White Paper on Propagation

European Association on Antennas and Propagation Working Group on Propagation.
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1 Introduction

This white paper has been collaboratively written by members of the European Association for Antennas and Propagation (EurAAP) Working Group on Propagation. Its intention is to describe, to a non-specialised audience, the depth and breadth of current studies into electromagnetic wave propagation and the technologies that it underpins. Leveraging the propagation of electromagnetic waves to create technology has been a constant human activity throughout recorded history. Indeed, some of the earliest forms of long distance communication, such as lighting fires as a means of warning that an enemy was approaching, date back to 1800 BCE[1] and can be considered a crude form of free-space optical communication, a research topic of considerable ongoing interest over 3800 years later. However our understanding and usage was necessarily basic and empirical until the pioneering work of Maxwell and others in the 19th century placed our understanding of the propagation of electromagnetic waves on a solid theoretical footing. This led to the explosion of propagation-enabled technologies which took place throughout the 20th century, including wireless telegraphy, broadcast radio and television, radar, satellite communications and cellular radio communications to name just some of the most notable. Despite this relentless progress propagation studies are far from being complete as a scientific discipline and there continues to be a fruitful interplay between application and theoretical study. Our ability to model, measure and shape EM wave propagation has improved continuously, serving as a driver of new technologies and sometimes, in return, being driven in response to potential societal and commercial opportunities afforded by other emerging technologies. Problems that were previously considered "solved" (in the sense of being sufficiently understood to enable innovation at that point in time) are regularly re-examined in the light of the continual need for more accurate and reliable information needed to underpin, for example, faster communication networks, more accurate radar systems and higher fidelity broadcasts. In parallel with this recent years have seen entirely new research fronts opening. One such example is meta-materials. Historically the challenge has been to understand how electromagnetic waves have interacted with natural (and simple man-made) materials. Now, it is possible to engineer so called metamaterials that interact with waves in "un-natural"[1] ways opening up a whole new engineering design toolbox.

The white paper is organised as follows. In section 2 the basic science that underpins the propagation of EM waves is described. Regardless of the technology, there are a small number of common physical mechanisms by which such waves propagate through, and interact with, materials and these are identified and reviewed. An overview is then given of the common methodologies by which propagation phenomena are studied and researched. Section 3 constitutes the main contribution of the white paper. Four key technology areas which are underpinned by electromagnetic wave propagation are described. In each case a state of the art is initially provided before technology-specific topics and methods are discussed in detail. The four technology areas are

- Terrestrial and mobile propagation
- Indoor and short range propagation
- Earth-space propagation, and
- Active and passive remote sensing.

Like all scientific disciplines propagation studies are increasingly collaborative, interdisciplinary, international and rapidly evolving. Consequently networking, timely dissemination of emerging results, standardisation and structured approaches to training the next generation of researchers are of increasing importance. Section 4 examines these activities before section 5 offers conclusions and identifies future directions.

2 Propagation Science: An overview

[1]Actually there are a small number of instances of naturally occurring metamaterials such as the layers of chitin in some butterfly wings that give their colours an iridescent quality

2.1 Basic propagation mechanisms

Electromagnetic (EM) wave propagation is an enabling mechanism for many different technologies, several of which will be explored in later sections of this white paper. As will be seen, while such technologies can be applied in many different environments and over many different distance scales, a common set of basic mechanisms underpins them all. These mechanisms are reviewed in this section.

Maxwell's laws [2] state that physically propagating electromagnetic waves are produced by charges in motion, with harmonically oscillating charges producing "pure" waves of a single frequency. Sources of EM waves can be natural, such as the sun, or man-made, such as an antenna, and characterising the fields radiated by a source is a challenging problem. Propagation studies focus on a complementary problem, that is what happens as these radiated fields interact with material located between the source and receiving antenna. When considered on smaller and smaller scales such material is intrinsically random and inhomogeneous, but the impact and extent of the randomness varies from application to application and depends on the wavelength being used. For example, in mobile radio it is increasingly possible to get accurate geographical information about the major physical features (hills, buildings etc) along a link, and it is often reasonable to model these as essentially homogeneous objects with known geometry and known material composition. Nonetheless such databases cannot include information about smaller scale or temporary variations such as vegetation the effect of which must be considered statistically. It is therefore useful to initially distinguish between propagation in homogeneous and inhomogeneous media.

Waves in homogeneous media: We first note that electromagnetic waves do not require a material to support their motion, unlike acoustic waves, for example. Specifically, electromagnetic waves can travel through a vacuum, a property which underpins their use in space-communications. The speed at which the wave front of an electromagnetic wave moves in a vacuum is one of the universal physical constants and has a value of just under 300,000 kilometres each second. The wave itself carries an electromagnetic field, the compound term "electromagnetic" emphasising the coupled, and hence unified, nature of the electric and magnetic fields. These fields are vector quantities, both posessing a time-varying amplitude and direction (the time-varying direction of the electric field being defined as the polarisation of the wave). The relationship between these fields depends on the distance from the source, and radio engineers distinguish between the near-field, transition, and far-field regions. The near-field region is characterised by a complex relationship between the electric and magnetic fields, which gives way to the far-field region where a simpler picture emerges whereby the field amplitudes decay inversely with distance. Consequently, the power density decays inversely with the square of the distance, essentially reflecting the fact that a constant amount of total source output power is being spread over a larger total surface area as the wave propagates further away. This *spreading loss* is essentially a consequence of the fact that all electromagnetic waves emanate from a finite size source, something that requires that the wave front, i.e. the locus of points whose electric field vector is at the same point in the cycle, is curved. While all physical waves display wave front curvature an often-used abstraction is that of the plane wave, used to locally approximate waves which are in the very far-field and consequently have wave fronts which are locally planar and whose spatial spreading is negligible (i.e. the wave amplitude can be assumed constant). A plane wave propagates in a direction perpendicular to the phase front and its electric field vector, magnetic field vector and direction of propagation are mutually orthogonal. While not physically realisable the simplified mathematical form of plane waves means that they are often used in models of how waves interact with objects.

While consideration of propagation in a vacuum is a useful starting point, and illustrates several key concepts, terrestrial applications require that electromagnetic waves propagate through a variety of physical materials such as water, air, building materials, vegetation, human tissue etc. The physical effect of these materials can be described with reference to their constitutive parameters, namely their electric permittivity, magnetic permeability and conductivity. These parameters capture the macroscopic effects of the material's atomic and molecular structure on any waves passing through them. For so-called linear, isotropic media these take the form of single numerical values with the first two often being expressed as relative quantities (that is relative to their so-called free-space values that characterise propagation in a vacuum). These effects manifest in several ways including a change in the wave's phase velocity (slowing, relative to the speed in vacuum). In addition, the constitutive parameters affect the characteristic impedance (the ratio of the amplitude of the electric and magnetic fields), and the wavelength (the physical distance between successive peaks or troughs along the wave). These effects are frequency-dependent which leads to dispersion effects as the individual frequencies which comprise a pulse travel at different speeds through the material. The presence of conductivity or dielectric hysteresis in so-called lossy media manifests itself as an extra reduction in the power density as the wave propagates (in addition to the spreading discussed previously). While the phrase spreading loss is arguably a misnomer (in that, globally, no power is lost as it is just spread over a larger area as the wave travels further away) losses due to conductivity are due to electromagnetic energy being dissipated as it is converted into heat energy.

While it is instructive to consider the behaviour of EM waves in infinite homogeneous media as above, in practice they propagate in complicated, heterogeneous, environments. We distinguish between scenarios comprising a set of reasonably well-defined recognisable large objects (for example a 5G phone signal travelling through air before striking a concrete building) and propagation through environments which are intrinsically random and heterogeneous (such as the troposphere). We consider the former case first. In such cases it is possible to describe propagation in terms of a small number of basic mechanisms.

Reflection, transmission, diffraction and scattering: While the behaviour of waves within any particular object made of a homogeneous material is, as previously outlined, relatively simple it is the behaviour at the boundaries between them (such as when a wave travelling in air strikes a wall) that greatly complicates the physical picture. In the most general sense, an electromagnetic wave undergoes **scattering** at the interface between two distinct media, a process which results in a proliferation of waves propagating in a variety of directions. Scattering is a complicated phenomenon and in practice it is useful to identify some idealised forms of the process. **Reflection** and **transmission** occurs when an incident electromagnetic wave strikes the face of an object which is locally smooth on a scale comparable to the wavelength. In such circumstances the incident wave produces a reflected wave travelling away from the face and a transmitted wave propagating into the object, the direction of propagation of both being governed by Snell's laws of geometric optics. In particular, the angle of reflection equals the angle of incidence while the direction of travel of the transmitted wave undergoes a discrete bend (often referred to as refraction) relative to the incident wave. The amount of power being reflected and the amount being transmitted depends on the level of impedance mismatch between the materials but the total amount of power must be conserved. **Diffraction** occurs when a wave strikes the sharp boundary between two such faces (such as at the edge of a building). In such instances the wave is scattered in a continuum of directions, as defined by the so-called Keller cone. It is by this mechanism that electromagnetic fields can propagate ("bend") into deep shadow regions with no direct line of sight to a transmitting antenna, a process by which cellular phone coverage in urban areas has traditionally relied. As the interface between regions becomes rougher, with finer details appearing at wavelength scales, these simple well-defined mechanisms of reflection, transmission and diffraction give way to the more general process of **surface scattering**, which as the name suggests results in a proliferation of waves being scattered diffusely across a wider angular range. A similar process of **volume scattering** occurs when waves interact with fine inhomogeneities within a material. It should be noted that the determination of scattered fields is often carried out statistically, given the uncertainty surrounding the physical form of such small scale inhomogeneities. This is in contrast to the generally large and accurately-described structures that produce reflections, transmissions and diffractions. The interaction of electromagnetic waves with complex geometries (such as aircraft) is often characterised the structure's radar cross section a measure of how the object scatters power in different directions.

Ray theory and multipath: The geometric picture inherent in the above descriptions lends itself to a commonly-used approach to modelling EM wave propagation, namely that of ray theory, whereby power is deemed to propagate along a discrete set of infinitesimally narrow tubes called rays [3] which travel in straight lines (in homogeneous media) and which can in turn produce reflected, diffracted, transmitted and scattered rays at material boundaries. The electric and magnetic fields can be computed along each such ray by the suitable imposition of the laws described above and the total field at a point is the vector sum of the fields associated with all rays passing through that point. This ray-based description is particularly useful at modelling multipath, the term given to the observation that the total electromagnetic field at a location in space is a superposition of many components produced by interactions between waves emanating from the source and those scattered from multiple points within the physical environment. In general, these components will arrive delayed relative to each other, from a variety of angles, and with a variety of phases and amplitudes. The net result of the resultant constructive and destructive interference effects is a field distribution that exhibits *fading* whereby the received power will vary greatly in strength (to the extent of almost vanishing) as one moves from one point to another, from one moment in time to the next, or from one frequency component to another.

Waves in heterogeneous material: Heterogeneous material can be discrete or continuous. In the former case propagation will take place as per the scattering mechanisms outlined earlier with the total fields being a, complicated, superposition of the fields produced by the individual scattering events [4]. An example of the continuous case regards the propagation in troposphere (the earth's lower atmospheric layer), which is characterized, for example, by ducting effects whereby the variation of the air's permittivity results in a continuous bending of the wave's trajectory (if such variation is smooth) or to scintillations, namely fast variations of the received signal (if such variations are more abrupt, random and localized). Plasmas represent a very particular case of heterogeneous material. A plasma is a electrically conductive fluid (e.g. gas), which consists of charges that are free to move: typically electrons, but also different species of positive and negative ions, as well as neutral particles. This is the case of the ionosphere, one of the outer layers of the earth's atmosphere (approximately ranging from 70 km to 400 km from the planet surface). Wave propagation in plasmas is primarily regulated by the interaction of the electric and magnetic fields of the wave with the charged particles, which, being free to move, are accelerated along non-rectilinear trajectories. As a main consequence, EM wave propagation in plasmas can occur only at frequencies higher than the so-called plasma frequency, which is primarily determined by the local charge density. Such waves undergo several phenomena such as attenuation, deflection, scintillation, depolarization, increase in the phase velocity beyond the speed of light (but associated decrease in the group velocity below the speed of light). On the contrary, waves at frequencies below the plasma frequency are completely reflected from the plasma layers

Waves in meta-materials: Historically the challenge of propagation studies was to understand how electromagnetic waves interact with the materials found in nature. However in recent years it has become possible to artificially engineer materials that can interact with electromagnetic waves in previously impossible ways. Such *meta-materials* generally comprise arrays of sub-wavelength elements (meta-atoms) whose aggregate behaviour on a macroscopic scale can be characterised by the material having a relative permittivity and/or permeability which is negative. Electromagnetic waves interacting with such materials are not governed by the laws of geometric optics and it is possible to use metamaterials to manipulate waves in seemingly un-natural ways (one theoretical possibility being to eliminate reflections from a body while bending waves around it, essentially rendering it invisible). Meta-surfaces are essentially two-dimensional meta-materials which can manipulate waves in the same way but, as they are flat, can be affixed to walls or surfaces and more readily used in applications where available space is constrained. Besides metasurfaces realized through electrically small meta-atoms, metasurfaces made with larger cells similar to printed antenna-array elements are becoming quite popular lately due to their conceptual simplicity and relatively easy reconfigurability. Such structures are basically reflect-arrays or transmit-arrays whose elements are connected to variable reactive loads (varactors) or using pin diodes to connect each other according to well-defined patterns. Reconfigurable arrays or metasurfaces are often called Reconfigurable Intelligent Surfaces (RIS) and their use as antenna components, passive repeaters and signal processing devices is currently under intense investigation .

