Mobile Radio Network Design in the VHF and UHF Bands

A Practical Approach

Adrian W. Graham, Nicholas C. Kirkman and Peter M. Paul

All of Advanced Topographic Development and Images (ATDI) Ltd, UK

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Foreword

In 1687, Sir Isaac Newton published his *philosophiae naturalis principia mathematica* or *Mathematical Principles of Natural Philosophy* postulating gravity, the very general law that held the universe together. Throughout the Enlightenment and ever since, engineers and scientists have sought the universal laws with which to explain the natural world in which we live. This desire to explain things spawned the idea that we can build and exercise models of our world that will describe how the systems that comprise it might function. Once proven to be useful in example cases, engineers and scientists can hypothesise, seek evidence and prove them generally.

Progress in modelling the radiocommunications domain effectively started with Kenneth Bullington's landmark paper in 1946 proposing the single knife-edge diffraction model. The body of knowledge has grown steadily since to a point where engineers can explain their world in high fidelity using computer simulation. The accuracy with which this can be done is astounding to the point that no-one should consider radiocommunications network deployment without simulation of their plans against these laws. In our risk-averse times it is the only way to effect risk control without huge expense in equipment, effort and sometimes lives.

That sets the scene for this book. Using 60 years of authoritative knowledge one can model the radiocommunications world. And yet two, maybe three, schools still exist today. Like the positivists of the Enlightenment, there are those who view that everything can be explained and it is just a question of mankind finding and using the necessary models. On the contrary there are those engineers who, like the Enlightenment's interpretivists, consider that radiocommunications is all a 'black art' with too many independent variables to permit anything but a 'feel' to be gained using very broad models. The third group fall into the disbelievers, retorting 'it's only a model' and hence not to be considered useful in any way. Let us be under no illusion. Modelling radiocommunications networks is now a science that is of age and those engineers who lean towards positivism can have their day. The laws exist. The error bands in these laws are known and when technology shifts the goal posts, the techniques exist to re-calibrate the laws. Be sure: every radiocommunications network can be modelled.

Models seek to give engineers the truth. Within this book there are two truths. The first is the positivist truth that the laws exist with known accuracy to afford engineers real, tangible benefit from modelling and from the parallel functions of spectrum regulation, network planning and measurement. The second is that Adrian Graham and his colleagues have put forward the most appropriate, specific and complete models spanning every part of the radiocommunications domain and every part of the radiocommunications project life cycle. In achieving this they have achieved the ‘Holy Grail’ of authorship: writing something that is actually useful to practicing radiocommunications engineers. By embodying their own experience, they have achieved a post-modern ‘Enlightenment’; a lifting of the myths that doomed radio-network planning and other simulation activities to be described as ‘black art’.

Now, engineers are the world’s worst project managers. Most fall into the Myers-Briggs ‘judgemental’ personality preference type. The result is a high desire to make early decisions and to foresee the result before the problem has been completely explored though simulation. The opposite would be to develop a process in which the project team can trust to lead them to success; something that in abstract everyone would agree makes more sense. This book identifies the project nature of radiocommunications regulation, modelling, planning and measurement. Several sections are devoted to the elicitation of requirements, discussing how one might describe the desires of radiocommunications users. Adrian, Nick and Peter have identified the criticality of this user requirement in setting the tone for the whole project leading to performance, acceptance and ultimately payment. Get the requirements wrong and the project will fail to satisfy these users; and yet many radiocommunications projects fall short of their final aim suggesting that engineers have much to learn. This book provides a framework for that learning.

Finally, I personally welcome this book. It is a most useful addition to company bookshelves wherever radiocommunications engineers work. Poor communications were cited in the report on the emergency services’ response to the bombings in London in 2005. Poor communications contributed hugely to the defeat of the British 1 Airborne Division at the Battle of Arnhem in 1944 and since then poor communications has been cited the world over whenever there is a critical need for human performance. And yet we engineers can model radiocommunications performance. We do need to impress on our management, accountant or economist colleagues that we have this competence and that we can tell them the risks surrounding the various options that they propose. That said, we need to get our story right. I welcome the book wholeheartedly because it defines specification parameters including one word that is the key to every wide area radiocommunications network, that is, coverage. This word of all words is the least well understood by the engineering fraternity. If you need definition or clarification of this and other parameters in the fixed, mobile, broadcast and satellite simulation world, read on.

