Guest Editorial for the Special Issue on Radio Wave Propagation

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Guest Editors: Tapan K. Sarkar, *Life Fellow, IEEE*, Guido Lombardi, *Senior Member, IEEE*, Vikass Monebhurrun, *Senior Member, IEEE* and Monai Krairiksh, *Senior Member, IEEE*

IN his seminal article [1], Gabor observed that *Communication theory has up to now been developed mainly on mathematical lines, taking for granted the physical significance of the quantities which figure in its formalism. But communication is the transmission of physical effects from one system to another, hence communication theory should be considered as a branch of physics. Thus it is necessary to embody in its foundations such fundamental physical data as the quantum of action, and the discreteness of electric charges... We observe first that all electric signals are conveyed by radiation. Even if lines or cables are used in the transmission, by the Maxwell-Poynting theory the energy can be located in empty space. Hence we can apply to our problem the well known results of the theory of radiation.* The point here is that in the design of the physical layer one has to apply other concepts besides the principles of communication theory. More recently, this point was further investigated by Ivrlac and Nossek [2], where they state that *Electromagnetic field theory provides the physics of radio communications, while information theory approaches the problem from a purely mathematical point of view. While there is a law of conservation of energy in physics, there is no such law in information theory. Consequently, when, in information theory, reference is made (as it frequently is) to terms like energy, power, noise, or antennas, it is by no means guaranteed that their use is consistent with the physics of the communication system. Information theory serves well as the mathematical theory of communication. However, it contains no provision that makes sure its theorems are consistent with the physical laws that govern any existing realization of a communication system. Therefore, it may not be surprising that applications of information theory or signal processing, as currently practiced, easily turn out to be inconsistent with fundamental principles of physics, such as the law of conservation of energy.* Ivrlac and Nossek further elaborate [3] that *there exist a number of fundamental principles in physics which can be stated as conservation laws, meaning that there are quantities which can be calculated for a physical system at one time, and when recalculated at a later time come out the same [4].* They further illustrates that an example is the law of conservation of energy... The movement of the planets around the sun can be obtained solely by following the implications of the laws of conservation of energy and angular momentum [5]. Moreover, the conservation laws are also deep principles for they relate to symmetry in physics [6]. For instance, conservation of energy implies that the laws of Nature are time-invariant, and vice versa. Also, in signal processing and information theory, the concept of energy is a prominent one. It appears as the energy required to transfer one bit of information, or one symbol of the signal alphabet, or sometimes in form of transmit power, i.e., the rate at which energy must be supplied per unit of time to maintain communication. Yet, interestingly, the fact that energy is conserved, which is of such fundamental importance in physics, apparently plays no role in standard textbooks on information theory [7], signal processing [8], communication theory [9] or signal theory [10]. The authors are also not aware of any research work in these areas where the remarkable fact that energy is conserved is explored or discussed. The reason for this strange absence of conservation laws in signal processing, information theory and related disciplines seems to be related to inputs and outputs which are each described by single variables, instead of by a pair of conjugated variables, like position and momentum in Hamiltonian mechanics [6], or voltage and current in circuit theory [11]. Therefore, to address the development of the physical layer adequately and to ensure that systems perform according to design criteria, it is necessary to merge the principles of electromagnetics, which are primarily related to antennas and maximum power transfer, to the issues of channel capacity and how it can be quantified using the principles of physics and the radiation efficiency of antennas rather than use of the maximum power transfer theorem [12].

Such principles should also be applied to the propagation of energy as in wireless communication. For example, when one turns on a switch in the power line, how does the energy travel on the wires? The contribution of Maxwell which is often missed in this context is that the energy does not travel through the electrons in the wires but rather through the electric (**E**) and magnetic (**B**) fields which reside outside the wire and they essentially travel at the velocity of light in the medium in which they are located. The electrons in the conducting wire travel typically at a very slow velocity. When a DC voltage is applied, the electron velocity will increase in proportion to the strength of the electric field. AC voltages cause no net movement of the electrons as they oscillate back and forth in response to the alternating electric field (over a distance of a few micrometers). For a 60 Hz alternating current, this means that within half a cycle the electrons drift less than $0.2 \mu m$ in a copper conductor. In other words, electrons flowing across the contact point in a switch will never actually leave the switch. Consequently, the energy transmission in an electrical engineering context is due to the propagating electric and the magnetic fields at the velocity of light and it is in no way related to the flow of electrons. The electric and the magnetic fields actually exist and propagate outside the structure. This follows directly from Maxwell's theory and it is this philosophy that revolutionized twentieth century science. An antenna radiates exactly in the same way. The induced currents on the antenna generate fields and it is these fields that propagate through space.

