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Fundamentals of Voice-Quality Engineering in Wireless Networks

Network operators are faced with the challenge of maximizing the quality of voice transmissions in wireless communications without impairing speech or data transmission. This book provides a comprehensive survey of voice-quality algorithms and features, interactions, and trade-offs, at the device and system level. It does so from the practitioner rather than the algorithm-designer angle, and this approach makes it unique. The author covers the root cause of the problems and available solutions, as well as methodologies for measuring and quantifying voice quality before and after applying the remedies. The book concludes by discussing interactions between impairments and treatments, trade-offs between solutions and their side-effects, and short-term versus longer-term solutions, using case studies to exemplify the key issues. Avoiding complex mathematics, the book bases its approach on real and sizable field experience backed up by scientific and laboratory analysis. This title is suitable for practitioners in the wireless-communications industry and graduate students in electrical engineering. Further resources for this title, including a range of audio examples, are available on-line at www.cambridge.org/9780521855952.

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Preface

Since the early 1990s and for the 13 years that followed I was in charge of specifying and managing the design and development of voice-quality enhancement algorithms and systems in Lucent Technologies, and later in NMS Communications. When taking on the task, I was astonished by the secrecy surrounding the make-up of the minute algorithm details that separated the exceptional from the second-rate performers; the ones that elevate the performance of the voice-quality algorithms to significant heights versus their counterparts, which adhere to standard textbook and public-domain prescriptions.

And although I found out that there was no lack of technical material addressing the subject of voice quality, I learned that the many books, articles, and papers devoted to the subject focused on the math, while steering clear of the practical heuristics that are the backbone of any successful implementation. Their analysis was mostly academic – deep, technically precise, but nonetheless narrow. It addressed a single aspect of voice quality, whether it was electrical or hybrid-echo cancelation, non-linear acoustic-echo control and suppression, adaptive and automatic gain control, or noise reduction, rather than an interactive blend. It was intended for the few subject experts and algorithm designers rather than the user, the product manager, the troubleshooter, the marketing and sales personnel, and – most importantly – those responsible for making decisions affecting quality of service and investment in voice-quality products.

It is a fact of life that many voice-quality troubles, by and large, comprise a sum of specific impairment categories or unanticipated interactions among multiple applications. For example: treatment of electrical or acoustic echo must take into account the potential presence and impact of accompanying noise and the presence of level control that may amplify imperfections. Tandem treatments of a single impairment may bring about unwanted side effects, which could develop into more of a problem when the impairments and their associated remedies embrace a blend of multiple categories. Noise on one end of the communications channel and echo on the other may interact in a non-textbook fashion, and may spit out deviant impairments. Replacing a traditional analog or a standard PCM PBX with a new high-tech VoIP type may result in a sudden burst of fresh complaints concerning echo that would not fade away. An upgrade to an existing voice-enhancement unit intended to improve particular voice quality features may trigger a rush of customer complaints concerning the customers' inability to communicate with their voice mailboxes, etc.

There are many more real-life examples differing from an academic exercise confined to a single impairment category or a single application. There are many more individuals,

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whose job responsibilities require an ability to diagnose rather than design, decide rather than develop, convince rather than fabricate.

I wrote this book to fill a void.

This book is unique in the sense that it integrates all aspects of voice quality into a single objective. Solutions to voice-quality impairments such as echo, acoustic echo, noise, and improper level are all related to each other. Practical algorithms must address interactions and mutual trade-offs before they can claim success. One may not treat acoustic echo without considering noise and noise reduction, comfort noise matching, and level optimization simultaneously. This book is focused on expediency while replacing the math with logical and practical reasoning and treating it only as a necessary means rather than an end. It bases its approach on real and sizable field experience backed up by scientific and laboratory analysis.

Furthermore, this book is unique in what it does not do. It does not drive deep into the math that makes the algorithms perform. It does not scare away those who view Greek letters, long equations, differential calculus, and Fourier transforms as programmers and designers' cuisine. It does, however, employ logical reasoning, intuition, and real-life ordinary examples to drive a point, and to provide a comprehensive understanding of how it all works, why it does not, and what spice can take it up a notch.