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Managing Director
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Preface

Mobile radio networks have risen in prominence over the last few years, primarily by the rise in popularity of cellular phones. It is important to recognise however that mobile radio technology fulfils a far wider range of applications that meet the demands of the modern world. These include the networks that allow police and emergency services to serve the public, military networks for operations and humanitarian support, and the mobile technologies that are vital to the safety of aircraft. These and many others beside make up the panoply of the mobile radio network domain. In this book, we look at the design of mobile radio networks in the VHF and UHF band. In each case, the design approach taken must reflect the unique requirements of the specific project, but there are design methods that can be applied to a range of mobile technologies and we have described some of these in this book. Throughout the book, we focus on the radio-related aspects of design; the location and configuration of base stations, tools and techniques for the analysis of network coverage and interference, design for capacity in the mobile to base station link and so on. We have included a chapter on fixed microwave links that are used to route mobile traffic to its destination, but again this focuses on the radio aspects of design rather than anything above the physical layer.

We have not addressed aspects such as traffic switching, access protocols or anything to do with the line aspects or the services carried by the networks. These subjects have received a great deal of attention in a variety of good books on the subject of radio technology. These books provide vital background to the reader in terms of understanding the technology and how it achieves the objectives of being a bearer for the services it is designed to cover. In writing this book, the authors wanted to avoid repeating this work, but instead to provide a practical tool for the radio network design engineer. This means focusing on those aspects that the designer has influence over, and spending less time on those aspects that the designer cannot change. We have tried to include material that radio engineers will need on a day-to-day basis, but not to spend time on derivations of complex mathematical formulae. Such derivations are generally already well covered in books also available and are not generally needed for day-to-day work. We have also looked at radio network projects from a wider perspective, so that the engineer can gain an understanding of other groups of people that are involved in the process. This is not filler material; more projects fail from business reasons than from technical ones, and the designer has a role in supporting the whole project.

We contend that modern radio network design implicitly depends on the use of computer-based radio planning tools; so much of the book is based on their use. We have provided guidance on features we believe any state-of-the-art planning tool should have, and how they are used in the network design process. In addition, we also focus on the data that must be used with planning tools for them to be effective. We have tried not to focus on individual radio technologies as far as possible, but rather to identify design concepts that can be tailored to many different technologies; we feel that learning these techniques is more useful than being able to crib from a prescribed process. We have been forced to omit many detailed design aspects and to provide no more than overviews on others, simply due to the space available in the book and the time available to create it, so we do not intend this book to replace others but rather to be a companion to other data sources; where possible, we have identified suitable sources of data such as ITU recommendations.

Our guiding principle has been to provide the sort of information we would have liked to avail when we first entered the world of radio network design, all in one place. We also intend to provide it to engineers that join our company, and we will expect them to refer to the book as they develop their careers in this domain. We have also provided information for those at a more senior level, such as project managers and others who are involved in radio projects or who need to be able to interpret the results produced by the techniques covered.

In writing this book, we have enjoyed the support of our colleagues and friends. We would like to thank the following people for their contribution and ideas:

John Berry, Cyprien de Cosson, Colin Desmond, Robin Hughes, Peter Johnson, Kevin Morrison, Sarah Roddis and John Talbot (of Emas Consulting).

Our particular thanks go to Ed Douglas of RSI (www.rsi-uk.com) for his invaluable contribution to the survey section, to M. Philippe and David Missud of ATDI SA (www.atdi.com) for their permission to use images of the ICS Telecom radio-planning tool, and to ATDI Ltd (www.atdi.co.uk) for permission to use partial screen shots of IMP Calc and other radio-planning tools and software components.

The authors hope you enjoy the book and find it useful. Readers may like to visit www.atdi.co.uk, where they will be able to find a range of useful radio planning calculators and tools that can be used in conjunction with the methods described in this book to solve many engineering problems.

