remarks.

2 MOTIVATION

The motivation for this paper could fit into one main question: after spending a lot of resources (both time and expenses) for obtaining data from measurements or ray tracing simulations, why to go through a complex parameterization process at all? Referring to the Fig. 1 once again, our main question is whether it is possible (or reasonable) to base RCM on *raw* data only.

This consideration originates from our efforts to contribute to the RCM development within COST projects, namely parameterization for COST 259 and COST 273 models [1-3]. In spite of these models being quite well defined, specific and detailed, there is a permeating lack of parameter definitions.

To be more specific, we performed exhaustive ray tracing simulations in order to calculate parameters for visibility regions (see Section 3 for definition) [6-7]. We had run simple, yet still quite time consuming 3D ray tracing simulations[1] and obtained some intriguing results. In [6] we

[1]The work and/or papers where we used ray tracing tool refer to ray tracing 3D analysis tool developed by Prof. Vittorio Degli-Esposti at the University of Bologna [8]

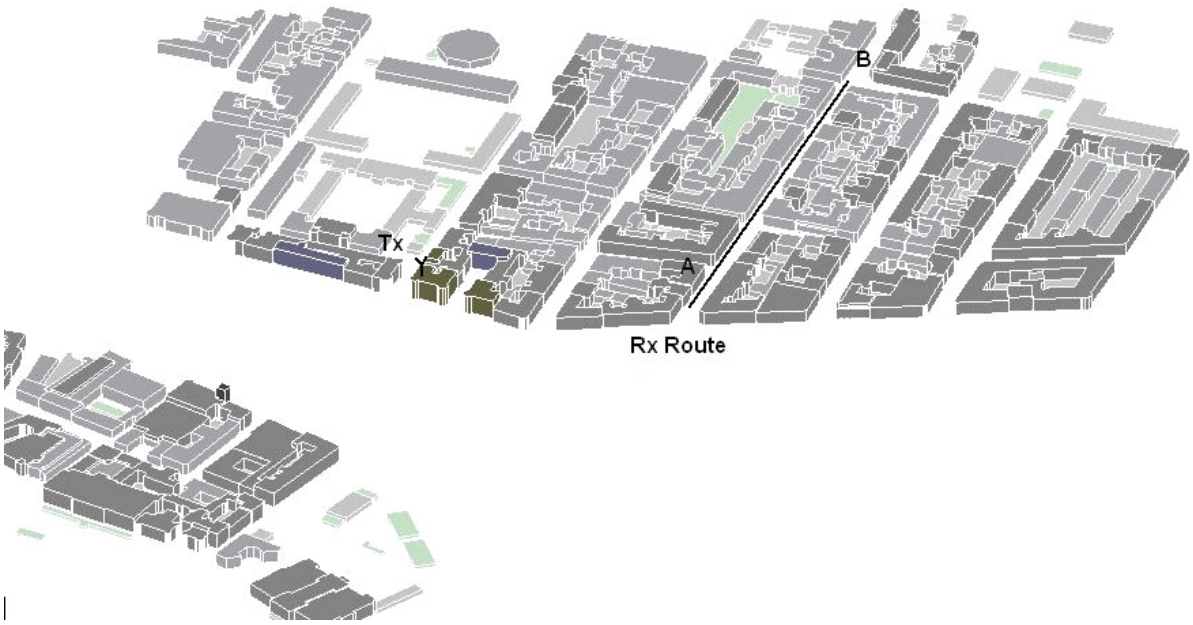

Fig. 2. Simulation scenario – 200 m long route in Stockholm

placed a 200 m long test route along a street on the map of Stockholm (Fig. 2). We ran simulation for 200 receivers at height of 2 m, with the distance between two adjacent receivers set to 1 m (this scenario describes the situation where the mobile station (MS) moves along a straight line and we track the multipath variations, with resolution of one meter). The transmitter was placed above the rooftop, so the whole scenario corresponds to the macro-cellular case, as defined in COST 259 model.

We took into consideration up to two possible events, which could be line-of-sight, reflections or diffractions (scattering wasn't considered at this point due to the computational time limits) and their combinations (1st and 2nd order reflections, 1st and 2nd order diffractions, 1st order reflections with consecutive diffractions and vice-versa). No line of sight was observed, due to the obstructing buildings, and also only a single pure reflection. In order to get insight into the dynamics of multipath variation, Fig. 3 shows, for each observation point along the path, calculated total power of the rays and power contributing exclusively to categories of observed propagation modes double diffraction mode, reflection & diffraction mode. All sums are done non-coherently. Only for the point at the 91st meter of the route, a single reflection is also detected.