This book is aimed at the network administrator, the product manager, the troubleshooter, the marketing and sales personnel, and those responsible for making decisions affecting investment in voice-quality products. It is intended to help them expand their knowledge, better their understanding of their own craft, and propose effective solutions without yielding to those math wizards who can decipher the magic **Σ** and convert it to a DSP code.

This book addresses the big picture of what it takes to communicate clearly at maximum fidelity without impairing speech or data transmission. It provides a comprehensive survey of voice-quality algorithms and features, interactions and trade-offs. It does so from the practitioner rather than the algorithm-designer angle, and this approach makes it unique.

The great difference between algorithm designers and practitioners is inherent in the definition of the problem to be solved. The algorithm designer starts the process by defining his or her scope in detail. The problem triggering the need for a solution is well defined. Its parameters are known and understood, and the focus is confined to a relatively narrow range. On the other hand, the practitioner is faced with voice-quality issues that may be stimulated by a combination of problems. His or her main issue is diagnosis and scope definition. The practitioner must resort to root-cause analysis that may infer a diagnosis consisting of interactions among a variety of impairments. The solution must, therefore, be more wide-ranging while keeping its focus on overall voice quality rather than one of its specific facets.

This book addresses common voice-quality problems in wireless communications, their root cause, available solutions, remedies, and methodologies for measuring and quantifying voice-quality scores, before and after applying these remedies. The concluding segments put it all together by addressing interactions among impairments and treatments, trade-offs between remedies and their corresponding side effects, and short-term versus longer-term solutions. The methodology employed for the closing analysis rides its course

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on top of trouble shooting and case studies. This approach provides a proper platform for scrutinizing symptoms that may be realized through combinations of impairments, improper application of remedies, or a blend of both.

The common voice-quality issues contended with in the book encompasses the phenomena of electrical and acoustic echo and echo cancelation, noisy ambience and noise reduction, and mismatched or improper signal levels and level optimization. The issues are analyzed as they relate to the specific codec environment they play in. CDMA and GSM wireless codecs possess different voice-quality features, their relative performance varies in different ways in the presence of noise, and similar treatments have dissimilar effects on the consequent voice quality. This book brings to light these particular parameters.

In fact, the literature is filled with excellent analytical and mathematically inclined texts. The majority of these books deal with a specific aspect or application such as noise reduction, non-linear acoustic echo, and VoIP. Unlike this work, which is intended for a relatively larger audience adopting a more encompassing application domain, the focus of most other texts is relatively narrow and comparatively deep. One more on that level may only address an audience which is already surrounded by plenty of stimulating material.

Books dealing with noise reduction are intended for the few subject experts and algorithm designers. They place heavy emphasis on the math, and they do a good job analyzing and dissecting the algorithms details.

Probably one of the best books on noise reduction is *Noise Reduction in Speech Applications* edited by Gillian Davis (managing director, Noise Cancelation Technologies Ltd.).[1] Before launching into the noise-reduction algorithm details, it provides a short introduction on digital-signal processing and adaptive filtering. It also includes descriptions of systems aspects; digital algorithms and implementations of single-channel speech enhancers, microphone arrays, and echo cancelers; and applications in the more specialized areas of speech recognition, internet telephony, and digital hearing aids.

Other books on the subject of noise reduction dig deep into the math and are aimed at the experts in the specific subject matter.[2]

Echo cancelation is treated in the common literature largely as a signal processing exercise. Electrical-echo cancelation comprises two processes – linear and non-linear. The linear process consists of an elegant mathematical procedure implemented via numerical iterative least-squares algorithms. The non-linear part is based on heuristics and tricks of the trade. In fact, some heuristics measures are used to improve the linear portion as well. The next two examples provide a representative sample for the literature in this area. Their analysis is mostly academic. They focus on the math underlying the linear portion of the algorithm, while steering clear of the practical heuristics that are the backbone of any successful implementation.