Glossary

AGA	Air-Ground-Air communications (aeronautical)
AM	Amplitude Modulation
ASRP	Arc Standard Raster Product – NATO file format for map image data
CBS	Common Base Station
CDMA	Code Division Multiple Access
C/I	Carrier-to-Interference ratio in dB
CIS	Command Information System
CNR	Combat Net Radio: military mobile radio network system
COTS	Commercial-Off-The-Shelf
CRP	Compressed Raster Product – geographic data file format
DDD	Detailed Design Document
DEM	Digital Elevation Model
DF	Direction Finding
DME	Distance Measuring Equipment (aeronautical)
Downlink	Link from base station to mobile
DRDF	Digitally Resolved Direction Finding
DTED	Digital Terrain Elevation Data – NATO file format for DTM data
DTM	Digital Terrain Model
DVOR	Doppler VHF Omni-directional Radio range (aeronautical)
EA	Electronic warfare Attack – jamming
EP	Electronic warfare Protection – protection from jamming, DF etc
ES	Electronic warfare Support – detection, direction finding etc
FAA	Federal Aviation Authority
FDMA	Frequency Division Multiple Access
FFZ	First Fresnel Zone
FH	Frequency Hopping
FM	Frequency Modulation
FS	Functional Specification
FSL	Free Space Loss
GIS	Geographic Information System
GPS	Global Positioning System
GTD	Geometric Theory of Diffraction propagation modelling method
GUI	Graphical User Interface
ICAO	International Civil Aviation Organisation

IF	Intermediate Frequency
IFF	Identification Friend or Foe
IMP	Inter-Modulation Product
IRF	Interference Rejection Factor of a radio receiver
ITT	Invitation To Tender
ITU	International Telecommunications Union
MTBF	Mean Time Between Failure
MCFA	Most Constrained First Assigned
MER	Message Error Rate
MGRS	Military Grid Reference System map projection
MMOFS	Minimum Median Operating Field Strength (dBμV/m)
MMOL	Minimum Median Operating Level (dBm)
MLS	Microwave Landing System (aeronautical)
MOS	Mean Opinion Score
MOTS	Mostly-Off-The-Shelf
MS	Method Statement
MTTR	Mean Time To Repair
NDB	Non-Directional Beacon (aeronautical)
Net	Military shortening of the term 'network'
NFD	Net Filter Discrimination
NGR	National Grid Reference map projection (e.g. UK NGR)
NM	Nautical Miles
ODBC	Open DataBase Connectivity standard for database
OFDM	Orthogonal Frequency Division Multiplexing
PAMR	Public Access Mobile Radio
PDH	Plesiosynchronous Digital Hierarchy (backhaul term)
PESQ	Perceptual Evaluation of Speech Quality
PM	Pulse Modulation
PMR	Private Mobile Radio
PSD	Power Spectral Density of a transmission
PSO	Probability of Successful Operation
PSTN	Public Switched Telephone Network
RFQ	Request For Quote
RSSI	Received Signal Strength Indication
Rx	Shorthand for radio receiver
SDH	Synchronous Digital Hierarchy (backhaul term)
SMM	Simplified Multiplication Method (multiple interferer calculation)
SNR	Signal-to-Noise Ratio
SSR	Secondary Surveillance Radar (aeronautical)
System value	Maximum permissible loss in a system (normally military)
TACAN	TACticial Aid to Navigation (aeronautical)
TDMA	Time Division Multiple Access
TETRA	TERrestrial Trunked Radio Access
TPC	Tactical Pilotage Chart
TS	Test Specification
Tx	Shorthand for radio transmitter

UAV	Unmanned Airborne Vehicle
UHF	UHF Band 300–3000 MHz
UMTS	Universal Mobile Telecommunications System
Uplink	Link from mobile to base station
URS	User Requirements Specification
UTD	Uniform Theory of Diffraction propagation model
UTM	Universal Transverse Mercator map projection
VDF	VHF Direction Finding
VOR	VHF Omni-directional Radio range (aeronautical)
VORTAC	Combined VOR & TACAN site (aeronautical)
WGS	World Geodetic System – geographic datum

PART ONE

1

Introduction

1.1 Mobile Radio Network Design in the Modern World

Over the last few years, mobile radio has emerged from being a niche technology to becoming ubiquitous throughout much of the world. Most people come directly in touch with the technology through mobile phones and the networks that serve them, but this is only one aspect of mobile radio. Mobile radio is, however, used for many other applications in networks that span the air, land and sea, and although not immediately familiar to most people, their use is essential to the standard of life expected in the modern world. It would be difficult for airline passengers to travel to their holiday destination without the dedicated aeronautical networks that aid smooth management of aircraft and their navigation. Police and other emergency services would be unable to serve the public effectively without the ability to communicate rapidly and securely. Table 1.1 shows some users, applications and technologies within the broader mobile radio sphere. The list is by no means exhaustive.