The objective of this special issue is to publish papers related to the basic physics of electromagnetism in the context of radio wave propagation. The first paper in this issue actually summarizes the various experimental data that have been published over the span of the last 80 years related to electromagnetic wave propagation over various environments. The interesting part is that the path loss of radio wave propagation is independent of the properties of the ground over which it propagates, be it be urban, rural, suburban, indoor or over water. The typical value of the path loss is 30 dB per decade of distance travelled. This implies that to travel a distance from 1 m to 1 km the path loss is 90 dB! It will be interesting to find out if any of the wireless systems are designed to encounter such a high loss. Very few of the published theoretical models actually display such behavior. Most of the propagation models are essentially related to curve fitting the experimental data and they do not even deal with the physics of the problem. Propagation of radio waves is an electromagnetic issue and not necessarily a statistical problem even though most of the proposed models approach the problem from that perspective. Yet, seldom can any of the existing statistical models predict the proper propagation path loss which is typically derived from experimental data in various environments and over different material grounds. Another objective of this special issue will be to illustrate with simulation and measured data the proper way to model radio wave propagation from a physics point of view. Therefore, the goal here is to publish papers which are based on Maxwellian physics and which address the basic physics related to propagation modelling that spans from guiding structures to antenna structures and propagation in complex media and environments and which can duplicate real experimental data without any massaging or any curve fitting. In addition, applications related to this topic are also considered.

A total of **70** papers from **28** different countries were initially submitted to the special issue. Further submissions were accepted until 31st October 2018. The number of initial and revised papers then total up to **145**. In general, the submitted papers were of good quality. Because of the production deadline, the special issue is split into two parts. In the first part **21** papers are presented. Some of the initially submitted papers are not included in this first part. They have been scheduled as a second part to appear in February 2019. Some good papers could not be accepted for this special issue because they were not dealing with the basic physics of propagation phenomena and therefore, they were considered out of scope. Nonetheless, these papers have been transferred to regular issues.

The title along with a brief description of what the paper is about is described. No attempt has been made to further subdivide the category of each paper as the descriptions state what the paper is about.

List of Papers in Part I

- *Survey of Available Experimental Data of Radio Wave Propagation for Wireless Transmission - Tapan K. Sarkar, Mohammad Najib Abdallah and Magdalena Salazar Palma*

This paper provides a survey of the various experimental data available on the value of the propagation path loss of radio waves in a cellular wireless environment. It is shown that they all exhibit that the electric field varies as $\rho^{-1.5}$ within a cellular radius of a few kilometers, where ρ is the radial distance of the receiving antenna from the transmitting one. This decay in the fields is equivalent to a propagation loss of -9 dB/octave or -30 dB for a decade of the distance. This value is independent of the nature of the ground, whether it be composed of rural, urban, suburban or water. The propagation path loss due to the presence of ground generates a loss of 90 dB when the signals travel a distance of 1 km. This value is rather large when compared to a loss of 30-50 dB produced by buildings, trees and similar artifacts. Therefore, the experimental data indicate that the effect of trees, buildings and so on have a secondary influence on the decay of the electric field with distance, the dominant one is the propagation loss over an imperfect ground. Outside the cellular radius of a few kilometers the path loss appears to be 12 dB/octave or 40 dB/decade of distance.

- *Supercomputing-Enabled First-Principles Analysis of Radio Wave Propagation in Urban Environments Brian MacKie-Mason, Yang Shao, Andrew Greenwood, and Zhen Peng*

A full-wave field-based computational methodology for radio wave propagation in complex urban environments is presented. Both transmitting/receiving antennas and propagation environments are modeled by first-principles calculations. System-level, large scene analysis is enabled by the scalable, ultra-parallel algorithms on the emerging high-performance computing platforms. The proposed computational framework is verified and validated with semi-analytical models and representative measurements.

- *Integrating Physics-Based Wireless Propagation Models and Network Protocol Design for Train Communication Systems - Neeraj Sood, Sami Baroudi, Xingqi Zhang, Jörg Liebeherr, and Costas D. Sarris*

Ray-tracing and parabolic equation models of 2.4 GHz propagation along tunnel and open air sections of London Underground is used to evaluate the performance of a communications-based train control (CBTC) system. We show that physics-based models lead to reliable predictions at the network level, similar in fidelity to using measured data and unlike using simplified channel models of the path loss exponent type.

- *Numerical and Experimental Investigations of Base Station Antenna Height on Cellular Network Coverage - Vikass Monebhurrun*

A test setup is deployed to study the influence of base station antenna height on the cellular network coverage. Both numerical and experimental investigations are undertaken to evaluate the received electric field levels for different heights of the transmitting antenna and several distances between the transmitter and the receiver.