After refining MS trajectory resolution we still observed a very dynamic, rapidly varying environment within a few

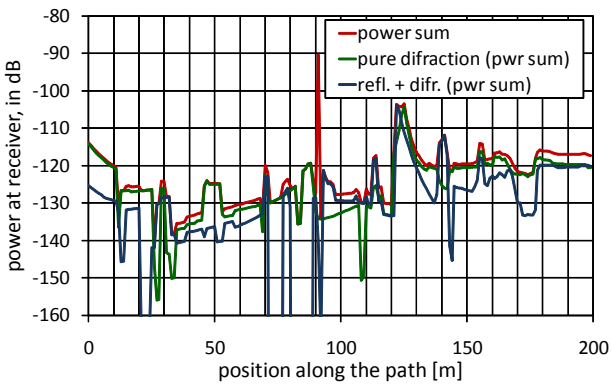

Fig. 3. Power of rays (non-coherent power sum) along the RX route (taken from [6]). Total power at each RX is given (red), as well as its separate constituents, power of double diffracted rays (green) and mixed reflected + diffracted rays. No line-of-sight (LOS) rays were present and only one pure reflection (the peak in the total power, at RX location at 91st m)

10s of centimetres [7]. If statistically processed, lot of data (or propagation possibilities) would be neglected. On the other hand, when replaced by a stochastic function, radio channel realisations become dependent on the random values of a specific distribution, which may yield realisations

far from reality.

In this paper we try to give a balanced answer to the question, if original channel records when used directly, though less in number of channel realisations, give more genuine results than output channel realisations from stochastic RCM.

The following sections will elaborate our hypothesis that rigorous ray tracing simulations or measurements can be used directly thus creating a new paradigm - deterministic reference channel models.

3 STOHASTIC REFERENCE CHANNEL MODELS IN BRIEF

Generally speaking, every reference radio channel model should fulfil two opposite requirements: it should be detailed in order to correspond to the real propagation conditions as much as possible, but also easily implementable on high-end standard PC equipment. In order to meet these two criteria, without giving up some kind of robustness and generality, a trade-off is achieved in terms of simplified, i.e. less realistic stochastic or "stochastic based" RCMs.

These RCMs are usually developed by parameterizing huge amount of data obtained from exhaustive measurements. Instead of measurements accurate ray tracing simulations could also be used. Since processing of data is laborious process, which in the end results in a simplified and potentially unrealistic model, we were motivated to consider somewhat different approach.

To illustrate advantages and disadvantages of deterministic and stochastic RCMs we will first take a look into some of standardized stochastic-based RCMs. For this paper we have chosen RCMs developed under the scope of COST[2] projects (namely directional COST 259 and double-directional COST 273 models for the future wireless networks with MIMO interface) since we have been involved in some of their actions.

COST 259 [1],[2] is geometry based stochastic channel model, which describes radio propagation characteristics in operating environment using 3-level structure:

1. *Cell Types* - macro-, micro- and pico- cells;
2. *Radio Environment* – defined for each cell type, generalized representation of the environment (urban, rural, hilly etc.);
3. *Propagation Scenarios* – random realization of multipath conditions; large scale parameters are constant within the propagation scenario.

[2]European cooperation in the field of Scientific and Technical Research

Specific environments in COST 259 model are defined by three kinds of parameters:

1. *external* - describe specific features of radio environment (e.g. frequency, height of the base station, height of the mobile station, typical distance from base to mobile station etc.);
2. *global* - describe propagation characteristics of a certain environment;
3. *local* - random realizations of parameters that describe instantaneous channel conditions in a local area.

Altogether, COST 259 defines 13 different radio environments, each with its own parameters. Specific parameters decrease complexity and enable the model to correspond well with the real-life scenario; large number of different scenarios gives the model generality.

COST 273 model [3],[9] was derived from COST 259 with several key differences [10]. First, a number of new scenarios have been defined (e.g. peer-to-peer, outdoor-to-indoor etc.) and all parameters (for both "old" and new scenarios) have been updated. The 3-level structure has been kept: in COST 273 also macro-, micro- and pico- cells are defined, but with one generic model for all radio environments. This generalization has contributed to the simplicity of concept, but reduced model's flexibility for adapting to, and modeling of, properties of different scenarios.

