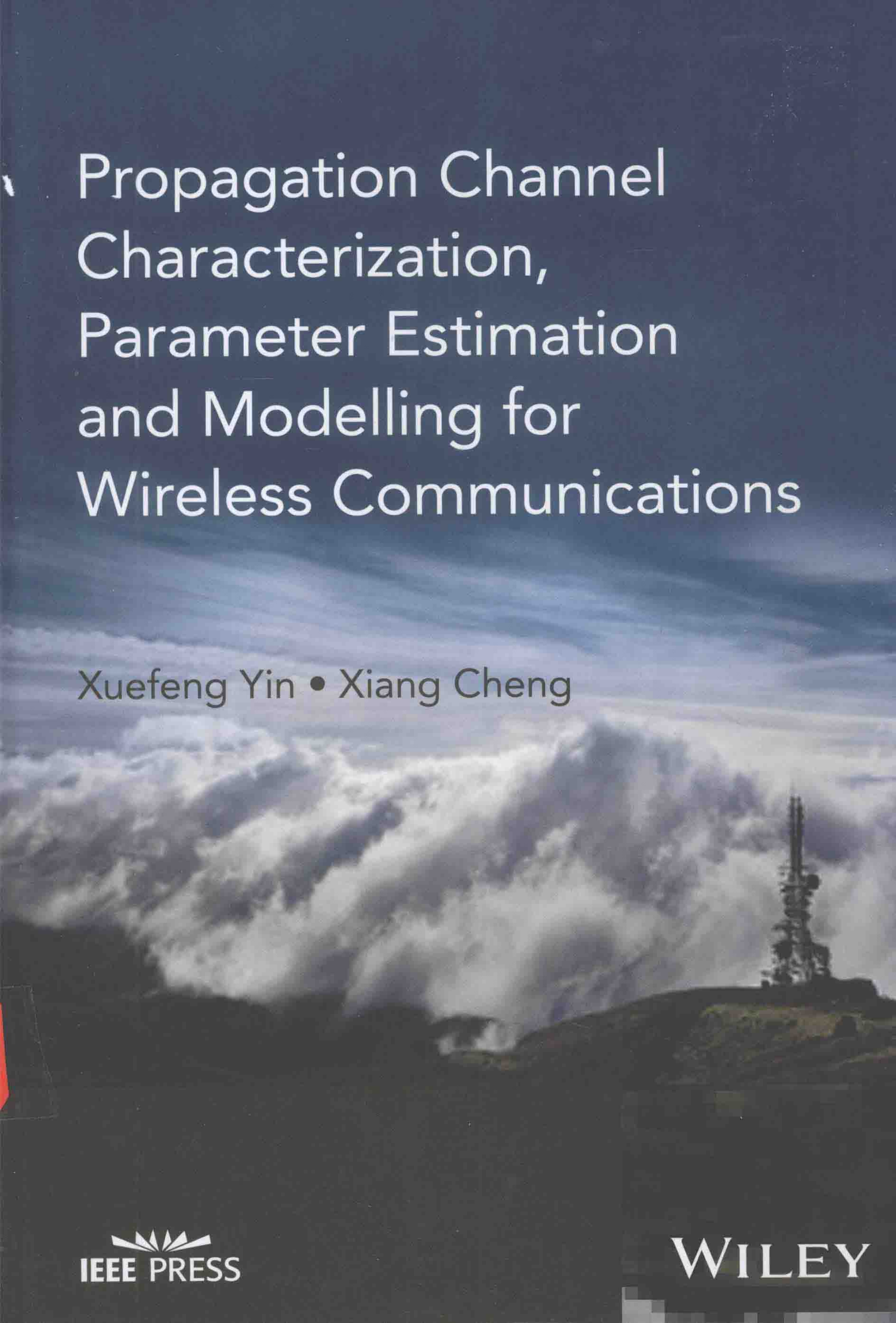

Propagation Channel Characterization, Parameter Estimation and Modelling for Wireless Communications

Xuefeng Yin • Xiang Cheng

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PROPAGATION CHANNEL CHARACTERIZATION, PARAMETER ESTIMATION AND MODELLING FOR WIRELESS COMMUNICATIONS

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Preface

The investigation of the propagation channel is becoming more and more important in modern wireless communication. The demand for spectral efficiency motivates exploitation of all channels that can possibly be used for communications. Nowadays, a common trend for designing physical layer algorithms is to adapt the transceiving strategy, either by maximizing the diversity gains or by utilizing the coherence of the channels to improve the signal-to-noise power ratio.