- *A Deterministic Propagation Model for Multipath Analysis at SKA Precursor Telescopes - A Case Study on MeerKAT - Temwani J. Phiri, David B. Davidson and P. Gideon Wiid*

Focusing on the 64-dish SKA precursor, MeerKAT, multipath effects in the core area comprising 44 dishes of 13.5m diameter in a 1km radius are investigated. a deterministic propagation model exploiting the method of moments (MoM) for antenna and real ground modelling and physical optics (PO) for representing scattering from metallic surfaces. In this way, the MeerKAT core was reproduced computationally and attenuation maps were produced revealing high and low risk regions.

- *Numerical Modeling of Ultrawideband Propagation Along a Wind Turbine Blade: Ondrej Franek, Shuai Zhang, Kim Olesen, Patrick C. F. Eggers, Claus Byskov, and Gert F. Pedersen*

Full-wave numerical analysis of an ultrawideband wireless link in frequency band 3-5 GHz along a 37.3m long wind turbine blade is presented. The method used for the analysis is the well-established finite-difference time-domain (FDTD) method with staggered Yee mesh. Simulated results are compared to data obtained from measurement on a real blade.

- *Enabling Description of Tropospheric Wave Propagation with the Parabolic Equation Accumulated Split Error Correction Method - Peipei Wei, Xiaoyan Du, Xinwei Hu, and Changyin Jiang*

Electromagnetic wave propagation in the troposphere is modeled by using the slip-step Fourier transform (SSFT) numerical algorithm to solve a parabolic equation (PE). In addition, an ASE correction method for PE, where the ASE is derived using the iteration idea of SSFT. On the basis of derivation results, the ASE is modeled based on propagation elevation angle distribution, which is estimated by ray tracing differential form.

- *Troposcatter Deviation Losses Study for OTH Microwave Propagation - Zhuang Wang and Mengnan Wang*

Microwave Over-The-Horizon (OTH) propagation via troposcatter mechanism may be used for passive sensing of remote radiation sources Due to the misalignment between scattering from the target and the receiving antenna system, additional losses due to azimuthal and elevation angles are necessary along with the receiving antenna pattern as well as the angle of arrival of the arrival scattered signal. Based on the scatter transfer function, the deviation losses are derived assuming Gaussian antenna patterns and verified by existing measured data.

- *Physical Methods for the Separation of the Contributions to the Earth-Space Cross- Polarization Discrimination Using Single-Polarized Satellite Beacon Signals - Flvio Jorge, Carlo Riva, and Armando Rocha*

The satellite communication systems employing either frequency-reuse schemes and/or polarization diversity to improve spectral efficiency are affected by depolarization induced interference due to both rain droplets and ice particles. Two physical methods, able to retrieve ice and rain contributions to total depolarization from single-polarized satellite beacon signals are here described, applied and validated on one full year of measurements carried out at Ka-band.

- *A Body-of-Revolution Implementation of the Parabolic Wave Equation with Application to Rocket Plume Attenuation Modeling - Reid K. McCargar, Karen M. Siegrist, James G. Reuster, Virendra Dogra, Jeff C. Taylor, and Ra'id S. Awadallah*

A method is described for modeling waves with three-dimensional variation propagating through an inhomogeneous body-of-revolution (BOR) with the paraxial direction chosen to be the axis of symmetry. The technique decomposes the initial field into independent modes that are propagated in parallel using two-dimensional solvers.

- *Plane Wave Diffraction by Arbitrary-Angled Lossless Wedges: High Frequency and Time Domain Solutions - M. Frongillo, G. Gennarelli, and G. Riccio*

This paper deals with the diffraction of a uniform plane wave impacting an arbitrary angled lossless dielectric wedge with planar surfaces. The knowledge of the diffraction coefficients in the frequency domain permits one to apply the inverse Laplace transform to obtain the time domain counterparts, which enable the evaluation of the transient diffracted field generated by an arbitrary plane wave.

- *A Bidirectional Ray-Tracing Method for Antenna Coupling Evaluation Based on the Reciprocity Theorem - Mehmet Mert Taygur, Ilya O. Sukharevsky, and Thomas F. Eibert*

A novel bidirectional ray-tracing method for solving antenna coupling problems is presented where the transfer function between the transmit and receive antennas is obtained by evaluating surface interaction integrals according to the reciprocity theorem. In order to eliminate the limitations of the reception spheres in the traditional unidirectional Shooting and Bouncing Rays (SBR) method, both transmitter and receiver are used for ray launching. The resulting rays are captured on an interaction surface, which is much more flexible in terms of size and shape than a reception sphere.