2.2 An overview of the approaches for propagation studies and development of models

The study of propagation can be carried out in several different ways depending on the complexity of the problem to be investigated, on the ultimate aim of the study, or on available resources in terms of pre-existing knowledge, measurement equipment and computation power.

Theoretical approach

Since a complete and powerful theoretical basis is available, in the form of macroscopic Maxwell's theory, to describe most electromagnetic wave propagation phenomena, a theoretical, or analytical, approach to the study of propagation is certainly possible. Due to the complexity of the mathematical formulation, such an approach is possible in practice only for the study of elementary propagation processes where the EM wave interacts with canonical obstacles through well-defined mechanisms such as reflection from an interface, edge diffraction, scattering from a spherical particle, etc. In several cases asymptotic analytical formulations can be derived and used, such as high-frequency approximations that are useful in ray-based propagation theory. In each case what distinguishes the theoretical approach is the use of a closed-form mathematical expression, derived in rigorous manner from Maxwell's equations, to describe the phenomenon. Examples of propagation studies using theoretical methods are :

- Ground or sea surface reflection using Fresnel reflection coefficients
- knife-edge diffraction for terrestrial propagation using Physical Optics

- Refraction and delay effects for ionospheric propagation
- Random sparse media propagation and scattering
- Scattering from rough surfaces using Beckmann-Kirchhoff theory
- Propagation in artificial environments (e.g. waveguides) and metamaterials

Experimental approach

In this case the researcher measures a certain number of parameters relevant to the propagation process, being careful to control and quantify both measurement accuracy (calibration) and uncertainty (error analysis). This approach has been used in the past and is still being undertaken in all the propagation research areas considered in this white paper. A typical example is the measurement of the impulse response on a mobile radio link in an urban environment using a Vector Network Analyzer or collecting attenuation data on an Earth-Space link from a satellite operating under various meteorological conditions. The design of the measurement setup and procedure is based on physical analysis and theoretical considerations. It is important to previously identify the sensitivity of the measured propagation parameters to environmental conditions (e.g., for tropospheric propagation: temperature, humidity, wind speed, rain drop size distribution, etc.) in order to characterize these parameters by ancillary measuring equipment (such as weather station, disdrometer, etc.). The outcomes of the measurement procedure can be used to derive empirical propagation models, for the validation of theoretical models or for the tuning of their input parameters. The final analysis of the measurement method should include also a discussion on limitations and possible improvements. Examples of propagation studies using experimental methods can be found in all propagation research fields :

- Long term Earth-space propagation measurements (addressing meteorological variations)
- Long term scintillation measurements on GNSS signals (addressing the variations of the solar and geomagnetic activity) for Navigation systems
- Short duration path-loss channel measurements (addressing space and/or time variations in the local urban or rural environment)
- Multidimensional channel sounding for different receiving positions along a route in a terrestrial link
- Natural surfaces backscattering measurements for future remote sensing missions

Propagation modelling

Subtly different from purely theoretical formulations or experimental characterizations are propagation models. Propagation modeling is a particular theoretical or experimental activity aimed at creating a simplified representation of propagation for a specific purpose. Since propagation in real-life environment is generally a very complex physical process, propagation models have been developed over the years to describe and/or simulate specific aspects of such a process in a simplified way. Propagation models are aimed at various purposes including design, deployment, optimization, simulation and real-time functioning of systems where electromagnetic wave propagation plays a key role, such as communication systems, remote-sensing systems and others. Propagation models can be classified into two categories: physical-deterministic models and empirical statistical models, with machine-learning based models being a recent development, mostly based on the latter but sometimes obtaining training data from the former. Physical-deterministic models are usually applied to site-specific problems such as the deployment and optimization of a radio network within a particular, specified, geographic area. Empirical statistical and machine learning models are often used for the design of radio interfaces, transmission techniques and for the simulation of radio channels. The three propagation model categories are briefly described below.

Physical-deterministic modelling

The physics-based approach, is based on electromagnetic theory applied to propagation in a specific, well-defined environment configuration (*site-specific* approach), and leads to the development of deterministic propagation models. This approach can be therefore defined as physical-deterministic. If the environment where propagation takes place is fully known, for instance through a proper environment database, then the theory can be applied and propagation can be simulated or predicted with good accuracy. For instance electromagnetic methods for the approximate and/or discretized solution of Maxwell's equations can be used, such as the Parabolic Equation Method, Finite Differences in Time Domain (FDTD), and others [5]. Such models generally require considerable computation resources in terms of memory occupation and/or computation time. Very important physics-based models, less demanding in terms of computation resources and particularly suitable to frequencies from the UHF band upward are ray models based on Geometrical Optics, with the addition of Geometrical Theory of Diffraction (GTD or UTD) to describe diffraction phenomena [6]. Ray models in the form of image-based ray tracing or ray launching are now widely used in both the academy and the industry.

Empirical-statistical modelling

Statistical modelling is necessary when the propagation environment, or the propagation phenomena taking place in it, are unknown to a significant extent. This happens when information on the environment are not available, or when modeling must describe general propagation characteristics in an entire environment category instead of being specific to a particular environment. Empirical-statistical models are based on the empirical observation (measurement) of the final effects of the propagation process, regardless of the detailed physical phenomena taking place in it, and can provide the statistical distribution of a given propagation parameter (e.g. path-loss) for a given propagation environment or environment category. Therefore, environment classification is necessary before empirical observation and modelling. Generally speaking, such models usually consist of a formulation with parameters that must be calibrated in order to obtain the best-match to measurements. Parametrization of the model for different environments vs. measurements is necessary to make it usable in such environments and might require a great deal of human labour and time. Statistical models however, cannot be used outside of their parametrization (or calibration) environment, and therefore cannot be applied or derived for environments where measurements are not available.

Machine-learning-based modelling

Similarly to Empirical-statistical modelling, Machine Learning (ML) modelling aims at learning an arbitrarily complex nonlinear function describing propagation parameters from a large set of measurements - or reliable computer simulations - for a given environment category [7]. Differently from Empirical-statistical modelling however, where the formulation is conjectured through human intuition and labour, in ML the target function is automatically inferred during the training phase which, although computationally expensive, requires limited manpower. Moreover, querying the output of a trained ML algorithm is typically computationally light. The goal is to train a ML algorithm that, given a set of input features characterizing a Tx-Rx pair and the propagation environment, predicts either the value or the statistical distribution of a given propagation parameter. Datasets usually have tabular form where records consist of a number of *input features* (e.g., link distance, Tx/Rx height, propagation medium characteristics, etc.) and a given *output label* (e.g. path loss, fading probability, etc.). Formally, a training, validation and test datasets $\mathcal{D}_{train}$, $\mathcal{D}_{val}$ and $\mathcal{D}_{test}$, respectively, are considered. During the *training phase* the ML algorithm is trained to learn the input-output function from data records in $\mathcal{D}_{train}$, during the *validation phase* some parameters are adjusted in order to favour correct training, while in the *test phase* the trained algorithm is run and tested vs. $\mathcal{D}_{test}$ by querying output for each input feature in $\mathcal{D}_{test}$ and comparying it with the corresponding, correct output.

3 Overview of propagation studies and methods for specific key areas

3.1 Terrestrial and Mobile Propagation

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Overview and State of the Art:

Terrestrial propagation has been studied since the dawn of wireless telegraphy, initiated by Guglielmo Marconi at the beginning of the 20th century. Initially studied mainly for radio broadcasting and for military applications, terrestrial mobile propagation became popular with the advent of the first cellular mobile radio systems in the eighties, and since then has been studied more and more extensively, for new frequency bands and environments throughout the evolution of mobile radio systems from 1st generation (beginning of the eighties) until the recent 5th generation (5G, 2019). The driving force behind mobile radio propagation studies has been twofold:

I. the need to develop field-prediction and planning tools for the deployment and the optimization of cellular networks, with particular focus on the placement, orientation and tilting of Base Stations' antennas to optimize radio coverage
II. the need to understand the characteristics of the radio channel for a variety of frequencies and environments for the design of the radio interfaces, antenna solutions and coding schemes, and ultimately for the development of channel simulators.

Since traffic density was not an issue in first mobile radio systems, high antennas on 20-30m-tall masts were used to achieve cell radii of several kilometres and cover large areas with limited infrastructure costs. Therefore, the study of mid-distance propagation with the purpose of determining radio coverage, fading statistics and channel parameters at the borders between cells was of paramount interest, where interaction with ground and shadowing due to large obstacles such as hills and large buildings were the main issues. Empirical models for large scale RF coverage based on the "path-loss exponent" such as the famous Okumura and Hata model [8] were developed and used.

With the evolution toward 2nd and 3rd generation systems and the consequent increase in traffic, the main focus shifted toward urban propagation and smaller cells, with the development of models for Over-Roof-top and street-canyon propagation where the interaction of the radio wave with building's roofs and walls and the presence of multi-path is explicitly considered taking into account urban maps or simplified link-profiles in the vertical plane [9][10]. The use of larger bandwidths spurred the development of wideband propagation models to describe the multipath time dispersion of the radio channel vs. link distance and other parameters in a statistical or deterministic way [11]. The trend continued with the advent of 4G (LTE) systems where the use of urban small-cells placed well below rooftop level and of MIMO techniques stimulated empirical and modeling studies on the multidimensional characteristics of multipath propagation, including polarization and angle dispersion at both the mobile and the base station [12][13].

Starting from the late nineties, the increasing availability of Geographic Information Systems (GIS) including high-resolution descriptions of both natural and man made obstacles (e.g. hills, buildings, bridges etc.) fostered the development and use of deterministic propagation models, such as ray-based models (image-based ray tracing, ray launching, etc.) that can achieve a higher accuracy level, with errors of the order of 5-8 dBs on both path-loss and other large-scale parameters such as root-mean-square (RMS) Delay Spread, Angle Spread etc.

Another application of deterministic propagation models is localization of the mobile terminal, and in particular (a) fingerprinting and (b) multipath-assisted localization. In (a) deterministic prediction is used as a surrogate of – or to complement – measurements to build a reference database where one or more propagation parameters (path-loss, power-angle profile, etc.) are stored for each pixel of a given geographical area. Run-time measurements performed by the system are compared with the reference database entries to determine the localization fix using maximum likelihood methods [14]. In case (b) ray-based modelling is used within the localization engine to determine image source positions generated by single-bounce reflections to improve the localization accuracy [15].

In the near future, the use of new frequencies in the mm-wave, THz and optical bands (e.g. for Visible Light Communications), smaller cells and larger bandwidths for beyond 5G systems will probably foster even more the development and use of deterministic, ray-based propagation approaches for the design, deployment and real-time operation of next-generation mobile radio systems, with a partial convergence of research on mobile radio and research on optical free-space propagation in terms of both approaches and methods.