Dr. Xiang Cheng and I have been working on topics relevant to channel characterization for years. My major research has been focused on measurement-based stochastic channel modeling using high-resolution estimates of the channel parameter from real measurement data. Xiang's work concentrates more on accurate yet easy-to-use channel modeling and simulation based on geometry-based stochastic channel modeling approach. This book is intended to cover both theoretical and experimental studies of channels by merging Xiang's and my own study results, obtained in the last decade. Most of the content has been published in journals and conference proceedings. New results that are still under review for publication are also addressed in order to give a complete presentation of specific topics. In general, the book can be viewed as a collection of the latest results in the field of theoretical and experimental channel characterization. The contributions of Dr. Xiang Cheng and myself to this book are equivalent.

There are already several books dedicated to channel investigations (Durgin 2003, Koivunen 2007, Parsons 2000, Saunders 1999, Pätzold 2002). Our book includes more of an introduction to the methods used for the steps of channel characterization than these earlier studies, instead of presenting only the final results. From this point of view, our book tells more complete stories about channels, linking the methods applied in the different stages of channel analysis. Furthermore, combining the description of theoretical and the empirical methods in one book helps the reader conceive more clearly the merits of these methods. Another feature of the book is that we also cover the methods used for extracting the parameters of generic models. Normally, books address channels in one or two chapters and do not describe and comment on the methods used for characterizing them. An example is the book by (Correia 2001). However, since readers usually want to know how realistic the models are, it is important to give a clear view of the underlying methods. Although some of the methods described in this book have also been described in the literature for general cases (McLachlan and Krishnan 1997, Stoica and Moses 1997), we focus on the adaptation of methods applied for analyzing the propagation channels.

This book can be used as a textbook for the courses dedicated for propagation channel characterization, or for parts of courses that focus on wireless communication systems and networks. We organize the book in such a way that the chapters are self-contained and can be selected individually for specific topics. We start in Chapter 2 by introducing the phenomena of propagation in wireless communication channels and the terminologies, and also the parameters used to characterize their properties. Then, in Chapter 3, the generic parametric models applied for representing multiple components in channel impulse responses are introduced. For stochastic behaviors of channels represented by these model parameters, statistical models are needed. We, therefore, review the approaches adopted in channel characterization and modeling; from their theoretical aspects in Chapter 4 and by using measurements in Chapter 5. The impacts of measurement equipment on the observations and model accuracy are also discussed in Chapter 5. Chapters 6 and 7 introduce the high-resolution channel-parameter estimation methods for extracting the parameters of the generic channel models from measurement data, based on deterministic specular-path models and statistical models, respectively. Chapter 8 elaborates the modeling procedure and key techniques for constructing stochastic models based on parameter estimates. At the end of the book, Chapter 9 illustrates specific channel models for different communication systems as examples of the methods and techniques introduced in this book.

Acknowledgements

This book is based on the publications written by the authors and their colleagues in recent decades. We are indebted to colleagues and students who have made valuable suggestions and comments leading to many important changes. In this regard, we are particularly grateful to the co-authors of the publications relevant to this book: Prof. Bernard Fleury, Aalborg University; Prof. Troels Pedersen, Aalborg University; Attaphongse Taparugssanagorn, Asian Institute of Technology; Dr. Li Tian, ZTE Technology; Stan X. Lu, Huawei Technology Company; Dr. Zhimeng Zhong, Huawei Technology Company; and Nicolai Czink. We also wish to acknowledge the valuable comments of the manuscript reviewers: Prof. Bo Ai, Beijing Jiaotong University and Prof. Jianhua Zhang, Beijing University of Post & Telecommunication.

References

Durgin GD 2003 *Space-Time Wireless Channels*. Pearson Education.

(ed. Correia L) 2001 *Wireless Flexible Personalised Communication (COST 259: European Co-Operation in Mobile Radio Research)*. John Wiley & Sons.

(ed. Pätzold M) 2002 *Mobile Fading Channels*. Wiley.

Koivunen J 2007 Characterization of MIMO propagation channel in multilink scenarios PhD thesis Helsinki University of Technology.

McLachlan GJ and Krishnan T 1997 The EM Algorithm and Extensions vol. 1. Wiley Series in Probability and Statistics.

Parsons JD 2000 *The Mobile Radio Propagation Channel* 2nd edn. John Wiley and Sons.

Saunders SR 1999 *Antennas and Propagation for Wireless Communication Systems*. John Wiley & Sons.