- *Fast Radio Wave Propagation Modeling in Tunnels with a Hybrid Vector Parabolic Equation/Waveguide Mode Theory Method - Xingqi Zhang, Neeraj Sood, and Costas D. Sarris*

This paper presents an accurate and efficient propagation modeling technique, combining the vector parabolic equation (VPE) and waveguide mode theory. The VPE method is applied to analyze propagation for a short distance from the transmitter. Subsequently, with the fields generated using VPE, a rectangular waveguide model of the tunnel is extracted, leading to rapid, analytical computation of fields over arbitrarily long distances.

- *Propagation over a constant impedance plane arbitrary primary sources and impedance, analysis of cut in active case, exact series and complete asymptotics - J.M.L. Bernard*

The electromagnetic field scattered by an arbitrary constant impedance plane, considering exact potentials for primary current sources composed of dipoles with arbitrary orientations is analyzed.

- *Wave Propagation Modeling of Tunnels in Complex*

Meteorological Environments with Parabolic Equation — Zi He, Ting Su, Hong-Cheng Yin, Ru-Shan Chen

Wave propagation in tunnels is analyzed using the parabolic equation (PE) method. As a result, the computational efficiency can be enhanced greatly. The propagation attenuation in the meteorological environment is estimated. In this way, the wave propagation in tunnels located in complex meteorological environment can be modeled by updating the refractive index for the parabolic equation.

- *Thermal Enhancement of Absorption of EM-Radiation in a Hot Magnetoplasma slab: M. S. Bawa'aneh, A. M. Al-Khateeb and Y. C. Ghim*

The problem of kinetic thermal effect on propagation characteristics of electromagnetic radiation incident on a hot Maxwellian magnetoplasma slab near a metallic surface is investigated. Reflection, absorption and transmission rates are calculated numerically for a set of parameters that may be suitable for a stealth plasma.

- *Integrated Shield Edge Diffraction Model for Narrow Obstructing Objects: Tim W. C. Brown,Mohsen Khalily*

A new simple and accurate model defined as shield edge diffraction is derived and validated suitable for frequencies above 10 GHz diffracting around obstructions that are narrow compared to the Fresnel zone width. The models are validated using both anechoic chamber as well as real environment based measurements at 10-12 GHz and 26 GHz.

- *On Geometric Optics over a Spherical Earth With an Exponential Refraction Index - Peter D. Holm*

The ray based method of geometrical optics is used for wave propagation over a spherical earth and also includes an exponential refraction index is analyzed.

- *Near-Field Focus Radiation of Multi-Beam Phased Array of Antennas Realized by Using Modified Rotman Lens Beamformer - Hsi-Tseng Chou, and Zong-Chen Tsai*

This paper presents the design of two-dimensional (2-D) phased array of antennas to radiate collinear multiple beams properly distributed for near-field (NF) focus (NFF) applications. The horizontal NFF beamforming network (BFN) is implemented by extending the basic concept of conventional Rotman lens beamformer (RLBF) for directional NFF multi-beam applications. This antenna set is realized at 2.45 GHz for RFID applications to demonstrate the implementation concept.

- *The Double PEC Wedge Problem: Diffraction and Total Far Field - Vito Daniele, Guido Lombardi, Rodolfo S. Zich*

The scattering of a plane electromagnetic wave by two separated arbitrarily oriented perfectly electrically conducting (PEC) wedges with parallel axes is examined. The solution is based on the recently developed semi analytical method known as Generalized Wiener-Hopf Technique (GWHT) that allows a comprehensive mathematical model of the problem in the spectral domain avoiding multiple steps of interaction among separated objects. The analysis is of interest in electromagnetic applications, and can be used to accurately predict path-loss in propagation with diffraction phenomena.

- *Physics Based Modeling of Experimental Data Encountered in Cellular Wireless Communication Tapan K. Sarkar, Heng Chen, Magdalena Salazar Palma and Ming-da Zhu*

This paper presents a physics based macro model that can predict with a high degree of accuracy the various experimental data available for the propagation path loss of radio waves in a cellular wireless environment. A theoretical macro model based on the classical Sommerfeld formulation can duplicate the various experimental data. And based on the analysis using the macro model developed after Sommerfeld's analytical formulation, one can also explain the origin of slow fading. A physical realization of the propagation mechanism is illustrated through Vander Pol's exact transformation of the Sommerfeld integrals for the potential to a spatial semi-infinite volume integral and thus illustrates why buildings, trees and the like have little effects on the propagation mechanism.

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