COST 259 model has introduced *cluster* approach. Cluster is defined as a group of rays with similar angles of arrival and time delay, which decreases both computational time and complexity. Later on, COST 273 introduced *twin-cluster*, which enabled modelling of multiple-interactions. Twin cluster is actually one cluster split up into two representations of itself (one as seen from the BS and another one as seen by the MS), where both realizations look identical, like twins. This opened another area of research, but also a kind of controversy, which we have addressed in [11]: should all rays be modelled as multiple-bounced (for simplicity) or should single-bounced rays be modelled as such, due to the fact that they are the strongest?

Another issue specific for COST models is introduction of *visibility regions*. Visibility region (VR) defines an area in which certain cluster is active or non-active.

This should contribute to the effectiveness of the model, however, its parameterization is still lacking. The literature available on this issue is rather limited and definition of typical parameters for VRs is in its early stage. Our preliminary work regarding VRs [6-7] has motivated us to write this paper.

Considering the number of various scenarios for which COST models are applicable, it is obvious why they are

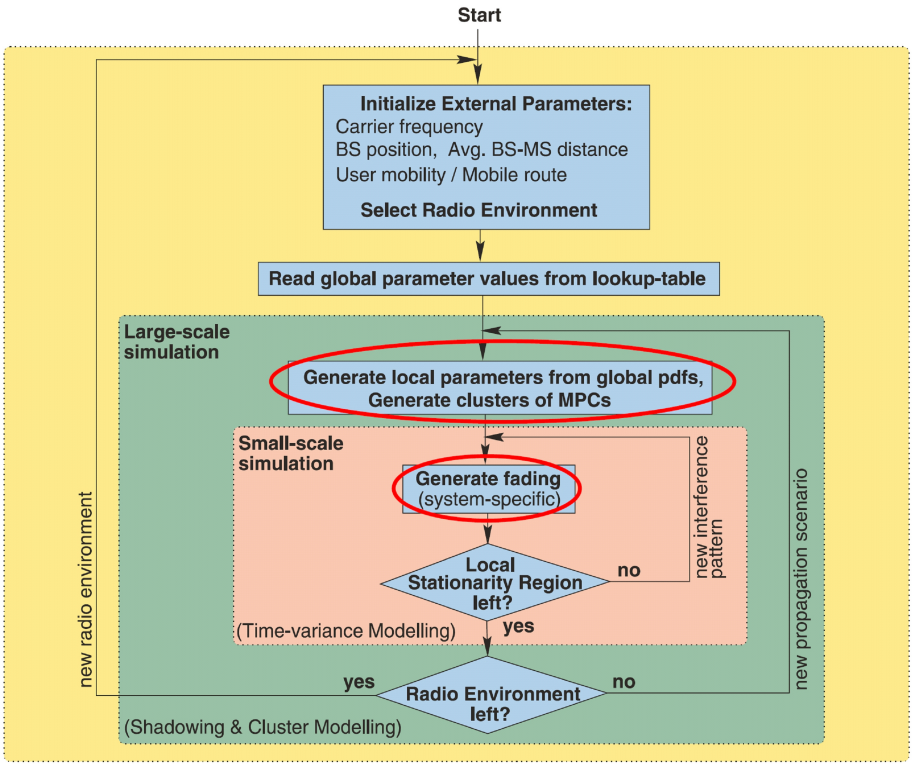

Fig. 4. Flowchart for the implementation of COST 259 model (taken from [1]). The random part of the flowchart is encircled red

considered as some of the most general. Still, they are stochastic and somewhat distanced from the real-life radio environment due to some assumptions, like assumption of a complex Gaussian delay tap statistics (which requires high number of multipath components) or simplified function of the shadowing effect during the transition between environments.

The structure of COST models defines a framework from which the channel impulse response can be derived. The implementation chart for COST 259 model is depicted in Fig. 4. It illustrates how a number of parameters are generated randomly, in accordance with corresponding distribution and parameter values (the random part of the flowchart in Fig. 4 is encircled red). This will not necessarily give erroneous results in terms of "realness", but because of the introduced randomness, there exists a substantial chance of unpredictable stochastic events that would cause occurrence of misleading final results.