Finally, it is worth pointing out that an increasingly important part of modern terrestrial mobile communications is represented by Vehicular Communications, where network layout is not always cellular. Outdoor multipoint-to-multipoint communications for example play an essential role in vehicular applications of wireless, e.g., trains, automotive and aircrafts. The wave propagation modelling methods for terrestrial cellular settings, i.e., ray-based methods and GSCM, are also capable of simulating realistic behaviours of radio link characteristics in this non-cellular setting [16],[17]. Other vehicular communication networks however make use of a cellular backbone, such as ground-to-train connections to provide cellular coverage inside passenger compartments. In all cases, the challenge is to identify meaningful wave interacting objects in rapidly varying environments. Moreover, usage scenarios are diverse, ranging from above-a-city environment for unmanned aerial vehicles to tunnel environment for trains [18]. Wave propagation analysis would therefore be specific for usage scenarios. The analysis would need both deterministic and stochastic treatment of the wave interacting objects and their scattered fields due to the huge diversity and complexity of the environments.

Methods of study and approaches

Given the intrinsic variability of mobile radio propagation, due to the variety of environments, frequencies, antenna types, to the presence of obstacles of *a priori* unknown characteristics, and above all due to the complete mobility of at least one of the two radio terminals, the classical approach to the study of land mobile propagation has been traditionally empirical-statistical. First experiments such as those carried out by Okumura et al (1968) collected a great number of field samples over a large, homogeneous urban area in Tokyo to capture the average trend of RF coverage vs. link distance in an urban macrocell. Later Hata (1980) derived a simple one-slope formula for mean path loss in the same environments by best-fitting Okumura data [8]. Since then, ETSI and other standardization bodies have derived many similar, Hata-like formulas for different environment, frequencies and system setups. At the same time, a great deal of experimental and theoretical research has been carried out to describe multipath and large-scale fading of the RF field around its mean value using various statistical distributions, such as Rice, Rayleigh, Nagakami, Weibull and others [19].

Similar empirical-statistical approaches have been chosen for wideband parameters such as the power-delay profile of the channel or its delay-spread, or the angle of arrival/departure power-distributions, following seminal work by Valenzuela, Turin, Rappaport and others [20].

The ultimate multi-dimensional experimental propagation investigations have been carried out within the framework of the European Cooperation Actions COST273-2100-IC1004-IRACON since the first years of the 21st century through the use of MIMO channel sounders such as those developed by Elektrobit (now Keysight) and MEDAV, that allow a complete characterization of the channel in the time, polarization and angle domain, with angle-domain resolution being only limited by the number of MIMO elements and their physical configuration in either cylindrical or spherical arrays [21].

Empirical-statistical models can provide the statistical distribution of a given parameter (e.g. path loss or RMS angle-spread) for a given environment or class of environments, and therefore environment classification is necessary before empirical observation or modelling. Parameterisation of the model for different environments vs. measurements is necessary to adapt the model and make it usable in different environments. Statistical models however cannot be used outside of their parameterisation (or calibration) environment.

An alternative approach is the physical-deterministic approach. It relies on the theory of radio wave propagation in free space and in presence of obstacles that encompasses specular and diffuse reflection from surfaces, diffraction from rectilinear and curved edges, surfaces, and vertices, as well as specific phenomena in typical environments, such as two-ray propagation in presence of flat terrain, street-canyon propagation and guiding effects, surface waves over terrain and forested areas, etc. Physical-deterministic models require complete information on the environment where propagation takes place, for instance through a proper GIS description, and generally achieve good accuracy. Electromagnetic methods can be applied to mobile radio propagation problems: for instance, the Parabolic Equation Method has been applied to propagation of radio waves over hilly terrain [22]. Such models however generally suffer from both high computer memory occupation and high computation time. Less demanding in terms of computation resources and particularly suitable to frequencies from the UHF band upward are Ray Tracing (RT) and Ray Launching

(RL) models based on Geometrical Optics, with the addition of Geometrical Theory of Diffraction (GTD or UTD) to describe diffraction from edges. If the environment can be described with simple canonical objects such as flat polygons and straight edges, which is the case for built up areas, RT/RL models can simulate multipath propagation in a quite efficient way even over large areas, especially if parallel computing solutions can be used [6].

Nevertheless, statistical modelling elements are necessary also in physical-deterministic models to account for the effect of environment details that are not included in GIS databases, such as building walls' indentations, ornaments, windows, balconies, or cluttering objects such as vehicles, street signs, or people. A few methods to model diffuse scattering from such objects in a statistical way within deterministic ray models have been proposed since the start of the new century, such as the Effective-Roughess model [23].

As mentioned above, hybrid statistical-deterministic approaches called Geometric Stochastic Channel Models (GSCM) have been developed for multi-dimensional channel simulation in the last years that gained much popularity and were standardized at international level [24]. In GSCM a distribution of scatterers with given spatial-temporal characteristics - that depend on the considered environment - generate ray clusters and therefore a given multipath channel realization with realistic spatial, temporal, correlation and fading characteristics.

Finally, Machine learning techniques, already introduced in 2, are being developed to model radio propagation in cellular radio environment [7]. If the training data set is large enough and properly chosen for the considered propagation environment, ML-based modeling allows for accurate prediction of both path-loss and wideband parameters such as RMS Delay Spread and others. However, environment classification, the selection of relevant environmental features, and the collection of a sufficiently large training dataset remain open challenges that still need to be fully addressed.

3.2 Indoor and Short Range

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Overview and State of the Art

Indoor and short range radio propagation became important towards the end of the 20th century with the advent of Distributed Antenna Systems (DAS), wireless access (Wifi 802.1x), peer-to-peer communications (such as Bluetooth) and, more recently, with IoT communications In the near future, with the advent of broadband wireless mm-wave and THz communications, indoor and short-range propagation will become even more important. Indoor and short-range propagation differs from land mobile propagation for the following main reasons:

• the radio terminals are immersed in the man-made environment and propagation not only interacts with, but takes place within buildings and man-made objects

• the propagation environment is mainly man-made, much smaller and more controlled than for outdoor propagation. Therefore, propagation can be considered more deterministic, with a narrower margin left to random phenomena

• differently from urban mobile radio propagation here propagation takes place mainly in line-of-

Sight (LoS), or at least with the presence of a dominant path that can be blocked by one or a few objects
• the environment often being confined within a room or a device case, propagation can be reverberant leading to a dense structure of received signals
• short range propagation must also include near-field and far-field propagation for wireless power transfer at HF, UHF and mm-waves
Indoor propagation is affected by many nearby objects like furniture, walls, moving persons and is characterised by a rather slow motion of the communication devices. Naturally "indoor propagation environments" covers a wide range of scenarios ranging from, for example, an underground mine to a sports-hall. In turn this leads to different categories of propagation scenarios [25]. Objects inside buildings vary largely in their reflecting characteristics resulting in a random-like structure of the wideband channel impulse response which can hardly be predicted by the geometrical layout of the environment only [25]. Signal blockage by walls may range from a few up to thirty dBs depending on the frequency, thickness and building material [26], such that the path loss might be severe and vary even over short distances [25], [27],[28]. Comparing outdoor to indoor wireless propagation parameters, the following differences has been noted [27]:
• indoor propagation exhibits stronger path loss with sharper changes for even small receiver or transmitter displacements
• the Doppler shift due to receiver movement is negligible in general
• the power delay profile of the indoor channel shows a denser structure with generally smaller excess delay reflecting into a smaller delay spread

In the rest of this section some research areas relevant to indoor and short-range propagation area are briefly summarized and references to representative research work are provided.

I. antenna /material interaction

One particular issue is the impact of the very close environment of antenna systems. Since indoor wireless networks make use of access points designed to be placed by anyone in their homes, it can be expected that there is no control over the nearby objects or structures. Depending on the frequency and on the nature of the antenna systems, these perturbations to the nominal antenna operation can be in the near field (i.e. for low frequencies and large antennas or multiple antennas), or more commonly in the intermediate or far field. In the former case it can be expected that the antenna may be detuned (e.g. for a very close metal object), while in the latter the impact will most be on the radiation characteristics, e.g. blocking certain propagation directions and reducing the effective degrees of freedom. On one hand omnidirectional antennas are more sensitive to nearby objects because they transmit/receive over 360°, on the other hand an object obstructing the beam of a directional antenna has an even more detrimental effect. All this means that the analysis of the impact of close disturbances must take into account critically the nature of the antennas [29],[30].

II. Measurement-based modeling

Many measurements and empirical-statistical models based on measurements for indoor propagation have been published during the last four decades. As the propagation environment can be quite diverse, models can be environment-specific or very generic. Surveys on different models and measurements can be found in [27],[28],[25]. One of the most popular channel models to simulate the wideband structure of the indoor channel is [31] and its extension [32]. The model simulates the channel impulse response by multiple clusters which consist of discrete rays whose delays follow a Poisson process with an exponential power decay which is consistent with reverberation room theory [31]. During the measurements in [31] multiple clusters have been found originating from strong reflecting obstacles like metal doors. Like rays within a cluster, the power of clusters decrease with increasing delay and the arrival times are modeled as a Poisson process. The model in [31] forms the basis for some standards such as the IEEE 802.15.4a propagation model [33].

III. Deterministic modelling

Short-range and indoor propagation can be suitably modelled using a deterministic approach due to the confined, controlled and artificial environment where obstacles are often geometric man-made structures such as buildings, walls, pieces of furniture, etc. Widely used propagation models for this case include ray tracing or ray launching, models [34]. At lower frequencies these models need to be complemented with proper diffuse-scattering models to describe the effect of electrically small objects and details not present in the environment description. At higher frequencies – e.g. mm-waves – small details can generate strong specular-like contributions and therefore should be taken into account in order to achieve a good prediction accuracy, leaving diffuse scattering models to describe the effect of surface roughness and material inhomogenities only [35]. Simplified deterministic models that only take into account propagation along the radial link profile and the presence of attenuation due to interposed walls have also been proposed [36][37]. Such models, although fast and fairly accurate in terms of path loss prediction, cannot give any information on multipath dispersion and still require the availability of a detailed floor plan. Given the relatively small propagation environment, even full-wave electromagnetic models such as FDTD or the Boundary Integral Equation method can be applied to indoor propagation when the frequency is not too high [38][39]. Such models usually require the discretization of the environment using a mesh-size related to the wavelength – e.g. half a wavelength - and are therefore challenging in terms of both computation time and memory occupation when the wavelength is very small compared to the prediction domain.

IV. Hybrid channel models

Deterministic models, albeit accurate, have the drawback of being site-specific and not suitable to channel simulation in environments where details or material characteristics are unknown. In Geometric-stochastic channel models, used for non site-specific channel simulation, generic scatterers are placed around the radio terminals according to a given statistical spatial distribution rather than according to a specific environment representation, then multipath is generated to get realistic realization of the radio channel [3GP2009]. In Full-scattering models [40] and models based on Graph Theory [41] walls and obstacles are described as a cloud of points (point cloud representation, often derived from laser scanning), rather than through actual maps, and propagation is described through multiple interactions of the radio waves with such scatterers. The former models are very suitable for high frequencies or rough surfaces where diffuse reflection is dominant. In the latter models, the application of graph-theory facilitates the inclusion of a virtually unlimited number of successive interactions, therefore describing to some extent propagation in reverberant indoor environments such as aircraft and train cabins. In Room Electromagnetics modelling, whose formulation is borrowed from room acoustics, reverberant propagation is described through the decay rate of the channel's power-delay profile, which is a characteristic of the room and doesn't depend on the location of the radio terminals within the room [42].

V. Mm-wave propagation and channel modelling The most distinguishing features of wave propagation at mm-waves, compared to below-6 GHz frequencies, are 1) higher link blockage losses and 2) more directionally selective scattering, leading to sparser multipaths. The first comes from the fact that many physical objects become electrically larger, while the second is explained by the wavelength becoming comparable to the roughness of many physically small objects. Observations of these distinguishing features by measurements are still scarce, preventing us from obtaining its full picture and generic mathematical model. A link blockage model due to building corners and human body is well established, while fewer studies exist for those of natural objects, e.g., [43], in outdoor short-range radio links. Sparsity of multipaths is usually discussed through clusters [44], [45], but their inter- and intra-cluster properties require more experimental evidence and analysis to draw a conclusion about the extent of sparsity and hence its mathematical models.

