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Preface

Radio frequency interference (RFI) is the kind of technical topic that creates anxiety in those who use radio waves for telecommunications. We refer to this mode as radiocommunication, a contraction adopted by the International Telecommunication Union (ITU) and which identifies our domain of interest. But, RFI is a unique form of disruption to radiocommunication in that it enters through the receiving antenna as do desired signals. Radio waves know no boundaries because of their unguided nature and ability to cross geographic and political boundaries. For this reason, the ITU long ago established radiocommunication as one of its primary areas of activity, conducted through ITU-R, where the *R* stands for radio.

This book is about the practice of identifying, resolving, and managing RFI across the broad range of radiocommunication systems and applications. This is a technical field which, like medicine, demonstrates how a science of maladies has a direct impact on daily life. Radio developed over the years from the two most basic modes of one-way broadcasting and two-way point-to-point communication, to the point now that literally all forms of communication, including the Internet, rely on it to reach the end user. In the latter case, the popular terms are "cellular" and "wireless," which seem to distinguish these uses from the classic term "radio." But those of us who work in and across these domains know full well that RFI is still a common denominator of concern and even trouble. RFI has become a high-stakes game where entire business plans and mission strategies can succeed or fail if RFI is not resolved.

We have evolved from a time when static and background noise were the main cause of reception problems and connection failures; now, RFI is often the determinant of performance and, importantly, system capacity. Achieving the right capacity becomes a financial issue in terms of revenue to a commercial wireless enterprise. We all recognize that the radio spectrum is a limited resource and must be reused many times over across geography and direction. This book is dedicated to proper consideration of RFI, wherein we can maintain the reliability and promote greater use of radiocommunication going forward.

To understand RFI one needs to understand the principle of radio: modern transmitters and receivers employing digital modulation and coding, directional antennas to achieve coverage and reduce RFI in the environment, the ways that radio waves propagate in space and across the landscape, and the mechanisms that can produce RFI in the first place. From that, we address how it can be characterized and resolved into a workable problem with practical solutions. Many readers will come into the topic of RFI with a solid background in radio engineering or practice. Others with less experience will still understand the importance of RFI and need for its resolution, but want some of the background that supports the necessary study and design (the "secret handshake" of radiocommunication art). For that reason, we provide sufficient description of radiocommunication so that all readers will be able to follow our exposition and apply its recommendations.

To that end, this book is organized into three broad topics: I) the requirements for and engineering of radiocommunication systems and technology, II) radio wave propagation, defining the direct and indirect paths on the Earth and between Earth and space taken by the desired signal and the undesired RFI, and III) the details of RFI analysis (particularly C/I assessment) and resolution strategies involving investigation and mitigation of problems before, during and after RFI is identified or experienced.

Part I includes Chapters 1, 2, and 3 and is a review of radiocommunication in the context of the RFI question. There is enough technical material here to be a basis for subsequent examination of RFI. Expert readers can scan this material and then move on to the core topics in the remainder of the book. Chapter 1 points out where the consideration of RFI fits within the overall field of electromagnetic compatibility (EMC) and why RFI problems require effective study and brainstorming. The coverage of radiocommunication system design in Chapter 2 is at a fairly basic level but is technically accurate. This is a good jumping off place for further study using the World Wide Web or other resources referenced with the chapter. Chapter 3 delves specifically into the sources of electromagnetic disruption to radiocommunication and provides a good review of such key topics as intentional and unintentional interference; intermodulation and spurious signal generation; interference from pulse sources (e.g., radar); and the key topic of C/I, also called protection ratio (addressed in greater detail in Chapter 6). These are considered throughout part I) for land-based (terrestrial) systems as well as space-based repeaters and signal sources.

Part II provides Chapters 4 and 5 to identify the various propagation modes that radiocommunication signals and RFI take between transmitting emitter (antenna or otherwise) and receiving antenna. This is a complex topic and dependent on propagation data collected and analyzed over past decades and through experience with radio systems. These extend from 100 kHz on the low end up to 100 GHz at the top of current millimeter wave development. Chapter 5 will be familiar to many who have involvement with radio since it covers propagation in free space. While this type of path may be unobstructed, there are key phenomena in the earth's atmosphere that both reduce (attenuate) signals and can allow RFI to propagate well beyond the horizon (rain scatter and ducting, for example). Obstructed paths are covered in Chapter 6 to address signals that may be blocked but nevertheless reach the receiver through a variety of means. The methods of knife-edge diffraction (Gourdet/Fresnel) and smooth earth diffraction (Bullington) are reviewed with examples provided. When mobility is introduced, the individual desired and RFI signals experience respective fading of their own that varies with time and position. The discussion includes methodologies for calculating the levels of signals for use in general assignment of spectrum to operators (which requires consideration of how transmission by one organization can produce RFI into the operation of another) and end users. Area coverage models such as Okamura and Langley-Rice are discussed with regard to their applicability.