Stoica P and Moses RL 1997 *Introduction to Spectral Analysis*. Prentice Hall.

List of Acronyms and Symbols

List of Acronyms

3GPP	Third Generation Partnership standards bodies
5G	Fifth generation wireless communications
AEE	average estimation error
AFD	average fading duration
AGV	autonomous guided vehicles
AoA	azimuth of arrival
AoD	azimuth of departure
ARA	acceptance rejection algorithm
ARIMA	autoregressive integrated moving average
AS	azimuth spread
ASA	array size adaptation
CBM	correlation-based model
CCDF	complementary cumulative distribution functions
CLEAN	an iterative beam removing technique
COMET-EXIP	covariance matching estimator-extended envariance principle
CoMP	cooperative multipoint
COST	Commission of Science and Technology
CRLB	Cramér–Rao lower bound
DECT	Digital European Cordless Telephone
DER	direction estimation range
DFER	Doppler frequency estimation range
DI	diffuse component
DML	deterministic maximum likelihood
DoA	direction of arrival
DoD	direction of departure
DRAG	dynamic range of array gain
ECM	environment characterization metric
EM	expectation-maximization
Emp.	empirical
EoA	elevation of arrival
EoD	elevation of departure
ESPRIT	estimation of signal parameters via rotational invariance techniques

Est.	estimated
E-step	expectation step
F2M	fixed to mobile
FB	Fisher–Bingham
FFHMA	fast frequency hopping multiple access
FHMA	frequency hopping multiple access
GAM	generalized array manifold
GBDM	geometry-based deterministic model
GBSM	geometry-based stochastic modeling
GR	Gerschgorin radii
HFB	higher frequency band
HRPE	high-resolution parameter estimation
IMT	international mobile telecommunications
IS-GBSM	irregular-shaped GBSM
ISI	improved initialization and search
ISM	industrial, scientific and medical bands
JADE	joint angle and delay estimation
LCR	level cross rate
LoS	line-of-sight
MD	mobile scatterer
MEA	method of equal area
MEDS	method of exact Doppler spread
METIS	Mobile and Wireless Communications Enablers for the Twenty-Twenty Information Society
MIMO	multiple-input, multiple-output
ML	maximum likelihood
MMEA	modified method of equal area
MODE	method of direction estimation
M-step	maximization step
MUSIC	multiple signal classification
NC-ML	non-coherent-maximum-likelihood
NFD	Newton forward difference
NGSM	non-geometric stochastic models
NLoS	non-line-of-sight
NSL	normalized side-lobe level
OLOS	obstructed line-of-sight
OMUSIC	orthonormal-basis MUSIC
OSM	orthogonal stochastic measure
PDF	probability density function
PDP	power delay profile
PE	pseudo-envelope
PMM	propagation-motivated model
PN	pseudo-noise
PSD	power spectral density
PSM	parametric stochastic models
RF	radio frequency

RIMAX	Richter's maximum likelihood estimation
RMSEE	root mean square estimation error
RS-GBSM	regular-shaped GBSM
Rx	receiver
SAGE	space-alternating generalized expectation-maximization
SCM	spatial channel model
SCME	spatial channel model enhanced
SD	static scatterer
SIOD	space-invariance of determinant
SISO	single-input, single-output
SML	stochastic maximum likelihood
SNR	signal-to-noise ratio
SoS	sum of sinusoids
SS	specular-scatterer
ST	space time
SVD	singular-value decomposition
SW	switch
TDL	tap-delay line
TDM	time-division-multiplexing
TEM	transverse electric and magnetic wave
Tx	transmitter
ULA	uniform linear array
V2V	vehicle to vehicle
Vec-MUSIC	vector-MUSIC
vMF	von-Mises–Fisher
VTD	vehicular traffic density
WINNER	wireless world initiative new radio
WSS	wide-sense stationary
WSSUS	wide-sense stationary uncorrelated-scattering
XPD	cross-polarization discrimination

List of Symbols

$\mathbb{R}$	real line
$\mathbb{C}$	complex plane
$\mathbb{S}^p$	p-dimensional sphere
$\mathbb{D}$	domains
$\otimes$	Kronecker product
$\odot$	Hadamard – that is, element-wise – product
$\Re\{\cdot\}$	real part of the complex number given as an argument
$\mathcal{I}\{\cdot\}$	imaginary part of the complex number
$\|\cdot\|_F$	Frobenius form of the vector or matrix given as an argument
$\lvert\cdot\rvert$	absolute value of the given argument
$\det(\cdot)$	determinant of the matrix given as an argument
$\mathrm{tr}(\cdot)$	trace of the matrix given as an argument