VI. Propagation for THz communications

The propagation characteristics described above for mm-waves also apply, to an amplified degree and with some peculiar features, to the THz band, that spans from 0.1 to 10 THz. Due to the high free-space isotropic path-loss, THz propagation is limited to LoS or quasi-LoS links, with blockage from humans, vehicles and objects representing a major issue that have been addressed in recent investigations and modelling efforts [46]. In order to cope with the high path loss, high directivity beams must be used for transmission, making beam alignment another critical issue [47]. Molecular absorption peaks cannot be neglected above 300 GHz and must be therefore taken into account or avoided by exploiting proper intra-peak transmission windows [48]. Another peculiarity of THz propagation is the very high available bandwidth, that mandates a ultra-wideband analysis and modelling of THz channels. Besides deterministic ray models, that appear to be very suitable for THz frequencies, several other THz propagation and channel models are available in the literature, especially for indoor environment [48].

VII. Short range models for massive MIMO

Installation of a large antenna array to an infrastructure device, e.g., a cellular base station and a wifi access point, leads to two distinguishing aspects in channel modelling. They are 1) variation of multipath condition across the large array and 2) inter-site and inter-user correlation effects. A large antenna illuminating multiple cellular sites exemplifies the first aspect, while guided wave propagation in e.g., corridors and street canyons, may lead to the inter-site and inter-user correlation of shadowing and angular power profiles of multiple radio access links. Both are generally referred to as spatial consistency of multipath characteristics at link ends. While not many experimental observations of those aspects are available such as [49], [50] due to the need to use complex channel sounding hardware, channel models handle those aspects well. Site-specific channel modelling based on ray-based methods can handle the mentioned two aspects, while state-of-the-art stochastic channel models [51][52] allow a partial or full support of the spatial consistency on the infrastructure and mobile sides.

VIII. Body area propagation modelling

Wireless Body Area Networks (WBANs), which are small-scale networks operating inside, on, or in the peripheral proximity of a human body, will play a very important role in the next generation of wireless systems, as they will allow the integration of wearable and/or handheld devices with the surrounding infrastructure [53]. Radio wave propagation in WBANs is significantly different from the traditional radio communication networks, due to the close proximity of the human body which is a very complex material with a relatively high permittivity, whose precise properties depend on the frequency of the radio signal. Thus, the parameters of the radio signals propagating in such networks depend on the electrical properties of the body and on the dominant propagation mechanisms supporting communication. The power of the received signal in WBANs depends on the distance between the transmitter and the receiver, the location of the wearable antennas, the properties of the tissues along the propagation path, the user's body shape (e.g. weight, height), their position (e.g. standing, sitting) and their motion (e.g. walking, running). It also depends on the propagation environment in which the WBAN operates (e.g. indoor, outdoor).

As the radio channel properties are significantly influenced by the fact that WBAN nodes can be placed at different distances from the body, WBAN classification is necessary. There are three types of WBANs. The first one is the in-body type, where at least one node is implanted or placed inside a human body. In this case the major part of the radio channel is placed inside the body as well. The second category is the on-body network with all nodes placed close to the body surface. There is a strong influence of the body shadowing effect and the body motion on this type of WBANs. Additionally, the creeping wave phenomenon should be also taken into account in on-body networks. The last kind of WBANs is the out-of-body type. In this case the communication takes place between the node placed on the user's body and the one placed in some external location (off-body) or on another user (body-to-body). In the out-of-body networks the properties of the radio channel are strongly influenced by the posture and motion of the user, as well as by the type of the environment.

Due to the diversity of network types radio channel modelling is a key issue for the proper operation of WBANs and is very important in designing wearable antennas, transceivers and communication protocols.

There are two main methods for channel modelling in WBANs. The first one is the use of simulation techniques, both full-wave and asymptotic, that have been well described in [54]. The second method is based on the measurements in realistic environments with a use of specialised testbeds and methodology, such as is described in [55]. These two approaches allow for elaborating different channel models, that can be found in the literature, e.g. [56], [57], [58] or [59].

Methods of propagation studies While the outdoor urban environment is dominated by large, geometric structures such as buildings, walls and bridges, and propagation mainly takes place in the far-field region, the presence of small complex-shaped objects such as pieces of furniture, books, appliances and humans as well, often close to the radio terminals, determines a difference in indoor propagation modelling in several cases [29]. The terminal's antennas are surrounded by objects that often interact with them, while the impact of major objects such as computer monitors, windows, lamps, etc. on propagation must be taken into account, especially at mm-wave frequencies. Scattering from such objects can be characterized in terms of radar cross section, that can be calculated using electromagnetic methods such as Finite Difference in Time Domain (FDTD), Physical optics, using ray tracing methods or simply measuring the RCS of different classes of objects in an anechoic chamber [60]. The impact of humans moving across the radio link is usually taken into account through human-blocking models [61]. Indoor propagation can be modeled with deterministic or statistical approaches. The two approaches have already been defined in 2. In the fully deterministic approach the propagation environment, the terminal positions and antenna characteristics are specified before applying the model in order to derive propagation parameters – path loss, channel transfer function, impulse response, etc. - for the considered case. In the statistical approach only the kind (or class) of environment is defined, and statistical distributions of propagation parameters – mean path loss, fading statistics, power-delay and power-angle statistical distributions, etc. – are derived as a function of generic parameters such as link distance, terminal height above ground, etc. As stated above, the limited dimensions of indoor and short-range propagation environments make deterministic modelling more suitable to such environments with respect to large scale outdoor propagation. Nevertheless, empirical statistical methods are necessary for the design and to derive general assessments of indoor and short-range wireless networks.

3.3 Earth Space Propagation

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Overview and State of the Art:
The idea of relaying communications to and from the Earth was conceived by Arthur C. Clarke. In his famous paper, published in 1945 [62], Clarke observed that a satellite flying along an Equatorial orbit with a radius of approximately 42000 km would have an angular velocity matching that of the Earth, and thus would appear as stationary to any location on the Earth from which the satellite is visible. It took slightly more than a decade to develop the technology necessary to launch the first satellite in 1957, namely SPUTNIK I (developed by the former USSR), flying along a low Earth elliptical orbit and carrying two payloads operating at 20 MHz and 40 MHz [63]. Several technology demonstration satellites were tested in the following years, and the first geostationary one, named SYNCOM 3, carrying two payloads at C-band[2], was successfully launched and operated only in 1964 [64]. In parallel to the development of these communication satellites, the space era initiated in 1957 also sparked the interest for space exploration. In a decade, robust programs were conceived by the former USSR and USA, culminating in the Apollo 11 mission to the Moon in 1969. The experience gathered with geostationary satellites was further consolidated with the development of the S-band reliable communication systems used during such missions [65]. Besides underpinning satellite based communication systems and space exploration missions, Earth-space propagation is also of paramount importance for Global Navigation Satellite Systems (GNSSs), which aim at proving accurate localization services worldwide on the Earth. The development of such systems began in the 1960s with the TRANSIT system (USA) which broadcast at 150/400 MHz, afterwards leading to the deployment of the GNSSs that are nowadays in use for a plethora of applications (GPS, GLONASS, GALILEO, BEIDOU, etc) all operating at frequencies in the L band [66], [67]. The development and evolution of all such systems occurred in parallel with the investigation of the effects induced by the atmosphere on electromagnetic waves, which are affected specifically by two layers: the ionosphere (extending roughly between 50 and 1000 km), whose main effects are limited to the kHz-MHz frequency range, though they are perceived up to approximately 12 GHz [68]; and the troposphere (extending from the surface up to about 60 km), which has a stronger impact on frequencies higher than 10 GHz [69]. More specifically, in the 1-100 GHz range, Earth-space communications systems and satellite-based navigation systems suffer from the following effects:
• Absorption: the electromagnetic power is absorbed by water vapor and oxygen due to resonance effects; as a result, the attenuation induced by gases is much stronger around certain specific frequencies (e.g. 22 GHz for water vapor and 60 GHz for oxygen) [70], [71].
• Attenuation: water particles scatter and absorb the power of waves whose wavelength is comparable with the particle dimension. Specifically rain drops, whose dimensions are in the order of millimetres, induce a strong attenuation on waves whose frequency is higher than 10 GHz [72]; water droplets suspended in clouds (orders of microns) cause a much lower attenuation, which appears at frequencies roughly higher than 30 GHz [73]; mixed-phase particles (melting ice) present in the melting layer (around the cloud base) have a similar effect as the one of rain drops [74], while dry snow has an impact only on systems operating at W band. Also the ionosphere can induce attenuation on electromagnetic waves from the imaginary part of its refractive index (due to collisions between electron and neutral molecules); for transionospheric links above 100 MHz, absorption is not significant, but it is at 30 MHz, especially with auroral and polar cap absorption.
• Effects on polarization: anisotropic particles in the troposphere will induce a change in the

[2]for more on the nomenclature of frequency bands see section 4

polarization of the wave (creation of cross-polarization) [75]. This is caused by rain drops (which tend to be elliptical), and by ice particles, which can strongly modify the polarization due to their marked anisotropy (e.g. ice needles). In addition, in the ionosphere, a linearly polarized wave will suffer from a gradual rotation of its plane of polarization due to the presence of the geomagnetic field and the anisotropy of the plasma medium (known as the Faraday effect) [76].
• Scintillations: strong spatial and temporal inhomogeneities of the refractive index in the troposphere, typically caused by turbulence and water vapor and pressure inhomogeneities, modify the wave front and induce fast fluctuations of the received signal [69]. The same effect is caused by abrupt inhomogeneities in the spatial distribution of the electron content in the ionosphere, especially in auroral zones (particle precipitation) or in the equatorial crests (plasma bubbles) [76].
• Signal delay: both the ionosphere (depending on the electron content distribution) and the troposphere [77] (depending mainly on oxygen and water vapor content) cause a group delay on Earth-space signal; this has a marked impact especially on GNSSs [66].
• Refraction: the continuous change in the vertical profile of the refractive index in the troposphere [78] (due to the variation of pressure and temperature with height) and in the ionosphere (due to the different ionization of the layers) induces a gradual refraction of electromagnetic waves, which can even lead to total ionospheric reflection in the MHz range [76].

The need to design reliable satellite-based communication and navigation systems fostered the investigation of all the detrimental effects induced by the atmosphere on electromagnetic waves. Significant efforts have been indeed devoted to studying the propagation of electromagnetic waves along Earth-space links, both on the experimental sides (propagation campaigns such as ITALSAT [79], OLYMPUS [80] and Alphasat [81]) and on the theoretical side (development of prediction models) [82]. Nowadays both the experimental and the theoretical activities are even more important in order to support the ongoing evolution of satellite-based communication and navigation systems. In fact, on the one side, the former systems are gradually shifting from the customary C/Ku bands (5-18 GHz) to the Ka/Q/V bands (18-50 GHz), which offer a larger bandwidth to enable more advanced services (e.g. Internet via satellite); unfortunately, as the frequency increases, the detrimental effects of the troposphere also increase, which in turn calls for more accurate models [83]. Also, while most of the propagation models are designed for geostationary links, there is an increasing interest in developing models that are also suitable for constellations of satellites on orbits closer to the Earth (e.g. low and medium orbits), which have been quickly developing in the last decade (e.g. the O3b fleet) [84]. On the other side, navigation systems and the corresponding augmentation systems (EGNOS, WAAS . . .) are being employed in an ever-increasing number of applications, with accuracy and reliability requirements that are becoming more and more stringent. Besides the customary L band, S-band and C-band signals have been investigated for future navigation applications. As the ionosphere characteristics are clearly driven by the solar and geomagnetic activities and can be severely impacted by Solar events (e.g. coronal mass ejection), the field of Space Weather is nowadays widely investigated in order to develop prediction models and alert tools for GNSSs performances and impairments [85].
Methods of study and approaches:
In general, modeling electromagnetic wave propagation for Earth-space applications requires a combined approach. One the one side, the interaction between electromagnetic waves and atmospheric constituents at microphysical level can be typically described deterministically; as an example, the extinction properties of single hydrometeors can be investigated using Mie's solution [86] (or similar approximate methods [87]), which provides analytical expressions to calculate