4 DETERMINISTICAPPROACH – THE IDEA AND METHODOLOGY

Deterministic RCM enables realistic performance testing of wireless systems with MIMO capability, by virtue of providing system simulations on pre-measured or pre-simulated (using accurate ray tracing analysis tools) set of double-directional geometry-based radio channels. Its flow chart is depicted as an upper branch of the Fig. 1b). Since every RCM ultimately relies on some realistic channel information, obtained either through measurement or through ray-tracing simulation, deterministic RCM would systemize these data in an accessible manner, a very precise database, so that wireless system testing can be performed directly on each of the recorded channels from the set. This not only bypasses cumbersome process of statistical evaluation of available channel data and parameter extraction necessary for stochastic RCMs, but ensures system testing on real channel data.

Introducing the "truly deterministic" RCM represents quite a challenge. However, this deterministic approach has been somewhat introduced through so-called *hybrid* models which typically use deterministic approach for defining radio environment and propagation conditions and then apply statistics for the effects which cannot be adequately described by deterministic models or are missing [12].

Deterministic RCM would actually be a database of real and accurate double directional channel models obtained by rigorous ray tracing simulations or from measurement campaigns. As much as measurements seem adequate, because they are done in real life environments, they have several drawbacks. Firstly, they measure signal

level, but do not provide information about the radio channel itself. Even with the state of the art equipment (e.g. channel sounders) it is difficult to determine all multipath components or their parameters, like angles of departure. Secondly, measurement campaigns are quite expensive and time consuming. Additionally, in order to provide reasonable and acceptable measurement results, in terms of standard deviation and errors, measurements need to be repeated, which makes measurement campaigns even more expensive and time consuming.

Alternative is ray tracing, a method based on the laws of optical geometry, namely the Geometrical Theory of Diffraction (GTD) [13] or the Uniform Theory of Diffraction (UTD) [14]. A signal, which is in real life electromagnetic wave, is represented as a simple ray, which is then *tracked* through the radio environment from the transmitter to the receiver. Depending on the propagation conditions along the paths, rays experience different modes of propagation such as line of sight, reflection, diffraction, scattering and/or their combinations.

Ray tracing can provide a very detailed spatial resolution and keep record of a high number of parameters (angles of arrival and departure in 3D, time delay, electromagnetic field strength etc), giving thus a detailed insight into the radio environment properties itself. This, along with lower costs and the fact that they are easier to conduct (compared to measurements), makes ray tracing models a reasonable alternative. However, the "success" of ray tracing model highly depends on how accurate and detailed data are. To clarify, ray tracing simulations are conducted over the database of radio environments. This database normally contains at least data about terrain (heights) and buildings (heights, shape, electromagnetic properties of walls), but sometimes also specific constructions, such as cranes, traffic signs, bus stations etc. Creating and updating such a database might be quite time consuming, but today it is actually done quite often with sophisticated planning tools, so it is no longer unavailable or hard-to-obtain information. Besides accurate databases, ray tracing model requires also a tool which could conduct simulations, calculate obtained values and finally process data (such as a 3D ray tracing tool in [8]). Furthermore, ray itself has its limitations (as it is two-dimensional and thus can provide infinite field resolution, which is not the case in reality), so in some future considerations ray might be replaced with a beam (this approach has already been applied in some papers within COST2100 project, as stated in [12]).

To conclude this section, this paper proposes ray tracing simulations as the main method for generating a set of double directional channel models as a base for deterministic RCMs due to the benefits of significantly less expensive equipment and proceedings. Measurements might be used for verification of specific scenarios or simply as an addition if available.

5 BENEFITS AND CHALLENGES OF DETERMINISTIC RCMS

5.1 What benefits deterministic models offer?

In order to cover all interesting scenarios for the model, current classification in COST 273 model [3], or its future improvements can be seamlessly adopted. All measurement or simulation campaigns, current and future, could be included in deterministic RCMs.

The deterministic RCMs overcome one drawback of stochastic RCMs that is typically neglected, i.e. assumed "insignificant" without deeper investigation: its unreliability due to the parameterization and due to implementation through random process, i.e. due to two independent causes. In more detail:

- parameterization process, no matter how ingenious and complex, introduces some distortion of reality due to its statistical nature of classifying a set of extreme complexity/diversity
- Implementation through random process causes loss of control over RCM realizations with the possibility of obtaining geometries/realizations with strong deviation from reality (uncertainty).

