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Principles and Techniques

Jacques Lavergnat | Michel Sylvain

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Jacques Lavergnat
University of Versailles/Saint-Quentin-en-Yvelines

Michel Sylvain
University of Marne-la-Vallée

Translated by

Dr John C. C. Nelson
School of Electronic and Electrical Engineering
University of Leeds

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Radio Wave Propagation

Preface

Propagation of electromagnetic waves through natural media is used in a large number of telecommunication systems currently in service; this will remain the case in the future, so predictions can be made on the basis of the present situation. Although some older systems such as transmission by ionospheric reflection and microwave beams are of reduced importance compared with new techniques such as fibre-optic links and with new wireless systems, some developed to a considerable extent, such as communication with mobiles (pedestrians, from this point of view, are considered as special cases of 'mobiles') and digital television broadcasting by satellites. In the context of 'wireless systems', radar remote detection, which encounters the same propagation problems, should be included in addition to telecommunication systems.

A fundamental characteristic of natural propagation media is their natural variability, both spatial and temporal, which cannot be controlled, but can be observed, and must be accommodated by specifying the transmitting and receiving terminal equipment so that the links established satisfy certain quality criteria.

Good understanding of the propagation mechanisms in these media must therefore constitute one of the basic elements of the culture of the telecommunications engineer, who, even if specializing in equipment or systems, must discuss matters with propagation specialists, and the two communities must have a common language.

At one time it might have been hoped that technical progress in both components and signal processing methods (modulation and coding of ever-increasing performance) would lead to freedom from analysis of propagation phenomena, their effects being reduced to an almost negligible background noise. However, this did not occur. On the one hand, the use of higher-performance techniques was accompanied by greater demands on the required quality (such as increased capacity, increased quality, which must be comparable to that of new guided systems, and reduction of transmitted power). On the other hand, expansion of systems and services sharing the same frequency spectrum creates an increasing need for exhaustive studies of possible interference between services; these studies constitute a particular propagation problem that remains very complex.

The present work provides an introduction to propagation in natural media (also called free propagation, in contrast to guided propagation). Consequently it is addressed to students at engineering colleges and students of certain disciplines, for whom it forms a first encounter with this domain. For this reason, the emphasis is more on the methods of analysis of propagation problems, the required adaptation of the laws of physics, and the solution of complex problems that sometimes require drastic approximations, than on the results of studies leading to methods of calculation (engineering rules) that are current at a given time. These rules can be found in specialized works, and are continuously updated in accordance with the advance of research.

Electromagnetic propagation in a natural medium forms a multidisciplinary domain drawing closely on statistical modelling, electromagnetism, and the physics of the propagating media. These three subjects are treated successively in the first three chapters.

A statistical description is the only satisfactory way in which to present the results concerning the study of media whose variable character has been emphasized above. Statistical considerations (which form the subject of Chapter 1) also have the advantage of showing why (experimental) studies of propagation are inevitably long and must be planned sufficiently early if their results are to be exploited correctly in the specification of new telecommunication systems.

Propagation problems are by their nature problems of electromagnetism. Chapter 2 describes the different mechanisms encountered and how they can be treated, taking account of the complicated geometries involved and the limited accuracy of available knowledge of the media.

Chapter 3 describes the natural media actually encountered (the atmosphere, the ionosphere, and the ground), but is restricted to those aspects of these media that are pertinent to propagation studies.

Chapter 4 shows, in several examples, how the concepts introduced in the three preceding chapters can be applied and combined to provide methods of calculation that can be used in practice.

Exercises are provided at the end of each chapter, and their solutions are grouped together in Chapter 5. Although some are sufficiently realistic for their results to be considered as a first approximation, this advantage is counteracted by an increased level of difficulty. Their study is, however, indispensable in order to become familiar with the subject. Note that some of the suggested exercises require the use of a programmable calculator.

From the point of view of prerequisites, a good knowledge of probability calculations and electromagnetism is sufficient. An appendix provides a concise summary of antennas for those who are not familiar with this topic.

Comment: Passages in small type, which contain clarification of certain points, can be skipped on a first reading.