the attenuation induced by a single rain drop as a function of the wave frequency and water temperature. Similarly the ionosphere mean electron content profile and Earth magnetic field can be described by global models (such as IRI, NeQuick, IGRF) and ionospheric effects on propagating signals can be evaluated using analytical formulas [88]. On the other side, the atmosphere is a complex propagation medium changing with time and space, and the intrinsic random nature of the phenomena taking place in the atmosphere calls for a stochastic approach; this is the case, for example, of the liquid water content in the troposphere (a key input to several models for the prediction of the effects due to clouds), which tends to follow a lognormal distribution [89], or the random temporal and spatial variations of the electron content value in the ionosphere irregularities, which can be only characterized in statistical terms [90]. The classical approach to developing Earth-space propagation models is the *empirical-statistical* one, mainly based on measurements. This class of models is characterized by methodologies that rely on a simplified description of the physical processes governing the considered effect; this approach typically leads to deriving basic expressions, whose parameters are determined (tuned) on the basis of previous observations collected during measurement campaigns. This is the case, for example, of some models aimed at predicting rain attenuation statistics by means of the path reduction concept [91], [92]: the key idea is that the total rain attenuation along the path can be modelled by starting from the specific attenuation calculated deterministically from the rain rate measured at the ground station, which is then multiplied by a path reduction factor to allow for the fact that the precipitation is highly inhomogeneous along the link. Though such a factor stems from physical considerations, its expression typically includes several empirical parameters, which are optimized by minimizing the model's prediction error against a set of measurements. This approach has the clear advantage of being rather simple, though at the expenses of accuracy and global applicability, which is limited by the inherent nature of the model (quite basic physically-based elements) and by the availability of measurements for model tuning (e.g. only some frequency bands included in the databases and/or data collected in sites not covering all the climates). More comprehensive and accurate models are developed following the *physical-statistical* approach. This class of models relies on the idea of including deterministic methodologies to a larger extent and of generating random fields of atmospheric constituents, whose main features are modeled stochastically. For example, this is the case of the Stochastic Models Of Clouds (SMOC) [89], which offers a methodology to synthesize high spatial resolution (1 km$\times$1 km) three-dimensional cloud fields. The liquid water content in clouds is modelled using the lognormal distribution, whose main parameters (mean and standard deviation values, spatial decorrelation properties) are linked to local coarse resolution (200 km$\times$200 km) Numerical Weather Prediction (NWP) products (e.g. made available worldwide by the European Centre for Medium-Range Weather Forecast). As a result, the effects of clouds on the Earth-space link can be assessed by integrating the liquid water specific attenuation along the path starting from the synthetic cloud fields. A similar approach has been applied to rain fields and rain attenuation in the SISTAR software [93]. Though obviously more complex, these kind of physical-statistical models are also more accurate, globally valid and applicable to scenarios more complex than just one link, i.e. potentially including several ground stations at continental scale. A quite recent evolution of physical models includes the employment of NWP models for the generation of full three-dimensional atmospheric fields at high resolution (e.g. 1 km$\times$1 km spatially and 5 minute temporally) [94]. This approach aims at further improving the accuracy of Earth-space propagation models, by making all tropospheric quantities available (e.g. pressure and temperature, water vapor, rain amount ...), which are key inputs of deterministic prediction models. Obviously, the main disadvantage of this class of models is the need for significant computational resources to reduce the long calculation times required by NWP models, which increase significantly when finer resolutions are to be used. This type of approach is not available yet for the ionosphere due to the very complex physics of the Sun-Earth interactions. Besides the classification outlined above, Earth-space propagation models can be distinguished also on the basis of the type of outputs that they produce. In fact, a broad class of them generates only statistical results, typically in terms of probability density function and/or complementary cumulative distribution function [95]. While this kind of output is vital for the design of some aspects of the communication system (e.g. to determine the power margin to be made available on an Earth-space link to counteract tropospheric attenuation) they are not sufficient to address some more complex ones. For example, this is the case of systems implementing Fade Mitigation Technique (FMTs) [96], advanced techniques required to guarantee the desired Quality of Service level when the detrimental impact of the atmosphere becomes too high to be handled using the customary approaches. In this case, time series of the channel state (not only statistics) are required to parameterize FMTs (such as spatial diversity [97] or time diversity [98]), which can be typically produced by channel models [99].

Short list / description of main reference models:

The main reference models for Earth-space propagation are all gathered in the P-series recommendation of ITU-R (International Telecommunication Union – Radiocommunication Sector [3], as selected and updated by the members of ITU-R Study Group 3 – Radiowave propagation. These recommendations target several applications, including terrestrial ones, but most of them concern Earth-space propagation for communication systems and GNSSs. The P-series ITU-R models are of different types, i.e. both empirical-statistical (e.g. rain attenuation statistics prediction model included in recommendation P.618-13) and physical-statistical (e.g. ionospheric electron content models such as IRI and NeQuick, and GISM scintillation model described in recommendation ITU-R P.531). Some examples are:

- P.531 - Ionospheric propagation data and prediction methods required for the design of satellite networks and systems
- P.618 - Propagation data and prediction methods required for the design of Earth-space telecommunication systems
- P.676 - Attenuation by atmospheric gases and related effects
- P.834 - Effects of tropospheric refraction on radiowave propagation
- P.838 - Specific attenuation model for rain for use in prediction methods
- P.840 - Attenuation due to clouds and fog
- P.1853 - Time series synthesis of tropospheric impairments

All the P-series ITU-R recommendations are freely available (in various formats and languages) at the following URL: https://www.itu.int/rec/R-REC-P/en. Also, for some models, a software code implementation is freely available at the following URL: https://www.itu.int/en/ITU-R/study-groups/rsg3/Pages/ionotropospheric.aspx.

3.4 Active and Passive Remote Sensing

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Overview and state of the art:

[3] for more details of the ITU-R see section 4

By definition remote sensing (RS) indicates the revealing of some properties of a target object without physical contact with the object itself. This is possible as long as the information is carried along the distance between the observer and the target by acoustic or electromagnetic (EM) waves. In case of EM waves, the information on the target is generated by wave-matter interaction and brought to the observer by EM waves traveling through matter [100]. Then, EM-wave features, such as power, frequency, polarisation, and phase, can be measured and processed to extract the information about the target. Thus, the scientific and technical challenges in RS reside in converting the observed EM-wave features into target properties. This is often called the retrieval problem. Not always the retrieval problem can be solved, but if so, the solution generally requires a comprehensive ensemble of analytical instruments, including electromagnetic, spectral, and statistical tools. Providing such a manifold background is laborious, so that the theory is sometimes abridged to expedite the applications. But treating the RS issues separately may be superficial, bewildering, and rapidly outdated. The ensuing risk is the fragmented and incomplete comprehension of the information content of the observations.

Given the essential nature of the RS measurements, the wave-matter interactions on which RS is founded are developed in a systematic manner from the basic electromagnetic models, clearly integrated by experimental results [101]. Basing the entire RS science and technology on the EM wave-matter interaction leads to a clear conceptual interconnection among its various aspects [102], [103]. The unified theoretical background then branches out depending on the intended application, the exploited range of the electromagnetic spectrum, the available sensors and observing technique. Since all the measured quantities stem from EM interactions, common basic behaviours are observed when the variations of the dielectric properties with wavelength are accounted for and reciprocity is exploited. Similarly, atmospheric propagation in RS requires to start from the abstract EM properties to the basic mechanisms of interaction and then to the behaviour of the observed quantities [101]. The wave-medium interaction is clearly the unifying key factor that explains the information on the observed targets that each type of observation contains. Highlighting the invariant fundamental features of the interaction with air, water, and land is key as they are expected to keep their value, even as new RS techniques and sensors are developed and exploited.

Listing all the RS techniques and spectral bands used to observe and retrieve target information can be tedious. However, a schematic classification may be useful. Generally speaking, RS techniques can be divided into passive and active RS [101]. While passive RS is performed by a passive system that only receives EM radiation, active RS exploits a transmitter and a receiver that respectively emits and receives EM radiation. Concerning the exploited spectral region, RS techniques are often distinguished into optical, based on visible but also near infrared and ultraviolet wavelengths, infrared, based on mid-, thermal-, and far-infrared wavelengths, and microwave, based on meter to sub-millimeter wavelengths. Passive RS instruments are typically radiometers (or spectroradiometers, if multi-channel), with the intent of measuring the radiation naturally emitted by the environment. Passive RS techniques can also exploit opportunistic transmitters, i.e. transmitters not designed for the RS goals but whose signal can be received (e.g., passive radar and navigation system receivers). Active RS techniques are often identified with the special case of radar (Radio Detection and Ranging, working at radio and microwave frequencies) and lidar (Light Detection and Ranging, working at optical wavelengths). Active RS systems are called monostatic when transmitter is collocated with the receiver, otherwise bistatic or even multistatic (if more than one receiver are used).

In terms of the observing platform, RS techniques may be distinguished in ground-based, when the instruments are installed at ground, airborne, when the instruments are installed aboard of an aircraft, balloon-borne, when the instruments are attached to an aerostatic balloon, and finally spaceborne, when the instruments are installed aboard of a spacecraft. In terms of the target type, RS techniques may be distinguished in tracking and surveillance RS, often used to monitor moving objects (e.g., vehicles) for civil and military applications (e.g., in ports and airports), and environmental RS, used to monitor different aspects of our planet (atmosphere, land, cryosphere, oceans), as well as extra-terrestrial objects (planets, stars). The RS techniques focusing on Earth monitoring are also called Earth Observation (EO) methods [103]. EO methods are often grouped according to the application, including but not limited to, atmospheric RS (e.g., temperature, wind, clouds, precipitation, composition), land RS (e.g., land use, land cover, vegetation, soil moisture, snow cover, urban development, agriculture, terrain movement), marine RS (e.g., sea surface temperature, salinity, wave height, pollutant concentrations, and currents), and natural hazards (e.g., droughts, flash floods, inundations, tsunami, forest fires, earthquakes, volcano eruptions).

Methods of study and approaches:
Typically, RS methods exploit a combination of forward models, i.e. numerical simulations of RS observations knowing the state of the target, and inverse methods, i.e., the retrieval of target parameters from RS measurements. Forward modeling is based on the EM field theory and radiative transfer theory, considering all wave-matter interaction and propagation phenomena [101], [104]. As such, forward modelling include the macroscopic dielectric modelling of natural media, which can be made of dispersive, dissipative, inhomogeneous, and anisotropic materials. Forward modelling also includes the emission of radiation from coherent and incoherent finite sources, e.g., the emission of thermal radiation, as well as transmission, absorption, and refraction through natural and anthropogenic media. It also embraces the scattering from single targets and distributed particles, as well as reflection from natural surface, including polarisation effects. Deterministic forward modeling can be rarely used due to the stochastic nature of natural media and surfaces and their wave-mater interaction. This means that the polarized field spatio-temporal covariance as well as polarized field coherence are treated by stochastic approaches by very often combining analytical solutions with statistical techniques. The primary theoretical EM forward models are:

- Radiative transfer for non-scattering atmosphere, including emission/absorption by atmospheric gases and hydrometeors.
- Discrete-ordinate radiative transfer numerical model for polarized brightness propagation, multiple scattering, and emission into random media with sparse distributed scatterers such as clouds, precipitation, snow and vegetation.
- Eddington and two-flux radiative transfer approximate models for polarized brightness propagation, multiple scattering, and emission into random media with sparse distributed scatterers such as clouds, precipitation, snow, and vegetation.
- Quasi-crystalline approximation radiative transfer model for polarized brightness propagation, multiple scattering, and emission into random media with dense distributed scatterers such as clouds, precipitation, snow and vegetation.
- Small-perturbation approximate methods for polarized field propagation in weak turbulence and scattering from weakly rough surfaces such as ocean surfaces.
- Physical optical models for polarized field scattering by relatively smooth and rough surfaces such as bare soils and crop fields.

- Integral equation method for polarized field scattering by medium-to-high rough surfaces such as bare rough soils and vegetation layer.