1 Gillian M. Davis (ed.), *Noise Reduction in Speech Applications*, CRC Press, (2002).
2 S. V. Vaseghi, *Advanced Signal Processing and Digital Noise Reduction*, John Wiley and Teubner, (1996).
E. Beranek and L. Leo, *Noise Reduction*, McGraw Hill, (1960).

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Electrical-echo cancelation is not addressed in most of the literature as a comprehensive application. One typical (and probably the best) example is the signal processing book *Digital Signal Processing: Principles, Algorithms and Applications* by John G. Proakis and Dimitris Manolakis.[3] It treats the subject as a side effect to sampling and reconstruction of signals. The analysis focuses on the linear part, and the approach is thorough yet theoretical. It does not address the practicality of canceling echo in real applications, although it does do a good job in providing the mathematical analysis of some of the application aspects.

The book *Least-Mean-Square Adaptive Filters (Adaptive and Learning Systems for Signal Processing, Communications and Control Series)* edited by Simon Haykin and B. Widrow[4] – as well as *Adaptive Filter Theory* by Simon Haykin,[5] which is a reference book for adaptive filters, a collection of papers by various authors – focus on the mathematical properties of the linear portion of the echo-cancelation algorithm. They do not treat the application as a realistic problem in search of a practical solution, but rather as a mathematical exercise seeking an academic illumination.

Acoustic-echo control in wireless communications is covered in *Advances in Network and Acoustic Echo Cancellation* by Jacob Benesty, Thomas Gansler, Denis R. Morgan, M. Mohan Sondhi, and Steven L. Gay.[6]

Once more, books on the subject of echo cancelation[7] provide a thorough mathematical analysis, and mathematical algorithms ranging from filtering via fast Fourier transform (FFT) in Schobben's book to a profound mathematical analysis in Borys' book concerning discrete Volterra series in the Z domain, non-linear filters etc. These mathematical analyses are interesting but they do not reflect the present issues and the latest implementations and treatments of acoustic echo in wireless networks. They are intended for a very small audience whose focus is merely academic.

Voice-quality enhancements and echo cancelation (EC) solutions have been evolving and have become essential elements in virtually every type of telecommunications network. This upward growth trajectory is expected to swell far beyond singular applications. Both voice-quality systems (VQS) and echo-cancelation equipment elements have penetrated all the blueprints of impending network infrastructures. The fastest growing segments of the industry, voice-over-packet (VOP) and 2G–3G wireless communications, continue to be key drivers posting fresh challenges and fostering innovative solutions that deliver high-performance voice communications.

One more aspect that makes this work unique is its accompanying audio illustrations. If a picture is worth a thousand words when describing a scene, then an audio illustration is

[3] John G. Proakis and Dimitris G. Manolakis, *Digital Signal Processing Principles, Algorithms, and Applications*, Prentice Hall, 1996.
[4] Simon Haykin and Bernard Widrow, *Least-Mean-Square Adaptive Filters*, John Wiley & Sons, (2003).
[5] Simon Haykin, *Adaptive Filter Theory*, 3rd ed., Prentice Hall, (1997).
[6] J. Benesty, T. Gansler, D. R. Morgan, M. M. Sondhi, and S. L. Gay, *Advances in Network and Acoustic Echo Cancellation*, Springer, (2001).
[7] Andrej Borys, *Nonlinear Aspects of Telecommunications: Discrete Volterra Series and Nonlinear Echo Cancellation*, CRC Press, (2000).
Daniel W. E. Schobben, *Real-Time Adaptive Concepts in Acoustics: Blind Signal Separation and Multichannel Echo Cancellation*, Kluwer Academic, (2001).

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worth no less when giving details of sound effects. Voice quality issues and solutions are best illuminated by way of audio demonstrations. The book would not be complete without accompanying audio files (www.cambridge.org/9780521855952) presenting specific cases pointed out within the text. These examples clarify and give life to the dry analysis while driving in convincing lines of reasoning.