In case of deterministic RCMs, all realizations are fully realistic (to the accuracy of measurements or ray-tracing analysis) and both of these uncertainty-causing factors are avoided.

For fair comparison between the two different wireless systems identical RCM realizations should be tested on both systems. We should not allow for running different random sets of RCM realizations even in case of stochastic RCM. Yet this would require nearly as much additional effort for users of stochastic RCM (e.g. database building and other programming and computer memory resources), at least for later comparison, as directly implementing deterministic RCM.

Finally, it may look attractive to use stochastic RCMs with an argument that it can generate much more channel realizations than the initial number of (measured or simulated, realistic) realizations. However, the price paid for obtaining new realizations in form of potentially misleading non-realistic realizations may be too high to accept.

5.2 What challenges face deterministic RCMs?

Deterministic RCMs would typically consist of a large database of measured paths, classified upon considered environments. In order to make it wideband, the record could

in general for each point on a path contain data about directions of departure and arrival (both azimuth and elevation), attenuation, time delay, and polarization data for each ray present (for calculation of MIMO matrix and Doppler shift). This requires management and implementation of a large database. Some compression techniques from image-processing may be applicable, since most rays do not vary significantly from point to point along the mobile unit trajectory.

There are many challenges, from conducting appropriate measurements/full wave simulations, adopting already available ones, and making them simulate the real channel which could then be applied on a certain modulation and coding technique.

6 CONCLUSION

It has been shown that there is some unreliability involved when using stochastic RCMs. This fact, in conjuncture with simplicity of deterministic RCM imply that deterministic RCM is perspective alternative to its stochastic counterpart. However, there are many issues to be resolved still, like database accuracy, problems in diffuse scattering modelling and challenges about computer implementation, since deterministic RCM would require a large database of realistic mobile unit trajectories, containing in each record all the necessary data about the rays present at their loci.

Deterministic RCMs could give information about multipath components in time and space (propagation delay, ray paths, angles of departure and arrival of the multipath field, etc.). Additionally, implementation of Doppler shift and co-channel interference could not be directly copied from their respective stochastic-model counterparts.

Deterministic models could, in some prospective future, offer all encompassing repeatable, reliable standard for verification and fair comparison of current and future wireless communication systems with MIMO schemes, of smart antenna systems and space-time coding techniques.

REFERENCES

[1] Molisch et al., "The COST 259 Directional Channel Model – Part I – Overview and Methodology", *IEEE Transactions on Wireless Communications*, vol. 5, No. 12, pp. 3421-3433, 2006.

[2] H. Asplund et al., "The COST 259 Directional Channel Model – Part II – Macrocells", *IEEE Transactions on Wireless Communications*, vol. 5, No. 12, pp. 3434-3450, 2006.

[3] L. M. Correia (Ed.), *Mobile Broadband Multimedia Networks (Techniques, Models and Tools for 4 G)*, Elsevier, 2006, 600 p.

[4] A. A. M. Saleh, R. A. Valenzuela, "A Statistical Model for Indoor Multipath Propagation", *IEEE Journal on Selected Areas in Communications*, vol. 5, no. 2, February 1987

[5] Q. H. Spencer, B. D. Jeffs, M. A. Jensen, A. L. Swindlehurst, "Modeling the Statistical Time and Angle of Arrival Characteristics of an Indoor Multipath Channel", *IEEE Journal on Selected Areas in Communications*, vol. 18, no. 3, March 2000

[6] R. Zentner, A. Katalinic, "Dynamics of Multipath Variations in Urban Environment", *Proceedings of the 3rd European Wireless Technology Conference 2010* (Paris, France), pp. 125-128, September 2010

[7] A. Katalinić, R. Zentner: "Microscopic Level of Visibility Regions for Urban Environment Scenarios", *5. European Conference on Antennas and Propagation – EuCAP* (Rome, Italy), pp. 2042-4046, April 2011

[8] V. Degli-Esposti, F. Fuschini, E. M. Vitucci, G. Falciasecca, "Speed-Up Techniques for Ray Tracing Field Prediction Models", IEEE Transactions on Antennas and Propagation, Volume 57, Issue 5, pp:1469 – 1479, May 2009

[9] I. Sirkova, "Overview of COST 273 Part I: propagation modeling and channel characterization", *Proc. of the XLI International Conference on Information, Communication and Energy Systems and Technologies - ICEST* (Sofia, Bulgaria), pp. 29-32, 29th June - 01st July 2006.