Conversely, inverse methods are needed to map the RS observations (of EM-wave properties) into the desired target parameters, e.g., bio-geo-physical characteristics of the observed target [105]. The so-called "curse" of RS consists in that simple inverse methods rarely lead to a unique and stable solution. Thus, several methodologies have been developed to tackle the issues with the non-uniqueness, instability, and sensitivity to initial conditions of the RS solution. Inverse methods may be distinguished in physical-analytical methods and statistical methods. Physical-analytical methods proposes a solution based on the inversion of the analytical relationship expressing the physical relationship between the observations and the target parameter. Thus, physical-analytical methods typically rely on an appropriate forward model. Conversely, statistical methods rely on the availability of a data set of simultaneous target parameters and RS measurements (or simulations), from which their bulk relationship can be derived through statistics. Among statistical methods are regressive methods, based on functional fits of parameter-measurements couplets, Bayesian methods, based on the a posteriori probability maximization and its statistical moments, and machine-learning methods, based on various classification and estimation techniques (such as feed-forward neural network, convolutional neural networks, random forests) trained by simulated and/or measured data.
Many approaches exist for active and passive RS remote sensing, which differ for sensor type, wavelengths, and observing platform. To name a few, key passive RS from ground include: multi-channel visible sun-photometry for aerosol and gas retrieval; Hyperspectral infrared radiometry for temperature and cloud retrieval; multi-channel microwave radiometry for temperature, humidity, cloud, and precipitation retrieval; Global navigation satellite system (GNSS) receivers for water vapor retrieval. Key passive RS from space/aircraft include: visible-infrared multispectral radiometry for air temperature, aerosol, clouds, and trace gas retrieval; infrared multispectral radiometry for surface sea/land temperature, vegetation, sea color, ice retrieval and target classification; microwave multispectral polarimetric radiometry for temperature, humidity, cloud, and precipitation retrieval; microwave multispectral polarimetric radiometry for surface sea wind/temperature, vegetation, ice retrieval and target classification. Concerning active RS, common approaches include: polarimetric multi-channel lidar for aerosol, cloud, and wind retrieval; multi-channel lidar ceilometer for aerosol and cloud detection; Differential Absorption Lidar (DIAL) for gas gas concentration retrieval; polarimetric Doppler radar meteorology for wind, cloud, and precipitation retrieval; passive radar for target detection and tracking. From space/aircraft, key active RS include: Synthetic aperture radar (SAR) for topographic retrieval as well as target identification, estimation, and tracking; Differential Interferometric SAR for high-resolution seismic facture, terrain movement, snow thickness; Polarimetric multi-channel lidar for aerosol, cloud, and wind retrieval; Multi-channel lidar ceilometer for aerosol and cloud detection; polarimetric Doppler radar meteorology for cloud and precipitation retrieval; radio occultation of global navigation satellite system (GNSS) signals for atmospheric temperature and humidity retrievals; surface reflectometry of GNSS signals for sea/land monitoring.

Short list/description of main reference models:
Reference models used in RS are primarily forward and inverse methods, based on electromagnetic and inversion theory, respectively. Among the reference forward models, the discrete-ordinate radiative transfer numerical model and the Eddington and two-flux radiative transfer approximate

models are used for polarized brightness propagation, multiple scattering and emission within random media with sparse distributed scatterers such as clouds, precipitation, snow and vegetation, while quasi-crystalline approximation radiative transfer model is opted for more densely distributed scatterers. Small-perturbation approximate methods are used for polarized field propagation in weak turbulence and scattering from weakly rough surfaces such as ocean surfaces. Physical optical models are used for polarized field scattering by relatively smooth and rough surfaces such as bare soils and crop fields, while integral equation methods are used for medium-to-high rough surfaces, such as bare rough soils and vegetation layer.
Some reference models for RS are gathered in the P-series recommendation of ITU-R. Some examples are:
- P.527 - Electrical characteristics of the surface of the Earth
- P.453 - The radio refractive index: its formula and refractivity data
- P.676 - Attenuation by atmospheric gases and related effects
- P.833 - Attenuation in vegetation
- P.836 - Water vapour: surface density and total columnar content
- P.837 - Characteristics of precipitation for propagation modelling
- P.838 - Specific attenuation model for rain for use in prediction methods
- P.840 - Attenuation due to clouds and fog
- P.1510 - Mean surface temperature
- P.1815 - Differential rain attenuation
- P.2041 - Prediction of path attenuation on links between an airborne platform and Space and between an airborne platform and the surface of the Earth
- P.2145 - Digital maps related to the calculation of gaseous attenuation and related effects
- P.2146 - Sea surface bistatic scattering
- P.2148 - Digital maps related to surface wind speed statistics

All the P-series ITU-R recommendations are available at: https://www.itu.int/rec/R-REC-P/en.

3.5 Free Space Optics

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Overview and State of the Art:
The idea of transmitting narrow optical beams of light through the atmosphere has been around since the early days of the laser. Indeed an optical transmission system is, in principle, very simple: it requires a modulated laser source, a telescope at the transmitting and receiving side of the link and a receiver, for instance a simple photon counter as a photodiode. Moroever, the development of 1.550 μm fiber optics technology has helped the availability of low-cost components as semiconductor laser sources and receivers. Optical Wireless Communications (OWC) are nowadays used for a plethora of applications including intra/inter-chip connections, visible light communication (VLC) via LEDs, localization and sensing (e.g. by LIDAR technology), point-to-point outdoor communication in terrestrial, underwater, ground-to-space and space-to-space scenarios. Strictly, the terms Free-Space Optics (FSO) or Free-Space Optical Communication (FSOC) refer to data communication over outdoor point-to-point terrestrial links, typically ranging from tens of metres up to a few km [106]. Sometimes, FSO is also associated with communication links involving at least one space or air terminal. FSO transmission wavelengths are in the near-IR bandwidth, specifically in the so-called first optical window (780-850 nm) and third optical window (centered around 1.550 μm).

The biggest advantage of FSO over radio-frequency (RF) is capacity. Tbit/s optical communication has been recently demonstrated over distances of about 1 km using wavelength division multiplexing [107]. In principle, a further increase in data rate can be obtained by generating Orbital Angular Momentum (OAM) light, i.e. wave propagation modes that are orthogonal in space [108]. Other advantages are unlicensed spectrum, immunity to RF interference, spatially confined beams, hence secure communications, frequency reuse and no interference.

Due to the extremely narrow-beams involved in FSO (typically from tenths of a mrad to a few mrad) and LoS communication, optical wave propagation is only influenced by the interaction with the atmosphere. FSO propagation impairments are basically the same as the ones affecting radio- and mmWave signals, even though the intervening atmospheric factors and the dominant particle-wave interaction mechanisms are somewhat different. The major degradation effects observed on an optical wave, sorted in descending order of relevance, are:

- Attenuation due to scattering from suspended particles (aerosol, fog, dust etc.) and hydrometeors (rain, snow and hail).
- Scintillations and wavefront distorsion due to the local inhomogeneities of the refractive index of the air, known as optical turbulence.
- Absorption by the atmospheric constituents (i.e. gases).

Theoretical analysis and experiments show that optical waves are more sensitive to adverse weather than radio waves. This weakness is maybe the major argument against considering FSO as a practical option for back/front-hauling connectivity in 5G and B5G wireless networks. Indeed, terrestrial FSO has been so far restricted, in civil applications, to niche markets, as temporary connectivity solutions during special events or to recover emergency or disaster issues. Moreover, FSO is being used in wireless LANs, for instance to provide links between buildings in campus and company environments.

Compared to the massive amount of RF propagation studies, FSO is relatively unexplored in the propagation community, as it has been traditionally a topic of research in optics. Even though the first experiments of laser transmission by gas lasers through the atmosphere are from the late 60s of last century [109], measurement campaigns with a statistical significance are rare in the literature [110]. Moreover, there is a lack of propagation data collected in the tropical and equatorial regions, where atmospheric conditions are generally less challenging than at mid-latitude for optical propagation, due to the lower occurrence of fog. Significant modeling efforts have been made and are still under way. In this respect, there are few important differences between optical and RF propagation through the atmosphere: i) several types of fine particulates that have no impact up to the mmWave band, can produce significant attenuation levels in FSO communications, as their size is comparable with the optical wavelength; ii) Raindrops and snowflakes are order of magnitude larger than the wavelength, which makes the forward scattering propagation mechanism much more efficient; iii) the impact of clear-air turbulence on the optical wavefront is higher, again due to the much smaller wavelengths involved. Actually, thick fog is able to produce optical attenuation values exceeding 100 dB/km, that are much higher than the ones induced by heavy rainfall over mmWave links [111]. Rain, falling snow and dust are responsible of significant laser attenuation values as well [112],[113].

An accurate prediction of attenuation through fine particulates requires the measurement of the Particle Size Distribution (PSD), which has been a challenging task for a while and needs rather expensive set-ups [114]. Simple empirical models of attenuation rely on the visibility, which is proportional to the inverse of the specific attenuation in the visible region of the spectrum. However, scaling attenuation from the visible to the infrared is not straightforward in the Mie scattering regime. Experimental results and models agree that attenuation from atmospheric particulates is basically flat with the wavelength from the visible window up to the near-IR range when visibility is less than about 500 m, which corresponds to moderate-to-heavy fog conditions, while it is sensitive to the PSD beyond this threshold, hence less predictable from visibility data only, Another drawback of this approach is that a lot of historical visibility data available were collected by human observers (e.g. only daytime measurements) and suffer from high uncertainties [115]. Multiple-scattering must be included in models as it significantly reduces optical attenuation through hydrometeors, particularly rain and snow. The multiple-scattering gain depends on precipitation intensity, path length, PSD and link parameters. Optical turbulence are the random fluctuations of the refractive index of the air, which are produced by local inhomogeneities primarily in the temperature field. The effects of the optical turbulence on a laser beam include random fluctuations of the intensity and phase of the optical field, beam spreading, loss of the spatial coherence of the wavefront, beam wander (i.e. movement of the beam center) and angle of arrival fluctuations [116]. Molecular absorption is basically a wavelength-selective phenomenon that separates the frequency spectrum in transmission bands (called window regions or windows) and absorbing regions. However, there is also a continuum absorption, which is slowly-varying with the wavelength and detectable within the window regions. A small attenuation component due to absorption is present on optical links at ground level in the IR windows and it is produced by the effect of water vapor and carbon dioxide [117].

Models highlight that fog reduces near-IR link availability well below the standards for carrier-grade operation required by backhauling applications (typically 99.999%) with the current IM-DD (Intensity Modulation & Direct Detection) technology. Possible solutions to this issue include the exploitation of the mid-IR band (10.6 μm), which, according to some studies has a better penetration through fog than near-IR [118] the adoption of parallel or dual-hop hybrid RF-FSO schemes [119], [120], or, again, relay-assisted (i.e. multi-hop) transmission. On the other hand, optical turbulence is usually not considered a critical factor as for availability of terrestrial links. However, it contributes to reduce the available margin, hence dumping FSO performance in terms of achievable data rate. The effects of optical turbulence can be mitigated by a number of countermeasures including optimization of system parameters in the design stage and adaptive optics [121].

As a result of the lack of measurements, the process of standardization of FSO propagation models is at an embryonic stage. There are two dated ITU recommendations on FSO design, i.e. ITU-R P.1814.0 (Prediction methods required for the design of terrestrial free-space optical links) and ITU-R P.1817-1 (Propagation data required for the design of terrestrial free-space optical links) released in 2007 and 2012, respectively, which are basically a collection of older works and outdated models (see Section 3.3 for details about how to access ITU-R documentation). Hence, differently from RF links, there is not a solid proof of availability of FSO links gathered from statistical models based on experimental evidence and valid on a global scale.

Methods of study and approaches:

As an optical wave travels through the atmosphere, attenuation due to particle scattering and scintillations due to clear-air turbulence produce an additional path loss. A fundamental step of FSO design is the assessment of the margin required to compensate for the atmospheric attenuation by an appropriate path loss model. Particle-light interaction can be described by deterministic models, through closed-form expressions in the case of simple shapes (e.g. Mie theory for spheres

[122]) or numerical methods for more complex particles (e.g. T-matrix [123], finite-difference time domain [124], etc.). However, the Earth atmosphere is a random medium due to the stochastic nature of the weather processes that determine the occurrence of atmospheric particles in the air. As a result, path loss propagation models are usually based on two layers: 1) a physical-empirical layer that connects the key atmospheric inputs to path attenuation, and 2) a statistical layer that derives the first order statistics of attenuation from the ones of the inputs. The path loss model output is a CDF of path attenuation, which feeds an FSO link budget equation where a number of system parameters are optimized to reach a target link availability. In coarse calculations, the statistical layer is missing and the link budget equation is solved assuming typical or worst case path attenuation conditions. The relationships between key atmospheric drivers and path attenuation are gathered either from electromagnetic theory or from joint measurements of path loss and weather parameters. The electromagnetic approach can have different degrees of complexity ranging from a simple single-scattering formulation [122] to forward-scattering or full multiple-scattering corrections (see [125] for a review of such methods). The multiple-scattering contribution is significant in the case of FSO propagation through rain and snow, because, if particles are much larger than the optical wavelength, an overwhelming fraction of the scattered light is irradiated in the forward direction. Multiple-scattering simulation based on the Monte-Carlo probabilistic approach [126], [127] models the propagation through an homogeneous medium filled with absorbing and scattering particles as a random walk of the photons travelling away from the transmitter section. It is intrinsically a wide-band channel model, as, besides path attenuation, it returns the coherence bandwidth of the atmospheric channel through the delay spread function, which in turn, is estimated from the time of arrivals of the scattered photons at the receiver section.