In this book, we will be looking at the design and optimisation of mobile radio networks operating in the VHF and UHF bands, with a brief look at microwave links that are sometimes used for backhaul (the fixed infrastructure used to direct calls to their destination). We have chosen not to include LF, MF and HF; not because they are unimportant, but rather that their design processes are somewhat different from that employed at frequencies above HF. The aim is to provide the mobile radio network designer or engineer with a practical toolkit of knowledge and techniques that can be brought to bear to a wide range of radio network design tasks. We will focus on the aspects of network design that are under the control of the radio network designer, rather than the nuts and bolts of the underlying technology. The reason for this is that while it is essential that engineers understand the basic principles of the technology, aspects such as the interface protocols and frame structure are not under the control of the typical radio network designer. Since there is no control, these aspects represent constraints rather than design factors in most mobile radio network design activities. Additionally, our focus is almost exclusively at the physical layer of the radio network design – in other words – the RF aspects from the output of the transmitter part of one radio to the input of a receiving

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Table 1.1. Some typical mobile radio applications.

Category	Typical users	Type of application	Typical technologies
Public cellular	Public	Mobile phone analog voice	AMPS, NMT-450. NMT-900, ETACS
		digital voice and data	GSM, EDGE, GPRS, UMTS, IS-95, IS-136
PMR	Business Outdoor activities Mountain rescue	Analog voice	PMR 460, MPT 1327
PAMR	Public safety Business	Mobile analog voice and data	APCO 16, MPT 1327
		Digital voice and data	TETRA, TETRAPOL, APCO 25, APCO 25/34
Aeronautical	Civil aviation	Voice	VHF AGA analog voice, UHF ground movements
	Military aviation	Data	VHF Data Link Mode 2, SSR Mode 2
		Navigation	VOR, DVOR, VDF, DME, TACAN, NDB, GBAS
		Landing systems	ILS, MLS
		Radar systems	Primary RADAR, secondary RADAR
Maritime	Coastguard	Analog voice	Marine VHF
	Port authorities Vessels Pilots Customs	Search and rescue	Marine VHF, GMDSS
Military	Military forces	Combat net radio	Clansman, Bowman, JTRS
	Paramilitary	Trunk radio (combat)	Parakeet, RITA, Autoko, Sotrin, Zodiac, Ptarmigan, MSE
		Trunk radio	TETRA, TETRAPOL
		Air-land-sea tactical data link	JTIDS, LINK 11-A, LINK 11-B, LINK 16 (TADIL-J), EPLRS
		Telemetry/command	UAV command links

radio. This includes the effects of feeders, the antennas used for transmission and reception, and the radio channel environment. We will extend this to include dimensioning for traffic, and we will examine design of backhaul for mobile radio networks. We will not be covering access protocols, switching or other line aspects of the design, as these are adequately covered in a wide variety of other books currently available. This leaves us with the physical positioning and orientation of antennas, selection of antenna types, radio equipment configuration, interference management, frequency assignment and dimensioning for mobile traffic. These aspects of design form a major part of the design of any mobile radio network, and they are usually under the control of the radio network designer, albeit with a wide array of technical and nontechnical constraints.

This book is also intended to be a *practical* guide to mobile radio network design. It is split into two parts. Part One covers some essential background, and Part Two looks at the practical aspects of network design. The emphasis on the practical aspect is intended to convey the fact that understanding a technology, being able to perform coverage simulations, frequency assignment, and so on, is, although vital in itself, not sufficient to bring a network from conception all the way through to implementation, rollout and use. More projects are doomed by poor understanding of customer's requirements, poor project structuring, poor communications and *not listening* than are ever limited by the technology being used – even though it is common to blame the technology as a convenient scapegoat. We, therefore, focus on these additional aspects throughout the book, mostly in Part Two.

A useful method of understanding the competing entities within a radio network design process is to consider the project in terms of 'stakeholders'. A stakeholder is an entity or person that can exert influence over the implementation of the network. The probability of successfully completing a project is maximised if the concerns of as many as possible stakeholders are addressed and minimised for the converse condition. We also focus on the necessity for the design team to continually work to meet the needs of the customer – where 'customer' may be any organisation on whose behalf the network is being implemented. Without that focus, the delivered network design may not meet the original requirements. We make no apologies for including these aspects, which some may not regard as 'pure engineering', but we contend that in the sense that engineering is applying technology to deliver a service to a customer, they are utterly essential. Part Two also examines practical methods of exploiting the radio planning tools and data to achieve specific objectives within the overall plan. Again, the emphasis is to allow the reader to be able to go off and perform these tasks and understand what they are doing. What we will not do is spend a major portion of the book describing specific technologies in great depth. Other books provide this type of information. We will only look at the most important aspects of mobile radio planning and we will try to provide information and skills that can be adapted for as wide a range of mobile technologies as possible. We believe it is more important to get across adaptable methods rather than focus on the planning of a single technology that will quickly lose its currency – although naturally we will include as much technical detail as is necessary and will illustrate the principles by describing how they are applied to specific technologies.