$(\cdot)^{\mathrm{H}}$	Hermitian of the vector or matrix given as an argument
$(\cdot)^{\mathrm{T}}$	transpose of the vector or matrix given an argument
$(\cdot)^{*}$	complex conjugate of the scalar given as an argument
$(\cdot)^{\dagger}$	pseudo-inverse of the matrix given as an argument
$(\ \cdot \ )$	scalar product of the given arguments
$\delta_{(\cdot)}$	the Kronecker delta
$\delta(\cdot)$	Dirac delta function
$\boldsymbol{I}_{(\cdot)}$	an identity matrix of dimension given as an index
$\mathrm{diag}(\cdot)$	diagonal matrix with diagonal elements listed as argument
$\lambda_d(\cdot)$	the dth eigenvalue of the matrix given as an argument
$\Pi_{(\cdot)}$	the projection operator onto the column space of the matrix given as an argument
$\boldsymbol{c}(\cdot)$	array response
$\boldsymbol{c}'(\cdot)$	the first derivative of the array response
$\Gamma(\cdot)$	the gamma function
$I_n(\cdot)$	the modified Bessel function of the first kind and order n
$\sigma_{(\cdot)}$	standard deviation of random variable given as an argument
$\boldsymbol{\theta}$	parameter vector
$\boldsymbol{\theta}_{\mathrm{S}}$	parameters with indices specified in a set S in a subset of $\{1, \ldots, p\}$
$\boldsymbol{\theta}_{\bar{\mathrm{S}}}$	parameters with indices listed in the complement of S intersected with $\{1, \ldots, p\}$
X^{S}	hidden-data space for $\boldsymbol{\theta}_{\mathrm{S}}$
S^{i}	index set in the ith iteration of the SAGE algorithm
$\boldsymbol{Y}(t)$	output signal from an antenna array
$\boldsymbol{W}(t)$	noise vector
D	total number of path components
$\mathcal{R}_1$	the region where the Tx array is confined
$\mathcal{R}_2$	the region where the Rx array is confined
$\boldsymbol{\theta}_{\ell}$	parameter vector associated with the ℓth path component
$\boldsymbol{A}_{\ell}$	the polarization matrix of the ℓth propagation path
$f_{k,m,p}(\boldsymbol{\Omega})$	the field pattern of the mth element of array k for polarization p
$\boldsymbol{u}(t)$	the input signal vector
$\boldsymbol{\Omega}$	a unit direction vector
T_t	a sounding period
T_s	a sensing period of a Rx antenna
T_r	a period separating two consecutive sensing intervals
T_{cy}	separation between the beginnings of two consecutive measurement cycles
T_g	the guard interval
σ_w^2	noise variance
λ	wavelength
M_1	the number of antennas in the transmitter site
M_2	the number of antennas in the receiver site
$\boldsymbol{r}_{k,m}$	the location of the mth element of array k

α_{ℓ,p_2,p_1}	weight of the polarization component with Tx polarization p_1 and Rx polarization p_2
$\Lambda(\cdot)$	log-likelihood function of the parameter(s) given as an argument
ν	Doppler frequency
$\check{\phi}$	estimation error of nominal azimuth of arrival
$\sigma_{\bar{\phi}}$	azimuth spread
$h(t;\boldsymbol{\theta})$	the spread function of the radio channel
$P_d(\boldsymbol{\theta})$	power spectrum of the dth path component with respect to $\boldsymbol{\theta}$
$P(\boldsymbol{\theta})$	power spectrum of the correlator output in the Rx with respect to $\boldsymbol{\theta}$
$\boldsymbol{H}(t)$	channel transfer matrix
$\tilde{\boldsymbol{H}}(t)$	channel matrix distorted by noise
$R_{(\cdot)}(\tau)$	autocorrelation function of the process given as the argument in the subscript
$R_{(\cdot)(\cdot)}(\tau)$	cross-correlation function of the two processes given as arguments
κ	concentration parameter
$\bar{\phi}$	nominal azimuth
σ_{Ω}	direction spread
q	differential order in the Newton forward-difference formula
h	step size in the Newton forward-difference formula
Δ	a forward shift operator in the Newton forward-difference formula
β	ovalness parameter in the Fisher-Bingham 5 distribution

Contents

1

Introduction

1.1 Book Objective

The characteristics of the propagation channel are of great importance for designing wireless communication systems, analyzing communication qualities, and simulating the performance of networks. However, in most books on wireless communications, propagation channels are usually presented in only one or two chapters, which describe the fundamental characteristics of channels – for example path loss, shadowing, and multipath fading – and present some standard models. Since the procedures for measuring the wireless channels, the methodologies adopted for parameter estimation, and the modeling approaches implemented are neglected in these books, it is impossible for readers to understand how the models are established for specific scenarios. This also results in suspicions about the applicability of models, and questions also arise about the appropriateness for implementation in channel simulations.