The effects of optical turbulence are assessed through the classical statistical theory of Kolmogorov. The mathematical framework moves from the concept of the mutual coherence function, that is the second moment of the spatial optical field. The process, though complex, provides analytical expressions for the aforementioned effects of optical turbulence on a laser beam. A comprehensive collection of models specialized to the different turbulence regimes, wavefront shapes (e.g. plane wave, Gaussian beam wave, etc), and FSO link parameters is in [116]. The dependence on turbulence strength is expressed through the structure parameter of the refractive index of the air C_n^2, which can be considered constant over a near-ground horizontal propagation path, even though it is time-variant over different time scales.

Drawing global statistics of the key atmospheric drivers is an open issue. Rainfall intensity, which is the basic input for deriving rain attenuation statistics, is standardized by ITU-R P.837 (Characteristics of precipitation for propagation modelling). On the other hand, attenuation models for propagation through suspended particles rely on ground-based visibility data, e.g. the Global Historical Climatology Network - Daily (GHCN-Daily) available at NOAA website, which have a coarse resolution in time (usually 1 hour) and are usually collected outside urban areas. The visibility field, especially when the visual range is reduced by fog, is affected by the environment, hence significant differences in the occurrence and severity of fog are expected moving from the heat island over the city centre into the surrounding areas. Moreover, the fog is affected by the local microclimate, hence the visibility field may have inhomogeneities over distances on the same order as typical FSO path lengths, which reflect into different CDFs for the visibility measured at different points across the link. Finally, C_n^2 data can be collected by scintillometers, or by measuring the vertical gradients of temperature, humidity and wind velocity [128] but the results are not easy to generalize. Simple C_n^2 models based on best fits of standard variables measured by weather stations [129], [130], are potentially more interesting for application on a global scale but need an extensive validation process.

Combining together the sources of atmospheric path loss into a unified model of total attenuation is another challenge as visibility-based models hold for suspended particulates only, while visibility itself is significantly reduced by hydrometeors and other particles. Assessing the mutual dependence between fog, rain and snow occurrence is important also for the assessment of hybrid RF-FSO systems. The different sensitivity to rain and fog of RF and FSO links is expected to increase the robustness of parallel hybrid links against propagation impairments enough to achieve carrier grade availability (typically 99.999%) though with a loss of capacity when the FSO link is in outage.

Besides path loss models, more complex propagation tools are necessary to help in the design of the mitigation techniques against short-term outages (down to milliseconds) produced by optical turbulence [131]. This aspect becomes very important when extremely high data rates are involved. For instance, simulators based on the Parabolic Wave Equation (PWE) and multiple phase screens reproducing the stochastic phase variations induced by optical turbulence are used to generate synthetic EM fields in the atmosphere [132]. The availability of flexible closed-form expressions and simulators has fostered many studies aimed at optimizing link set-ups, spatial diversity schemes and modulation and coding under turbulent conditions [131], [133]–[135].

4 Publication, dissemination and impact

Propagation research is a complex and rapidly evolving discipline. To maximise impact emerging knowledge must be shared effectively and efficiently while research efforts are increasingly transnational and interdisciplinary and require international cooperation and coordination. In this section we review the major publications, conferences, reference associations, standardisation bodies and other international efforts operating in this space.

4.1 Journals publishing propagation-related research

Propagation is a broad discipline, and valid research can comprise a host of activities from research into fundamental electromagnetic effects, measurement campaigns, numerical modelling etc. Nonetheless a publication or similarly novel public contribution can be expected to have a number of attributes, whatever the area. These include several of the following

- A complete and accurate description of any data used
- A rigorous methodology underpinning any measurement or modelling work
- A novel application area
- A robust validation against a suitably chosen “ground truth" validation data (experimental or numerical)

Below we include a non-exhaustive list of journals that publish work on propagation. The list has been compiled by our section contributors and will hopefully serve as a reference to researchers who are seeking to disseminate their work. We include International Standard Serial Number for the print (ISSN) and online (eISSN) versions of the journal as appropriate. The last four columns indicate which application areas are (predominantly) included in the journal and the following key applies: TM - Terrestrial and Mobile, IS - Indoor and Short Range, ES - Earth Space, RS - Active and Passive Remote Sensing.

Publisher	Journal Name	ISSN	eISSN	TM	IS	ES	RS
IEEE	Aerospace and Electronic Systems Magazine	0885-8985				X	
IEEE	Antennas and Propagation Magazine	1045-9243	1558-4143	X	X	X	
IEEE	Antennas and Wireless Propagation Letters	1536-1225	1548-5757	X	X	X	
MDPI	Atmosphere	N/A	2073-4433				X
EGU	Atmospheric Chemistry and Physics (ACP)	1680-7316	1680-7324				X
EGU	Atmospheric Measurement Techniques (AMT)	1867-1381	1867-8548				X
Elsevier	Atmospheric Research	0169-8095	1873-2895				X
IET	Communications	1751-862	81751-8636	X	X		
IEEE	Communications Magazine	0163-6804	1558-1896	X	X		
John Wiley & Sons Inc.	Electronics Letters	0013-5194				X	
Taylor and Francis	European Journal of Remote Sensing	N/A	2279-7254				X
IEEE	Geoscience and Remote Sensing Letters (GRSL)	1545-598X	1558-0571				X
IEEE	Geoscience and Remote Sensing Magazine	2473-2397	2168-6831				X
IEEE	IEEE Access	2169-3536	2169-3536	X	X	X	X
John Wiley & Sons Inc.	IET Microwaves, Antennas and Propagation	1751-8725		X	X	X	
Hindawi Limited	International Journal of Antennas and Propagation	1687-5869	1687-5877	X	X	X	
Cambridge University Press	International Journal of Microwave and Wireless Technologies	1759-078	71759-0795	X	X		

Publisher	Journal Name	ISSN	eISSN	TM	IS	ES	RS
John Wiley and Sons Ltd	International Journal of Satellite Communications and Networking	1542-0973				X	
AGU	Journal of Geophysical Research (JGR)	0148-0227	N/A				X
Springer	Journal of Infrared Millimeter and Terahertz Waves	1866-6892	1866-6906	X	X		
Pergamon-Elsevier	Journal of Quantitative Spectroscopy and Radiative Transfer	0022-4073	1879-1352				X
IEEE	Journal of Selected Topics in Applied Earth Observations and Remote Sensing (JSTARS)	1939-1404	2151-1535				X
IEEE	Journal on Selected Areas in Communication	0733-8716	1558-0008	X	X		
EURASIP	Journal on Wireless Communications and Networking	1687-1472	1687-1499	X	X		
IEEE	Open Journal of Antennas and Propagation	N/A	2637-6431	X	X	X	X
PIER	Progress in Electromagnetics Research	1070-4698	1559-8985	X	X		
AGU	Radio Science	0048-6604	1944-799X	X	X	X	X
MDPI	Remote Sensing	N/A	2072-4292				X
Springer	Remote Sensing Applications-Society and Environment	2352-9385	2352-9385				X
Taylor and Francis	Remote Sensing Letters	2150-704X	2150-7058				X
Elsevier	Remote Sensing of the Environment	0034-4257	1879-0704				X
EurAAP	Reviews of Electromagnetics			X	X	X	X
IEEE	Trans. Geoscience and Remote Sensing (TGRS)	0196-2892	1558-0644				X
IEEE	Transactions on Antennas and Propagation	0018-926X	1558-2221	X	X	X	
IEEE	Transactions on Communication	S0090-6778	1558-0857	X	X		
IEEE	Transactions on Instrumentation and Measurement	1557-9662				X	
IEEE	Transactions on Wireless Communications	1536-1276	1558-2248	X	X		
IEEE	Wireless Communications	1536-1284	1558-0687	X	X		

Optica Publishing Group	Photonics Research	N/A	2327-9125	X	X	X	X
Optica Publishing Group	Optics Express	N/A	1094-4087	X	X	X	X
Optica Publishing Group	Applied Optics	2155-3165	1559-128X	X	X	X	X
IEEE	Journal of Lightwave Technology	1558-2213	0733-8724	X	X	X	X
IEEE	Journal of Optical Communications and Networking	1943-0620	0733-8724	X	X	X	X
IEEE	Photonics Journal	1943-0647	1943-0655	X	X	X	X
Elsevier	Optics Communications	N/A	0030-4018	X	X	X	X

Table 1: Journals publishing research on propagation

4.2 Major conferences featuring propagation research

There are many international conferences dedicated to disseminating propagation research and promoting networking opportunities. These differ in terms of size and focus with some of the larger ones also promoting advances in antennas, electromagnetics etc. We provide a non-exhaustive list below. Again the last four columns indicate which application areas are (predominantly) included in the journal and the following key applies: TM - Terrestrial and Mobile, IS - Indoor and Short Range, ES - Earth Space, RS - Active and Passive Remote Sensing.

Organising body	Conference Name	Acronym	TM	IS	ES	RS	Notes
IEEE	Advanced Satellite Mobile Systems	ASMS			X		Mainly focused on system aspects, but also dealing with propagation topics
AGU	AGU General Assembly	AGU GA				X	American Geophysical Union General Assembly. Held annually in USA.
IEEE	Asia-Pacific Conference on Antennas and Propagation	APCAP	X	X	X	X	
URSI	Beacon Satellite Symposium	BSS			X		Every 3 years Focussed on ionospheric propagation and Space Weather
EGU	EGU General Assembly	EGU GA				X	European Geophysical Union General Assembly. Held annually in Europe.
EurAAP	European Conference on Antennas and Propagation	EuCAP	X	X	X	X	Largest European conference in AP. Held annually
European Commission	European Conference on Networks and Communications	EuCNC	X	X			
	European conference on Radar in Meteorology and Hydrology	ERAD				X	Focusing on radar meteorology.
URSI	General Assembly and Scientific Symposium of the International Union of Radio Science	URSI GASS	X	X	X	X	Wide spectrum conference. Held every two years
IEEE	Global Communications Conference	GLOBECOM	X	X			
IEEE AESS	IEEE Radar conference					X	Organised by the IEEE Aerospace and Electronic Systems Society

IEEE GRSS	International Geoscience and Remote Sensing Symposium	IGARSS				X	The flagship conference of the IEEE Geoscience and Remote Sensing Society (GRSS). Held annually.
IEEE	International Symposium on Antennas and Propagation	ISAP	X	X	X		Asia / Australasia. Annually.
IEEE	International Symposium on Antennas and Propagation	AP-S	X	X	X	X	Normally held in the USA. Held annually
IEEE	International Symposium on Personal, Indoor and Mobile Radio Communications	PIMRC	X	X			
PIERS	PhotonIcs and Electromagnetics Research Symposium,	PIERS	X	X			Also known as Progress In Electromagnetics Research Symposium
AMS	AMS Radar meteorology conference	AMS				X	Focusing on radar meteorology.
IEEE / CeTeM	Specialist Meeting on Microwave Radiometry and Remote Sensing of the Environment	MicroRad				X	Focusing on passive microwave radiometry.
SPIE	SPIE Remote Sensing	SPIE RS				X	Organised by Society of Photo-Optical Instrumentation Engineers Remote Sensing
USNC-URSI	Radio Science Meeting	NRSM	X	X			
IEEE	Photonics Conference	IPC	X	X	X	X	Cover vast technical areas within the photonics community including propagation
IEEE	Optical Fiber Communication Conference	OPC	X	X	X	X	Global event for optical communications and networking
SPIE	SPIE Photonics West LASE	LASE	X	X	X	X	One of the topics is Free-Space Laser Communications
IOP	International Conference on Optical Communication and Optical Information Processing	OCOIP	X	X	X	X	Many topics in the area of optical communication and optical information processing

Table 2: Conferences publishing research on propagation

4.3 Reference Associations, Standardisation Bodies and Training Schools

Author: Antonio Martellucci, European Space Agency, The Netherlands

Research in propagation is facilitated by a number of international bodies who promote activities, coordinate development, and provide regulatory and standardisation functions so that emerging technologies can be successfully and seamlessly integrated into existing frameworks.

