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# MIMO System Technology for Wireless Communications

Edited by
George Tsoulos

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*(from the back cover)*

# *Pyrsia: Optical Telegraph of Kleoxenos and Dimoklitos*

According to the Greek historian Polyvios, *Pyrsia* (communication via optical signals using torches — Greek: *pyrsos*) was invented by Alexandrine engineers Kleoxenos and Dimoklitos (4th century B.C.) and was further improved by Polyvios. The operation was based on the following concept:

1. Separate the Greek alphabet into groups of letters, generating an appropriate matrix.
2. Combine two groups of big torches, visible from a considerable distance with the help of diopters, in order to depict the appropriate letter (e.g., left/right torches represented lines/columns, respectively).

In order to start transmission of a message, two torches were used from one end, and the other end acknowledged that it was ready to receive the message, using two torches as well. Then assuming, for example, a 5 × 5 grouping of the Greek alphabet, and that lines/columns were represented by the left/right torches, if the letter "Θ" were to be transmitted, it would be represented by two torches on the left and three on the right (see photo below). Obviously, transmission of long messages was achieved by repeating the above method [e.g., the word "ΠΥΡΣΙΑ" is (4,1), (4,5), (4,2), (4,3), (2,4), (1,1)].

Furthermore, different groupings of the alphabet (e.g., 8 × 3) could also be used along with other methods of encryption (e.g., letters from right to left), for additional security.

Several elements of modern communications (some discussed in this book) are evidenced in this ancient Greek telecommunication system.

*Lines*

*Columns*

| | | | | |
|---|---|---|---|---|
| Α | Β | Γ | Δ | Ε |
| Ζ | Η | Θ | Ι | Κ |
| Λ | Μ | Ν | Ξ | Ο |
| Π | Ρ | Σ | Τ | Υ |
| Φ | Χ | Ψ | Ω | |

Pyrsia: Optical Telegraph of Kleoxenos and Dimoklitos.
(Photograph from the Museum of Telecommunications of the Greek Organization of Telecommunications.)

# Preface

Use of multiple antennas at both ends of wireless links is the result of the natural progression of more than four decades of evolution of adaptive antenna technology. Recent advances have demonstrated that multiple-input-multiple-output (MIMO) wireless systems can achieve impressive increases in overall system performance. The potential to provide the next major leap forward for wireless communications has led this technology to becoming the next frontier of wireless communications. As a result, it has received the attention not only of the international R&D community, but also of the wireless communications industry. This is evidenced from the international standardization efforts in the context of UMTS (e.g., 3GPP) and IEEE 802.11 (for wireless LANs) and also in the context of proposals for next generation (4G and beyond) wireless systems.

This book, *MIMO System Technology for Wireless Communications*, is a compilation of the work of several authors. The goal is not only to provide a complete reference source for readers interested in MIMO systems, but also to provide up-to-date information on several key issues related to the technology. For this reason, considerable effort was made to cover most of the elements of the technology and the related issues, some of which are not currently treated in the available textbooks. Following this direction, the following chapters are included in the book:

| | |
|---|---|
| Chapter 1 | Spatio-Temporal Propagation Modeling |
| Chapter 2 | Theory and Practice of MIMO Wireless Communication Systems |
| Chapter 3 | Information Theory and Electromagnetism: Are They Related? |
| Chapter 4 | Introduction to Space–Time Coding |
| Chapter 5 | Feedback Techniques for MIMO Channels |
| Chapter 6 | Antenna Selection in MIMO Systems |
| Chapter 7 | Performance of Multi-User Spatial Multiplexing with Measured Channel Data |
| Chapter 8 | Multiuser MIMO for UTRA FDD |
| Chapter 9 | Multifunctional Reconfigurable Microelectromechanical Systems Integrated Antennas for MIMO Systems |
| Chapter 10 | Multi-Antenna Testbeds for Wireless Communications |
| Chapter 11 | Gigabit Mobile Communications Using Real-Time MIMO-OFDM Signal Processing |
| Chapter 12 | Network Planning and Deployment Issues for MIMO Systems |

The chapters are organized so the reader builds upon the information provided and gradually reaches a point where more complex (system) issues are discussed. In this process, the reader is introduced to propagation modeling, theoretical and realistic performance analyses, space–time codes, different systems, implementation options and limitations (antenna arrays, channel knowledge, etc.), practical system development considerations, field trials, and network planning issues. Also, readers wishing to study further specific aspects of MIMO technology will find the references cited in each chapter particularly useful.*

**George V. Tsoulos**

* Another useful source of information on MIMO technology is a recent two-part special issue from the *IEEE Communications Magazine*:

"Adaptive antennas and MIMO systems for wireless communications — Part I," *IEEE Communications Magazine*, special issue, October 2004, G.V. Tsoulos (Guest Editor).

"Adaptive antennas and MIMO systems for wireless communications — Part II," *IEEE Communications Magazine*, special issue, December 2004, G.V. Tsoulos (Guest Editor).

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# *The Editor*

**George Tsoulos** graduated from the National Technical University of Athens, Department of Electrical and Computer Engineering, Greece, in 1992 and earned his Ph.D. from the University of Bristol, U.K., in 1997.