Furthermore, fast-growing wireless communication networks and services bring greater demands for high spectral efficiency. Numerous techniques have been used, all essentially exploiting the resources from propagation channels. For example, parallel spatial channels are resolved and utilized by multiple-input, multiple-output (MIMO) techniques for diversity or multiplexing. Similar MIMO techniques in other domains, such as in polarizations and in wavefronts, have been developed. It is of no doubt that future wireless system design will be more and more adaptive to the environments in which they are used. Network architecture design is also becoming increasingly complicated in order to make the most use of specific channels. For example, the techniques of distributed antennas, massive MIMO, relay, cooperative transmission, and joint processing all require detailed knowledge of channels in both a stochastic sense and in site-specific scenarios. Therefore, channel characterizations based both on theoretical approaches and real measurements are going to become critical in the future.

Considering the multiple aspects of a channel, it is actually a "mission impossible" to write a book that is sufficiently comprehensive that every topic of channel studies is included. This book is written with the aim of covering only some aspects of the propagation channel:

- the high-resolution approach of analyzing channels based on measurement data
- stochastic channel modeling either using empirical parameters or based on simulation of scattering.

Propagation Channel Characterization, Parameter Estimation and Modelling for Wireless Communications, First Edition.
Xuefeng Yin and Xiang Cheng.

The objectives of this book are threefold. First, the book provides the fundamentals of both empirical measurement-based and theoretical-scattering-based channel modeling. The topics covered are widely spread, touching on the fields of wideband channel measurements, model parameter extraction, stochastic model generation, and theoretical channel modeling. Second, the book provides some updated channel models, which can be used for practical simulations. Engineers in the wireless communication industry can therefore use them to evaluate their system performance. Thirdly, this book highlights ongoing trends, revealing some fresh research results that might be interesting for researchers when designing new systems.

1.2 The Historical Context

1.2.1 Importance of Channel Characterization

The statistical characteristics of channels can significantly influence the design of wireless communication systems. For example, the path-loss model, based on the measurements in specific regions, can be used to determine the appropriate value of the separation between cells, in order to keep the interference below a certain threshold. Shadowing models can be used to determine the maximum and the minimum transmission power in order to avoid blindspots in the coverage. Multipath fading models, which include the fading rate and fading-duration characteristics, can be used to determine the packet length and the transmission rate. Delay spread models can be used to evaluate the frequency selectivity of the environment, so as to determine the coherence frequency bandwidth or the separation of the orthogonal channels in the frequency domain. Doppler frequency spread models can be used to calculate the coherence time of the channel, and therefore determine the cycle duration to renew the estimate of channel coefficients. The models in the spatial domains, for example the cluster-based bidirectional models, can be applied to determine the antenna beamwidth in beamforming applications, or to calculate the degrees of freedom for channels with MIMO configurations. Stochastic models themselves are based on extensive measurements in many environments categorized into specific types, such as outdoor, indoor, urban/suburban, and so on; they are therefore valid in similar environments.

The model parameters can be used to determine the many thresholds used in communication systems. For example, for frequency hopping multiple access systems, the frequency offsets due to the Doppler effect of the channel, and the timing problems due to the multipath arrivals at different time instants, can cause a certain portion of the desired signal's energy to appear in spurious adjacent frequency bins; consequently the detection of the desired signal becomes difficult [Joo et al. 2003], and the detection matrix may have erroneous entries [Yegani and McGillem 1993]. With the knowledge of the delay-Doppler frequency dispersion behavior of channels in certain environments and scenarios, the threshold level of envelope detectors can be appropriately selected. Furthermore, if the instantaneous knowledge of the channel dispersion characteristics is available, the channel can be equalized accordingly.

1.2.2 Single-input, Single-output Channel Models

Channel investigation started at the end of the 1960s [Okumura et al. 1968]. At that time, wireless systems were built for voice communications using frequency division multiple