Standardisation and Regulation

The ITU-R is a sector of the International Telecommunications Union (ITU), a United Nations specialised agency. The ITU-R regulates radio spectrum usage worldwide to ensure interference free radio services through its periodic World Radio Conferences (usually every 4 years). It also issues publicly available recommendations, reports. fascicles and publishes handbooks, which are the results of Radiocommunication Study Groups activities in the study periods between World Radio Conferences. Participation to ITU-R Study activities is open to States, Organizations and Academia that joins ITU. In this framework, ITU-R Study Group 3 performs studies on Propagation of radio waves in ionized and non-ionized media and the characteristics of radio noise via its Working Parties, 3J "*Propagation fundamentals*", 3K "*Point-to-area propagation*", 3L "*Ionospheric propagation and radio noise*" and 3M "*Point-to-point and Earth-space propagation*". Working Party meetings are usually held once per year and are followed by Correspondence group activities during the intersession period. Study Group 3 collects and maintains a database of propagation measurements (DBSG3) used in its studies to develop and test models for the recommendations and provides free access to propagation Software products and reference validation data. ITU-R P recommendations on radiowave propagation provides a free and comprehensive set of data and prediction models for several applications, including among the others: Earth-space telecommunication systems and terrestrial paths (ITU-R Recs. P.618 and P.21001); Optical communications on Earth-space and terrestrial paths (ITU-R Recs P.1621, P.1622 and P.1814); Interference among the stations on Earth and in space (ITU-R Recs P.452 and P.619). From time-to-time Study group 3 and its WPs organize Scientific workshops, e.g the CLIMPARA meetings in collaboration with URSI, and the EuCAP Workshops in collaboration with EuRAAP. Another international organisation driving standardisation work is The Institute of Electrical and Electronics Engineers (IEEE). The IEEE have maintained a standard governing letter designations (e.g. X band) for radar-frequency bands since 1976. These are consistent with the ITU nomenclature in some cases further sub-dividing ranges. The IEEE is a leading developer of industry standards across all its areas, including radio. These are developed via working groups, comprising experts from industry, academia, government agencies etc.

Reference Associations

There are number of international reference associations who aim to promote and coordinate activities locally and worldwide.

Association	Website	Notes
IEEE Antennas and Propagation Society (IEEE APS)	ieeeaps.org	Founded in 1949, this society publishes several journals, sponsors international conferences and is active worldwide through over one hundred local chapters.
IEEE Geoscience and Remote Sensing Society (IEEE GRSS)	grss-ieee.org/	Over seventy chapters worldwide. This society publishes several journals and sponsors conferences worldwide, including the flagship International Geoscience and Remote Sensing Symposium
European Geophysical Union (EGU)	egu.eu	Promoting Earth, planetary and space science research in Europe. Its activities include publications, conferences, outreach and education, career development
American Geophysical Union (AGU)	agu.org	Established in 1919 the AGU publishes over 20 international journals and convene a number of specialised meetings, summits and conferences each year.
Union Radio-Scientifique Internationale (URSI)	ursi.org	Under the International Council for Science. Promotes and coordinates activities relating to radio science, including publications and conferences. Grand Assembly first held in 1922 and every three years since 1954.
European Association for Antennas and Propagation (EurAAP)	euraap.org	Promotes and coordinates European activities relating to antennas and propagation, most notably through the annual EuCAP conference, the European School of Antennas and Propagation and specialised working groups.

Table 3: Reference Associations

Education and outreach is a key activity of many international organisations. Below is a non-exhaustive list of some training schools which are in the area of propagation.

Organising body	Website	Notes
COST INTERACT	interactca20120.org	Runs a number of workshops and training schools for PhD students / industry representatives
EurAAP	euraap.org/esoa-in-brief	EurAAP's European School of Antennas and Propagation run a number of week long PhD summer schools
European Space Agency (ESA)	esa.int/Education/ESA_Academy	Comprising two interconnected pillars - Hands-on space projects and the Training and Learning programme.
European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT)	training.eumetsat.int	EUMETSAT Training supports users in the in the application of EUMETSAT data, services and products.
National space agencies (e.g. CNES France, ASI Italy, NASA US, JAXA Japan)		Various courses run by national agencies.
International society for optics and photonics (SPIE)	https://spie.org/	SPIE mission is to strengthen the global optics and photonics community through conferences, publications, and professional development
IEEE Photonics Society	https://ieeephotonics.org/	As part of IEEE, organizes, contributes to and participates in technical conferences, journals and other activities covering all aspects of photonics in order to share and disseminate breakthroughs.

Table 4: Training Schools

4.4 Commercial or open source tools related to propagation

Below is a selection of some of the tools used in propagation science

Name	Modelling method	TM	IS	ES	RS	Notes
Remcom Wireless Insite	Ray Launching	X	X			All, including diffuse
Altair Feko (Winprop, NewFasant)	Ray Launching, GTP and PO	X	X			
EDX Wireless	Uses X3D Remcom	X	X			
Siradel Volcano	Ray Tracing	X	X			
COMSOL Multiphysics	(Ray optics module)	X	X			The Ray Optics Module is an add-on to the COMSOL Multiphysics® software
Wireless Simulation : Mobile CDS	Ray launching (Urban environment using google maps)	X	X			Not diffuse
Radio Mobile		X	X			Outdoor environments
ITU-R Study Group 3 propagation SW	Some models included in the P-series ITU-R recommendations.			X		Open source: available at the following URL: https://www.itu.int/en/ITU-R/study-groups/rsg3/Pages/iono-tropo-spheric.aspx
tbupdown: Line-by-line microwave radiative transfer	Non-scattering				X	Evolution of the Millimeter-wave Propagation Model (MPM). Open Source: https://tinyurl.com/MWRTMxxx
ARTS: Atmospheric Radiative Transfer Simulator	Scattering				X	Radiative transfer model for the millimeter and sub-millimeter spectral range. Open Source: https://www.radiativetransfer.org
SNAP: Sentinel Application Platform for RS Earth Observation data processing					X	Software for Copernicus Sentinel data handling. Open Source
PyRad: Python Radar open software for radar meteorology					X	Library of tools for weather radar data handling. Open Source
PyRTlib: Python open software for atmospheric radiative transfer					X	Library of tools for non-scattering atmospheric attenuation and radiative transfer. Open Source: https://doi.org/10.5194/gmd-2023-171
ENVI-IDL: Interactive Data Language for Earth Observation data processing					X	Commercial
Matlab	Toolboxes for data and image processing				X	Commercial

5 Conclusions and Future Challenges

Electromagnetic propagation studies play a crucial role in understanding the behavior of electromagnetic waves as they travel through different mediums and environments. These studies are crucial for the design and implementation of numerous applications, including wireless communication systems, remote-sensing and radar systems, satellite communications, and Internet of Things (IoT) networks to name a few. This white paper is aimed at defining the scope of electromagnetic propagation, at providing an overview of its theoretical background and a snapshot of the current state-of-the-art in electromagnetic propagation studies. Moreover, it provides an overview of the different modelling approaches in electromagnetic propagation and highlights future prospects for research in the field.

The current state-of-the-art in electromagnetic propagation studies is characterized by significant advancements across various aspects. Improved modeling techniques enable more accurate predictions of wave propagation behavior in complex scenarios. Advanced measurement setups and techniques allow for the precise characterization of propagation channels, facilitating the development of robust communication systems. Additionally, as the emergence of new frequency bands has expanded the possibilities for wireless communication, remote sensing and other applications, new studies have addressed measurement and modeling of propagation at such frequencies. In recent years, there have been notable advancements in understanding multipath effects, which occur when waves scatter from obstacles in the propagation environment. Researchers have made progress in modeling these effects, which can be exploited to improve communication capacity of wireless networks and to achieve improved system reliability. Powerful ray-based, deterministic models allow for the accurate simulation of multipath propagation for site-specific design and planning of wireless systems. Applying Machine Learning techniques may also enable the derivation of high-performance propagation models. This is particularly useful in cases where large datasets are available for training, while the complexity of the environment and/or the propagation process can hinder the development of accurate empirical or physics-based models.

The study of electromagnetic wave propagation between the Earth surface and the space around, including the atmospheric effects is also becoming crucial due to the increasing importance of satellite communication networks and Global Navigation Satellite Systems (GNSSs). Various detrimental effects such as absorption, attenuation, polarization changes, scintillations, signal delay, and refraction caused by the atmosphere on Earth-space signals are briefly illustrated in the paper. Different approaches to studying Earth-space propagation, including deterministic and stochastic modeling are presented. The use of Numerical Weather Prediction (NWP) models for generating atmospheric fields is also mentioned, together with the importance of ongoing research and development in Earth-space propagation models to support the evolution of satellite-based communication and navigation systems, their shift towards higher frequency bands and the need for models suitable for constellations of satellites on orbits closer to the Earth.

The use of optical frequencies, with their huge bandwidth and peculiar propagation characteristics is also very important and justifies an entire technology branch referred to as Free-Space Optics (FSO). FSO involves transmitting narrow optical beams of light through the atmosphere for various applications, including short-range intra/inter-chip connections, visible light communication, and outdoor communication scenarios. FSO communication typically occurs over point-to-point terrestrial links and uses near-infrared wavelengths. FSO offers higher capacity compared to radio-frequency communication and has advantages such as unlicensed spectrum, immunity to RF interference, secure communication, and frequency reuse. However, outdoor, medium-range FSO propagation is affected by the cited atmospheric factors, and has therefore been limited to niche markets due to its vulnerability to adverse weather conditions. This paper discusses the challenges in modeling FSO propagation and the need for standardization and measurement campaigns. It describes the methods and approaches used to study FSO, including path loss models, particle-light interaction models, and simulation techniques for multiple-scattering and optical turbulence effects.

As mentioned above, electromagnetic propagation is also at the base of remote sensing techniques, that represent the most important techniques for the extraction of environment information using electromagnetic waves. Different remote sensing techniques based on active and passive systems, as well as optical, infrared, and microwave approaches, are discussed in this white paper. The document also categorizes remote sensing approaches based on the platform used, such as ground-based, airborne, and spaceborne techniques. It further highlights various applications of remote sensing, including atmospheric, land, ocean, and natural disaster monitoring. The methods and approaches used in remote sensing are outlined, distinguishing between forward models (numerical simulation of RS response) and inverse models (retrieval methods of target parameters), and covering relevant topics as dielectric modeling, reflection, scattering, transmission, absorption, thermal radiation emission, polarization effects, and radiation from coherent and incoherent sources. Stochastic approaches are often used due to the random nature of natural environments. The document also mentions different methodologies for solving inverse problems in remote sensing, such as physical-analytical methods, statistical regressive methods, statistical Bayesian methods, and machine learning techniques. Additionally, the document also hints at reference models used in remote sensing, including the discrete-ordinate radiative transfer model, Eddington and two-flux radiative transfer models, quasi-crystalline approximation model, small-perturbation methods, physical optical models, and integral equation methods.

All considered, electromagnetic propagation represents a fundamental and extraordinarily wide range of research and application topics that require a variety of study approaches, including experimental, theoretical, simulative, and encompasses multiple disciplines ranging from physics, maths, electrical engineering and computer science. Looking ahead, the future prospects for electromagnetic propagation studies are promising. Advancements in this field have the potential to revolutionize various industries and technologies. For instance, as wireless communication systems continue to evolve, understanding the propagation characteristics of higher radio frequency bands and THz frequencies will be crucial for achieving faster data rates, lower latencies and greater network capacity. However, the future of electromagnetic propagation studies also presents challenges. Increasing complexity in propagation environments, such as industrial scenarios with complex obstacles, demands sophisticated modeling techniques and optimization algorithms. Spectrum scarcity and competition pose additional obstacles: interference and coexistence issues become more pronounced as the number of wireless devices increases, necessitating interference mitigation techniques and the cohexistence of different transmission techniques, including the use of optical frequencies. Moreover, addressing security and privacy concerns becomes paramount as wireless connectivity becomes more pervasive. In conclusion, electromagnetic propagation studies are currently at the forefront of technological advancements, enabling improved wireless communication, radar systems, satellite communications, and IoT applications. The future prospects for this field are bright, with the potential for groundbreaking developments and widespread impact. By addressing challenges and pursuing targeted research, researchers and industry professionals can shape the future of electromagnetic propagation studies and unlock new opportunities for innovation and connectivity.

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