Contents

1

The How and Why of Propagation

1.1 GENERAL

The propagation of electromagnetic waves can be approached in different ways. Firstly, it is that part of electromagnetism that is concerned with the transport of electromagnetic energy from one point to another through a medium specified by its electrical properties in the wider sense. The concepts and methods relating to this problem lie in the domain of physics. From this 'academic' point of view, the practical use of electromagnetic waves has given rise to a particular problem, which it is customary to describe as 'studies of wave propagation'; This has its own characteristics, and is the subject of this work.

This point of view mingles physical considerations with those associated with envisaged applications. As time advances, applications become diversified and refined; examples are radar techniques, remote sensing in space, and remote fault tracing. The large number of applications and their variety does not prevent the approaches adopted in each case proceeding, or having to proceed, in a unique manner.

Historically, refinements of techniques have led to the evolution of the perception of propagation problems. Initially, the goal was to be able to estimate the level of electromagnetic energy at every point in order to be able either to dimension systems (e.g. the number of relays in a point-to-point link or the power of a radio transmitter) or to determine the spatial coverage (e.g. the range of a radar). It was therefore thought – quite naturally at the time – to be possible to separate propagation phenomena from the use to which they were being put. As techniques became more complicated, notably with progress in signal processing, it was soon realized that this concept was illusory and that in reality each application required a specialized approach. Consequently this work forms part of a collection dedicated to the teaching of telecommunications; examples will be drawn principally from this domain, and the example of a simple link between two points will be examined first.

1.1.1 The Propagation Channel

Propagation concerns electromagnetic systems; they can be distinguished schematically into five sections (Figure 1.1): the two electronic devices forming the transmitter and receiver at the two ends of the link, the medium that supports the transmission itself, and the two antennas that form the interfaces with it. The most natural definition of the propagation channel is to identify it as the medium traversed by the electromagnetic waves. This definition, however, entails many ambiguities.

What is important is that the receiver recovers the information that the transmitter sends to it without error. Two phenomena impede the accomplishment of this task: on the one hand, the transmitted signal suffers alterations in the course of propagation (due to attenuation, various distortions, etc.); on the other hand, electromagnetic perturbations either of natural origin (e.g. cosmic noise) or man-made (e.g. industrial noise) will become superimposed. Characterization of a propagation channel implies the capability, in some manner, to deduce the received signal as a function of the transmitted signal. The commonest and simplest case is that where the channel can be considered, with respect to the characteristic times of evolution of the medium, to be constant; it is then described as stationary and some of its properties can be specified by a transfer function $H(f)$ or an impulse response $h(t)$. The received signal can thus be written as $s_r(t) = s_t(t) * h(t) + n(t)$, where $s_t(t)$ is the transmitted signal and $n(t)$ is the perturbation noise captured by the receiving antenna (the symbol $*$ indicates convolution). With this formulation, it seems that the effects of the medium and those of the transmission system have been completely separated, apart from the fact that the antennas have a

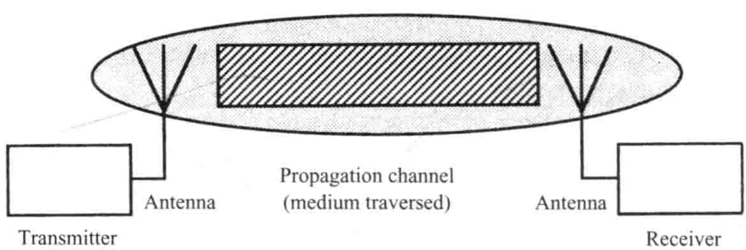

Figure 1.1 Simplified configuration of a radio link

direct influence on $h(t)$. In fact, it is clear that the response of the medium depends on the manner in which it is excited, not merely by the angular extent involved. If, for example, the lobes of the antennas permit several propagation paths for the electromagnetic energy, there will be multiple trajectories that will not lead to the same impulse response, at a distance, as that obtained in the presence of a single propagating trajectory. Reality is therefore more complex, since the medium itself influences the characteristics of antennas. The conductivity of the ground and the presence of water or snow on the antenna structures can significantly modify their radiation diagrams. In certain cases, it is more appropriate to include the antennas in the propagation channel.