[10] P. Almers et al., "Survey of Channel and Radio Propagation Models for Wireless MIMO Systems", *EURASIP Journal on Wireless Communications and Networking*, volume 2007, 2007.

[11] R. Zentner, A. Katalinic, R. Nagy, "Qualitative Comparison of GSCMs with Single, Mixed and Multiple Bounce Schemes", *Proceedings of 51st Conference Electroncs in Marine*, Zadar (Croatia), pp. 279-284, September 2009.

[12] R. Verdone, A. Zanella (Eds.), *Pervasive Mobile and Ambient Wireless Communications*, COST Action 2100, Springer Verlag, 2012, pp. 79-84

[13] J.B. Keller, "Geometrical Theory of Diffraction", *J. Opt. Soc. of America*, vol. 52, No.2, pp. 116-130, Feb. 1962

[14] D.A. McNamara, C.W.I. Pistorius, J.A.G. Malherbe, *Introduction to the Uniform Geometrical Theory of Diffraction*, Artech House, Boston London, 1990

Ana Katalinić Mucalo graduated electrical engineering at University of Zagreb in 2005. Since graduation she has been with Radiocommunications Department at Croatian Post and Electronic Communications Agency (HAKOM) as an Expert for Microwave and Satellite Networks, dealing mostly with frequency planning and interference analysis of fixed point-to-point and satellite links, as well as with cross-border coordination for fixed networks. She is also engaged in work of CEPT working group SE (Spectrum Engineering), which deals with compatibility studies and development of sharing criteria between different radiocommunications services and provides technical background for ECC decisions and recommendations. Her research interest is related to radio channel modelling for MIMO wireless systems, focusing especially on dynamic multipath effects, visibility regions parameterization and implementation of mobility. Currently, she is preparing her PhD thesis on Deterministic Radio Channel Modelling. She has published several scientific papers in conference proceedings and participated in European Union funded project for wireless communications COST2100. She is IEEE member and currently serves as Croatia Section GOLD Affinity Group Chair.

Radovan Zentner graduated electrical engineering at University of Zagreb in 1994. Since 1995 he served as research assistant at University of Zagreb where he also received his Ph. D. in 2002 (with honours). His research focus is on radio channel modelling for MIMO systems, broadband microstrip antennas and arrays, multiple antenna schemes for wireless communications and heuristic optimisation techniques (genetic algorithms). He published more than 30 scientific papers in journals and conference proceedings. He participated in several European Union funded projects in antennas (COST 260, COST 284) and wireless communications (COST 273, COST 2100). Since 2011, he is an appointed management committee member of COST IC1004 project: Cooperative Radio Communications for Green Smart Environments. He holds the assistant professor position at University of Zagreb Faculty of Electrical Engineering and Computing. He is a member of IEEE, and has served as Joint AP-MTT Chapter Chair of Croatia Section. Currently, he serves as AP Chapter Chair of Croatia Section.

Nikola Mataga graduated electrical engineering at University of Zagreb in 2007. He started his Ph.D studies at University of Zagreb Faculty of Electrical Engineering and Computing in 2009. Focus of his research activites is on reference radio channel modelling for MIMO systems. He started his career as a communications system engineer at MICRO-LINK, a wireless consulting company. Currently he holds a position of Technical director in the same company. While working at MICRO-LINK, he coauthored several technical papers on current technological issues of radio technologies.

AUTHORS' ADDRESSES

Ana Katalinić Mucalo, B.Sc.
Radiocommunications Department,
Croatian Post and Electronic Communications Agency (HAKOM),
Jurišiceva 13, 10 000 Zagreb, Croatia
email: akatalinic@gmail.com

Asst. Prof. Radovan Zentner, Ph.D.
Department of Radiocommunications and Microwave Engineering,
Faculty of Electrical Engineering and Computing,
University of Zagreb,
Unska 3, 10 000 Zagreb, Croatia
email: radovan.zentner@fer.hr

Nikola Mataga, B.Sc.
Technical Director at MICRO-LINK,
Franje Fuisa 12, 10 000 Zagreb, Croatia
email: nik.mat@gmail.com