From 1994 until 1999 Dr. Tsoulos was a research associate and then a research fellow at the University of Bristol, working in the area of smart antennas for wireless communications. From 1999 until 2002 he was with the Global Technology Group of the PA Consulting Group, in Cambridge, U.K., where he worked for a range of leading companies across the world in the design and analysis of advanced wireless communication systems. In 2003 he joined the Institute of Communication and Computer Systems of the National Technical University of Athens (NTUA), in the context of the EC-funded research program, ENTER.

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# Contents

# 1

# *Spatio-Temporal Propagation Modeling*

**G.E. Athanasiadou**

**CONTENTS**

## 1.1 Introduction

The evolution of wireless communications from analog to digital led to the enhancement of early propagation models, which provided information about power, in order to also consider time delay information. Further consideration of the space domain either with space diversity or smart antennas or, nowadays, MIMO systems has also pushed the evolution of propagation modeling toward more complex spatio-temporal considerations.

In this context, there is a plethora of radiowave propagation models, each developed and used for different applications. The right choice is critical for specific analyzes and depends on system and operational parameters such as the environment, speed, accuracy, cost and ease of use. Generally, experience has shown that for scenarios and parameters that are not very site specific, sufficient accuracy can be achieved at reasonable simulation speeds, with stochastic models. On the other hand, for more site-specific scenarios, more complex ray-tracing models that employ geographical databases are required to provide reasonable accuracy, but at the cost of increased run times.

This chapter starts with models that were developed in an attempt to describe propagation characteristics for space diversity and smart antenna applications. Then models developed to provide the necessary channel information for MIMO applications are discussed. Obviously, measurement campaigns played a key role in the development of these models, and hence, important results from such activities are reported for both cases.

Several references are cited throughout this chapter, but there are some good sources of information that the reader will find particularly useful, such as [1–5].

## 1.2 Directional Channel Modeling

Figure 1.1 shows that there are three different sources of scattering that affect signal propagation between the base station and the mobile:

1. Scatterers around the mobile station (MS): Similar height or higher than the mobile, hence, the received signal at the mobile usually arrives with wide angular spread.
2. Scatterers around the base station (BS): Generally, the energy arrives at the BS from identifiable clusters, which correspond to different propagation mechanisms (e.g., single reflections from high objects or from rooftop diffractions or street-guided propagation with multiple reflections from the building walls, etc.). For different operational

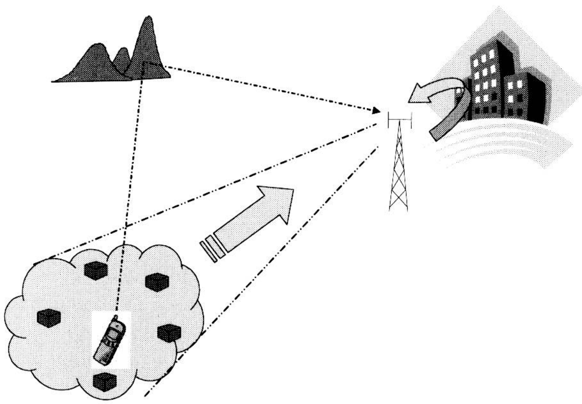

**FIGURE 1.1**
Scattering sources for radiowave propagation modeling.

scenarios there are different characteristics, e.g., in macrocells (BS at the same level or above the surrounding scatterers), multipath is contained within a relatively small angular spread with relatively low delay spread. In microcells (BS below rooftops), the angular spread is larger than in the macrocell case.

3. Multipath from remote scatterers is another possibility, e.g., in rural operational scenarios. It is usually contained within a very small angular spread but contributes large delay spread.

From Figure 1.1 we can see that each signal from the $k^{th}$ user experiences a different multipath environment, described by the amplitude ($\alpha_{i,k}$), phase ($\psi_{i,k}$), time delay ($\tau_{i,k}$), Doppler shift, and Angle-of-Arrival (AoA) components (time varying). A convenient way to characterize the radio channel is through its channel impulse response, which when modified to consider the AoA of the multipath components for an antenna array, produces the vector channel impulse response:

$$\mathbf{h}(t,\tau) = \sum_{i=1}^{K} \alpha_{i,k} \exp\left(-j\psi_{i,k}\right) \mathbf{a}\left(\varphi_{i,k}, \theta_{i,k}\right) \delta\left(t - \tau_{i,k}\right)$$

where $\mathbf{a}(\varphi_{i,k}, \theta_{i,k})$ is the complex array response vector of the receive antenna elements ($x_m$, $y_m$, $z_m$) for the $i^{th}$ multipath direction ($\varphi_{i,k}$, $\theta_{i,k}$) and operating frequency $f$:

$$\mathbf{a}\left(\varphi_{i,k}, \theta_{i,k}\right) =$$

$$\left[1 \cdots \exp(j\frac{2\pi}{\lambda}(m-1)\left(x_m \cos\varphi_{i,k} \sin\theta_{i,k} + y_m \sin\varphi_{i,k} \sin\theta_{i,k} + z_m \cos\theta_{i,k}\right)\right]$$