My dear friend and colleague, Dr. Cristian Hera, a bona fide expert in the field of voice quality, put most of the audio recordings together. He also reviewed the manuscript and his valuable suggestions, amendments, and contributions greatly enhanced its merit.

The experience and know-how expounded in the book were accrued during my engineering-management tenure at Lucent Technologies and during my role as vice president of voice-quality systems technology in NMS Communications. During that time, I shared analysis, research, field experience, laboratory evaluations, and simulations, with my kitchen-cabinet team of expert engineers, Andy Stenard, Cristian Hera, Joseph Papa, and Neil Dennis. The time we spent together enriched and expanded my grasp of the subject matter. I am also indebted to another team member, Ron Tegethoff, for letting me include descriptions of his tracer probe and adaptive far-end echo-cancelation algorithms (see Chapter 13 and Chapter 3, respectively).

During the writing of the book, I benefited greatly from discussions I had with Bob Reeves, Rapporteur of the ITU study group 16, Question 6, who has been leading the effort pertaining to the publication of the latest issues of G.168, G.169 and G.160. Furthermore, Bob provided me with the plots used in Figures 9.2–9.6, for which I am grateful.

And finally, it has been my dear wife, Shelly, without whose pressing I would never have brought this work to a close. She has been the reason the writing has reached the editor’s and publisher’s desks.

She won. I dedicate this work to her.

If you ever thought (for even just a moment) that EC and VQS were “out-of-style equipment,” “passé technologies,” or “old economy paraphernalia,” then reading this book and listening to the recordings will probably make you do an about-face and set your perspectives on a telling expedition. Try it and see!

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Abbreviations

1XMC	1X multi channel
2.5G	2nd + ½ generation (enhanced 2G wireless network)
2G	2nd generation (wireless network)
3G	3rd generation (wireless network)
3GPP	3rd generation (wireless standards) partnership project
3XMC	3X multi channel
8-PSK	8-(state)phase-shift keying (modulation)
A/D	analog-to-digital converter
AbS	analysis by synthesis
ACELP	algebraic code-excited linear prediction
ACR	absolute category rating
ADPCM	adaptive differential pulse-code modulation
AEC	acoustic-echo control
AGC	automatic gain control (same as ALC)
AIUR	air-interface user rate
a.k.a.	also known as
ALC	automatic level control
AMI	alternate mark inversion
AMR	adaptive multi-rate
ANSI	American National Standards Institute
ARPU	average rate per user
ATM	asynchronous transfer mode
ATME	automatic test and measurement equipment
BER	bit error rate
BIST	built-in self-test
BSC	base-station controller
BSS	base-station subsystem
BTS	base transceiver station
CC	continuity check
CCITT	International Telephone and Telegraph Consultative Committee
CCS	common-channel signaling
CDMA	code division multiple access
CED	called-station identification
CELP	code-excited linear prediction

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C/I	carrier to interference
CM	configuration management
CN	core network
CO	central office
Codec	encoder/decoder
CPE	customer-premises equipment
CPU	central processing unit
CSD	circuit-switched data
CSI	called-subscriber identification
CSS	composite-source signal
D/A	digital-to-analogue converter
D-AMP	digital advanced mobile phone service
dB	decibel
dBov	dB to overload point
DCME	digital circuit multiplication equipment
DCS	digital command signal
DEC	digital echo canceler
DIS	digital identification signal
DMOS	degradation mean-opinion score
DP	delay processor
DS0	digital-signal level 0
DS1	digital-signal level 1
DSL	digital subscriber line
DSN	delta signal-to-noise
DSP	digital signal processor/processing
DTDT	double talk-detection threshold
DTE	data terminal equipment
DTMF	dual-tone multi-frequency
DTX	discontinuous transmission
EAD	echo-activity detection
EC	echo canceler, echo cancelation
EDGE	enhanced data rates for GSM evolution
EEC	electrical-echo cancelation
EFR	enhanced full rate
EMC	electromagnetic compatibility
EMI	electromagnetic interference
EMS	element-management system
ERL	echo-return loss
ERLE	echo-return loss enhancement
ERP	ear reference point
ES	errored seconds; echo suppression
ESD	electromagnetic compatibility
ESF	extended super frame