Part One of the book introduces essential background information that radio network planners must be aware of, and some aspects such as propagation models and constructing link budgets that must be understood in as much depth as possible. Much of this can be found in other publications, but we intend to present it in a way that has proved very successful during many of the training courses we have run on the subject. The second part moves on to the practical aspects of mobile radio network design. Before going on to do this, however, we will spend the rest of this chapter looking in outline at the 'business' environment in which the activity of radio mobile network design resides. We will come to the technological aspects later, but first we will put the whole design process into its business context. Note that the term 'business' is not intended to refer exclusively to commercial organisations, but rather to any organisation performing network design or otherwise involved in the process. This can include government departments, military planners, police forces and any other defined groups. The common factor is that each of these businesses serve some kind of customer, whether on a paying basis or not.

1.2 Network Stakeholders

Radio networks never exist in isolation. In fact, a wide variety of people and groups will be involved in some manner during the design and operation of a radio network. This is illustrated in Figure 1.1, which shows the stakeholders that may be involved in a specific project. The figure also illustrates the interactions between stakeholders and demonstrates the principle that one stakeholder may not be able to directly influence another; they may have to go through other stakeholders or indeed there may be no direct influence path.

The importance of examining stakeholders and being aware of their presence is to help ensure that each important stakeholder is addressed during the project; the importance or otherwise of a particular stakeholder can only be determined by identifying their existence and considering them in turn. One crucial factor is not to confuse stakeholders with shareholders; a stakeholder need not be dedicated to ensuring the success or a project – they may indeed be dedicated to destroying it. The design team may therefore have a task to undermine these stakeholders by providing technical information to help refute their claims, for example. This important area is examined further in Chapter 6.

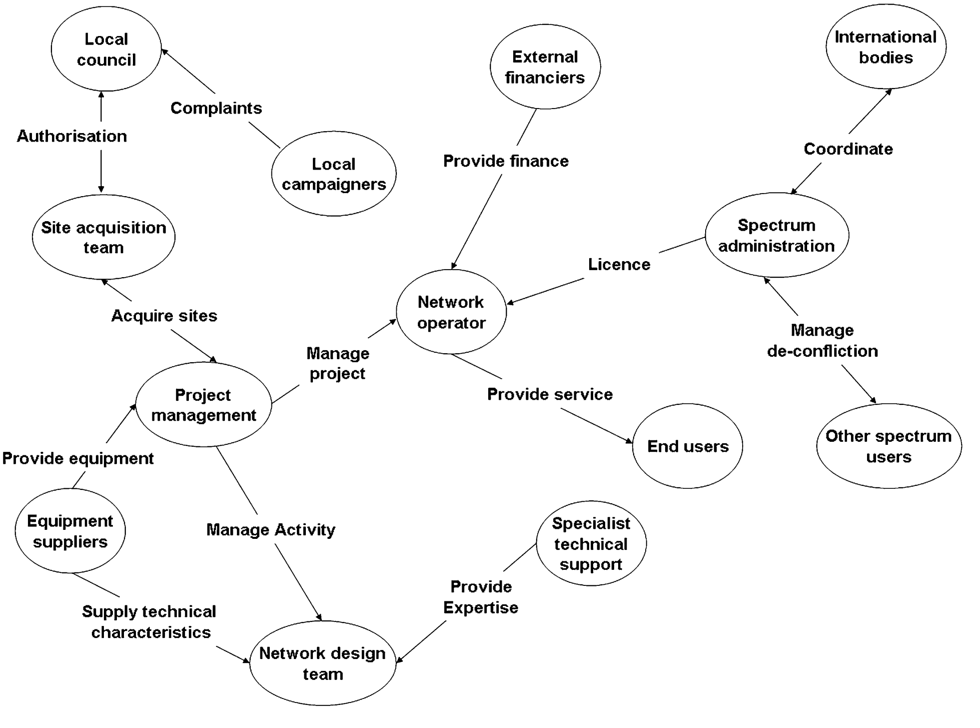

Figure 1.1. Network design stakeholders. Note that the list of stakeholders does not just include those dedicated to the success of the network.