This brings us to Part III with Chapters 6, 7, and 8, addressing the subject of how RFI can be evaluated properly and dealt with effectively. First, we see in Chapter 6 how various forms of RFI affect the desired signals. It's not enough to know how much RFI is present; we must know and be able to quantify the impact on a victim service from the presence of a given type and level of RFI. Much of the effort in RFI resolution ends up going into this question, especially if parties to the discussion must agree on what is an acceptable impact on service quality for a given RFI condition. Fortunately, it can be addressed analytically using equations and computer number crunching, and through actual laboratory tests using the types of equipment to be fielded.

Chapter 6 gives some practical examples to provide a jumping off place for detailed study in a specific RFI case. These include quantitative studies done of 4G LTE sharing with radar and applicability of path analysis software available on the commercial market. Some proven ways of addressing RFI once it is identified and understood are covered in Chapters 7 and 8. There is never a final answer to all cases of RFI but Chapter 7 provides a number of proven tools and methodologies, especially spectrum analysis and spectrum monitoring. Chapter 8 follows in a similar vein by laying out practical spectrum planning techniques that can be introduced in many cases. This listing grows with time, as we gain experience with new systems and as technology advances in such areas as radio direction finding (RDF) and RFI cancellation.

In looking ahead, we offer Chapter 9 as a prospective for RFI resolution in future radiocommunication systems. Most of what we need is already known and being applied on a piece-meal basis. But, new models of how spectrum could be allocated and shared are of great interest in a world where more services are desired by the global population. We address the topic of cognitive radio, where intelligence within the system uses "white spaces" of spectrum that is currently lost due to the rigid rules of allocation and limitations on radio network management. So far, this topic has been of interest mainly to researchers in universities and regulators wishing to grant more access. In time, many of these ideas will be tested in limited trials (in the US and elsewhere), and some will be implemented to mitigate the RFI that comes with increasing access to spectrum.

This book comes out of the author's 50 years of experience with radiocommunication in general and work involving RFI in particular. It's not that one starts out to be an RFI practitioner; it happens as you get involved with real radiocommunication systems and have to solve these problems as they are recognized to exist or, worse, when they raise their ugly heads. There is profound hope in our ability to understand RFI and find those solutions that work and are economical. But, as is always the case with systems engineering practices, you can pay for the solution now, or pay a lot more later.

The author wishes to thank the organizations and individuals who contributed the materials identified in the reference lists with each chapter. Specifically, I acknowledge the guidance and learning in the past from very experienced engineers I've had the pleasure knowing: Col. Jacques Deygout of the French Army; Jorge Fuenzalida and Hans Weis, formerly of COMSAT; Dr. Klaus Johnsen and Chuck Sanderson, fellow Hughes engineers; and Professor Egon Brenner, my first EE

professor at CCNY. Also vital to the success of this project was the encouragement from the staff at Artech, including the publisher, and the acquisition team who assisted at each step. The technical reviewer, Ray Sperber, really took on this project as a partner so that it represents the real world in all its dimensions and maintains its validity and relevancy in the years ahead. The original idea for a book on RFI arose in Indonesia in the late 1970s during the Palapa satellite project, with the help and encouragement of R. Wikanto and Dr. Arifin Nugroho of the Indonesian Public Telecom Corporation (PERUMTEL).

I want to express my heartfelt appreciation and love for my wife, Cathy, and our two wonderful daughters, Sheri and Michelle. They are the ones who make a book like this become a reality.

Contents

Part I
Radiocommunication Systems and the RFI Environment

CHAPTER 1

The What and Why of RFI in Radio and Wireless Communications

Radio frequencies (RFs) lie in the broad spectral range of 100 kHz to 100 GHz and employ the principles of radio wave propagation and electrical communications. We concern ourselves here with how what emanates from a transmitting antenna of one radiocommunication system causes radio frequency interference (RFI) that enters the receiving antenna of another. By "what," we mean the fact that one radio signal can deteriorate proper reception of other radio signals by preventing the associated receiver from properly detecting the information, or data, on that particular signal. By "why," we mean that the RF spectrum must be shared by many users and many applications in point-to-point communications and broadcasting; as a result, no user can expect to enjoy any particular part of the spectrum on a dedicated basis. These principles are explored in detail in this book, but the idea is relatively simple.