Propagation studies therefore have the purpose of characterizing the propagation channel in order to improve communication. This improvement can be made in several ways, either by adapting the coding system, which is called channel coding, or by using corrective devices such as equalizers or even by making use of space and/or frequency diversity.

1.1.2 Transmission Performance

'To improve communication' is a very general expression, which should be examined more closely. Transmission of information is an activity that belongs to the domain of *services*. The quality of a service inevitably has a subjective aspect related to the user. This aspect has been evident since the origin of the wired telephone, and the concept of the 'average ear' has been introduced by means of the psophometric curve, which specifies quantitatively the frequencies that are useful for the comprehension of a vocal message.

When possible, the quality of a service is determined with the help of an objective measure – that is, one that can be measured independently of the observer. In narrowband analogue systems, the measure used is very often the signal-to-noise ratio. In systems with digital modulation, the probability of binary errors is much used. On the other hand, the value of this quantity above or below which the link is considered to be bad is generally related to the subjective impression of the 'average customer'.

Examples: In digital telephony, a bit error rate of 10^{-3} is considered to be the maximum permissible to retain acceptable intelligibility.

In the packet transmission system called Transpac the maximum permitted bit error rate is 10^{-9}.

In radio broadcasting using frequency modulation, a signal-to-noise ratio of 9 dB is generally considered to be the minimum to obtain good listening quality; with amplitude modulation, such a value would satisfy only a few listeners.

There are cases where it is not possible to use an objective parameter. A programme of subjective tests based on a sample of potential customers is then carried out. This is often the case when the information to be transmitted is an image – since what is a good image? To emphasize the difficulty, it has been noted on certain occasions that the human brain prefers the addition of a little noise – believe it or not – to lower the contrast!

Looking at matters more closely, it is evident that the problem is even more complex. Consider the case of the digital telephone. When the error probability threshold is exceeded, the link is reputed to be poor. Since the propagation channel may change, this immediately raises the question of the time distribution of the periods of poor quality. It is generally considered that a second is erroneous if, during that second, the bit error rate is greater than 10^{-3}. Consider a transmission at 140 Mbit/s; a bit error rate of 10^{-3} then corresponds to 140 000 errors in one second. The following extreme situations can be considered:

- There are 14 million errors affecting three successive seconds during one month. The bit error rate is 3.3×10^{-2} during these three seconds, which are thus erroneous. The probability of exceeding the threshold is $3/30 \times 86\,400$, or 1.15×10^{-6}.
- In the same month, the total number of errors is the same, but they are now distributed among 100 different seconds, affecting each one with 140 000 errors. This time, there are 100 erroneous seconds during the month.

It is clear that these two situations do not provide the same listening comfort for the subscriber. From a theoretical point of view, the requirement is to characterize the random signal to form the bit error rate as a function of time. This could be a vast undertaking. For simplicity, the *quality* of the link is defined by calculating the percentage of time during which the bit error rate threshold is exceeded and the *availability* of the link is determined by calculating the number of erroneous seconds. Some services are more sensitive to the quality, others to the availability. Similarly, some atmospheric phenomena (e.g. multiple trajectories) have more effect on the quality, while others (e.g. rain) also have an influence on the availability. Determination of tolerance thresholds that define the performance of a link evidently cannot be made in the context of a single country – this is the responsibility of international organizations (notably the ITU), which will be mentioned again at the end of this chapter.

1.2 THE NATURE OF THE MEDIUM CONCERNED

It is well appreciated that the presence of natural media is the fundamental element of all propagation studies. In this section, only a general presentation of these media will be made; a more detailed analysis is the subject of Chapter 3.

For situations in which the transmitter and receiver are above the surface of the Earth, it is the atmosphere and the ground that play a crucial role. More precisely, their electrical properties are the determining factors. As these properties depend greatly on frequency, this can be used to classify the problems encountered.

1.2.1 Frequency Ranges

It is customary to divide the frequency scale into different ranges. For frequencies less than 300 GHz but greater than 30 kHz, the most common classification uses the free-space wavelength as a criterion (Table 1.1).