RFI is something that occurs by the very nature of this means of communication; as spectrum use increases, so does RFI. It is analogous to vehicle traffic on highways and streets. With little or no traffic (e.g., at 2 a.m.), traffic flows freely at the posted speed; with high traffic (during rush hour in major cities), traffic is intense and we all have to watch out carefully as we drive. That doesn't mean that traffic cannot be handled in heavy situations; just that there must be techniques and tools to help address those places and periods of congestion. Similar analogies can be drawn with respect to flying airplanes on air routes.

RFI is one category of a much broader field of electromagnetic practice involving:

- Electromagnetic interference (EMI) is disturbance that affects an electrical circuit due to either electromagnetic induction or electromagnetic radiation emitted from an external source. EMI occurs due to physical proximity of components and elements of an electronic device or system, whether through cabinets, cables, or antennas. RFI is a subset of EMI, as discussed above.
- Electromagnetic compatibility (EMC) is the branch of electrical sciences which studies the unintentional generation, propagation, and reception of electromagnetic energy with reference to the unwanted effects that such energy may induce. The goal of EMC is the correct operation, in the same electromagnetic environment, of different equipment that uses electromagnetic

> phenomena, and the avoidance of any interference effects. Emission issues are related to the unwanted generation of electromagnetic energy by some source, and to the countermeasures that should be taken to reduce such generation and avoid the escape of any remaining energies into the external environment. Susceptibility or immunity issues, in contrast, refer to the correct operation of electrical equipment, referred to as the victim, in the presence of unplanned electromagnetic disturbances.

The mechanisms for EMI are illustrated in Figure 1.1 [1]. We see many paths for EMI to take, beginning at the signal line with conducted coupling at the bottom and multiple other potential paths crisscrossing among the principle elements of both the interfering and interfered-with (victim) systems. At the top is the RFI path (of primary interest in this book), indicating radiated coupling between the antennas (the dashed arrow). Keep in mind that we are speaking of two normally unconnected systems and that the radiated coupling is undesired. It should be possible to eliminate the non-RFI paths through proper design, construction, and testing of each of the operating systems. Often, one of these paths ends up the cause of a specific interference issue. When RFI arises in an operating system, we often must consider all paths for the interference to take, which makes this illustration particularly valuable.

The definitions of EMI and EMC are meant to distinguish these related (and important) practices from our focus on RFI. The radiocommunication systems operating on licensed or otherwise authorized frequencies can meet all of the relevant EMC requirements and still cause RFI to one another. This is because one person's RFI is another person's communication, and vice versa. It is up to the designers and operators of these radiocommunication systems to minimize how RFI impacts their respective operations. To address and control RFI (i.e., the "how"), we use the same principles of radio engineering as are applied to the design of the systems

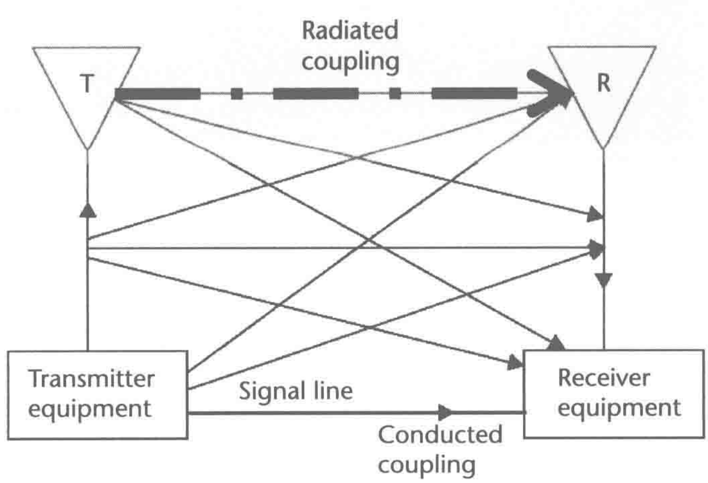

Figure 1.1 Coupling of EMI between two different radio systems [1]. RFI is illustrated as "radiated coupling" between the antennas; all other paths are unintentional and avoidable (although still possible in a working system).