Designation by letters (e.g. K, X) is also encountered; these are not standardized, and are used largely by the radar community.

At frequencies less than 30 MHz, propagation is strongly influenced by the conductivity of the ground, which depends on its nature and the season and also by the ionosphere which is the ionized part of the atomsphere between altitudes of 50 and 1000 km. Furthermore, for an antenna situated close to the ground, the latter significantly modifies the radiation diagram.

At higher frequencies, the importance of the ionosphere becomes less but does not disappear completely (it causes fluctuations in phase and amplitude). The low part of the atmosphere, called the troposphere plays the principal role for frequencies above 300 MHz.

At even higher frequencies, beyond 6 GHz, meteorological phenomena such as rain and snow become dominant.

1.2.2 The Effects of Terrain and Topography

The ground, in its natural state and when cultivated or built up, imposes conditions on the spatial limits of all propagation problems. At frequencies greater than 30 MHz, it is the geometrical configuration of the ground and/or the topography that have the greatest influence, although some phenomena, such as multiple trajectories, can be particularly sensitive to the reflectivity of certain areas such as lakes.

Table 1.1 Classification of frequencies by wavelength

Frequency	Wavelength	Abbreviation
$3 < f < 30$ kHz	Myriametric	VLF (very low frequency)
$30 < f < 300$ kHz	Kilometric	LF (low frequency)
300 kHz $< f <$ 3 MHz	Hectometric	MF (medium frequency)
$3 < f < 30$ MHz	Decametric	HF (High frequency)
$30 < f < 300$ MHz	Metric	VHF (very high frequency)
300 MHz $< f <$ 3 GHz	Decimetric	UHF (ultra high frequency)
3 GHz $< f <$ 30 GHz	Centimetric	SHF (super high frequency)
30 GHz $< f <$ 300 GHz	Millimetric	EHF (extremely high frequency)

It is clear, taking account of the wavelengths in use, that a detailed description cannot always be obtained. The ground will always be described statistically – and the difficulties in solving propagation equations in the presence of conditions with random limits do not need to be emphasized!

1.2.3 Effects of the Ionosphere

The ionosphere is the high part of the atmosphere, where the pressure is very low ($<10^{-2}$ hPa). Because of this, under the action of solar radiation, the molecules and atoms that make up the atmosphere can dissociate to give rise to ions and free electrons, which are bound together essentially by electromagnetic forces. In fact, the pressure is so low that the rate of recombination of charged particles supports the semipermanent presence of a double population of negative particles (electrons and anions) and positive particles (cations). This forms a weakly ionized plasma.

As will be seen later (Section 3.4), the ionospheric medium has several characteristic frequencies, among which the most important for electromagnetic wave propagation are the following:

- the plasma frequency, which is directly proportional to the square root of the concentration of the electrons and, at the maximum ionization level, has a value between 10 and 20 MHz;
- the electronic gyrofrequency, which characterizes the rotation of the electrons about the lines of force of the Earth's magnetic field and is of the order of 1 MHz.

It follows that it is predominantly frequencies in the HF range that are affected by ionospheric effects. The term 'affected' is somewhat pejorative, since it is the presence of the ionosphere that permitted the first short-wave radio links! This example shows that the effects of propagation can also be at the origin of new telecommunication services.

Historical note: The ionosphere and radio communication have lived together to mutual advantage from the start of the twentieth century. During the nineteenth century, electromagnetism was developed primarily in laboratories. It was only with the appearance of Branley's 'coherer' in 1886 that experiments in the free atmosphere were developed. There followed antennas due to Popov and above all the incredible long-distance communication experiment, beyond the horizon, that Marconi achieved in 1901 between Poldhu in Cornwall and Newfoundland. The clarity of reception at the time may be dubious by today's standards – nevertheless the news had a considerable impact on the scientific and industrial community. Eminent scientists such as Poincaré and Sommerfeld tried to explain the observations in terms of diffraction around the terrestrial globe, but in vain – the orders of magnitude were not appropriate. Kennely and Heaviside jointly re-established a theory, due to Gauss, which postu-