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EVRC	enhanced variable-rate codec
eX-CELP	extended code-excited linear prediction
Fax	facsimile
FD	flat delay
FDM	frequency-division multiplexing
FFT	fast Fourier transform
FIR	finite impulse response
FLR	far-end level regulator
FM	fault management
FNUR	fixed network user rate
FR	full rate
GMSC	gateway MSC
GPRS	general packet-radio service
GSGSN	gateway SGSN
GSM	Global-systems mobile
GUI	graphical user interface
HATS	head and torso simulator
HDLC	high-level data-link control
HEC	hybrid-echo canceler
HLC	high-level compensation
HLR	home-location register
HR	half rate
HSCSD	high-speed circuit-switched data
Hz	hertz
IEC	International Electro-technical Commission
IFFT	inverse fast-Fourier transforms
IMT-20	international mobile telecommunications – 2000
IP	internet protocol
IRS	intermediate reference system
IS	international standard
ISC	international switching center
ISDN	integrated-services digital network
ISLP	inter-system link protocol
ITU	International Telecommunication Union
IWF	inter-working function
IXC	inter-exchange carrier
kbps	kilobits per second
LAN	local-area network
LBR	low bit rate
LCP	linear-convolution processor
LEC	local-exchange carrier
LFV	line-format violation
LHD	long-haul delay

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LPC	linear prediction coefficients
LQ	listening quality
LTP	long-term prediction
MCC	mobile-control center
MG	media gateway (CDMA-2000)
MGW	media gateway (3GPP)
MIPS	million instructions per second
MJ	major alarm
MN	minor alarm
MNB	measuring normalizing blocks
Modem	modulator–demodulator
MOS	mean-opinion score
MOS-LQO	mean-opinion score – listening quality objective
MOS-LQS	mean-opinion score – listening quality subjective
ms	millisecond
MS	mobile station (2G)
MSC	mobile-switching center
MTBF	mean time between failures
MUX	multiplexer
NC	noise compensation
NEBS	network equipment-building system
NEST	near-end speech threshold
NHE	near-end hybrid equalizer
NLMS	normalized least mean square
NLP	non-linear processor; non-linear processing
NM	noise matching
NPLR	noise-power-level reduction
NR	noise reduction
NRLC	noise reduction with level compensation
NS	noise suppression
NSF	non-standard facilities
NSS	non-standard set-up
OAM&P	operation, administration, maintenance, and provisioning
OC-3	optical carrier signal level 3
OMC	operation and maintenance control
OS	operating system
OSS	operations support system
PAMS	perceptual-analysis measurement system
PBX	private branch exchange (a small to medium switch)
PCC	per-call control
PCM	pulse-code modulation
PCME	packet circuit multiplication equipment
PCS	personal communication service

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PCU	packet control unit
PDC	personal digital cellular
PESQ	perceptual evaluation of speech quality
PMG	packet-media gateway
PNLMS	proportionate normalized least mean square
POTS	plain old telephone service
PSI-CELP	pitch synchronous innovation – code-excited linear prediction
PSQM	perceptual speech-quality measure
PSTN	public switched-telephone network
PVC	permanent virtual circuit
QoS	quality of service
RAI	remote-alarm indication
RAN	radio-access network
RAS	remote-access system
RCELP	relaxed code-excited linear prediction
R_{in}	receive in (port of the VQS)
RMS	root mean square: also remote-management system
RNC	radio-network controller
R_{out}	receive out (port of the VQS)
RPE	regular pulse excited
RT	remote terminal
SDH	synchronous digital hierarchy
SF	superframe
SGSN	service GPRS support node
S_{in}	send in (port of the VQS)
SMV	selectable-mode vocoder
SNR	signal-to-noise ratio
SNRI	signal-to-noise ratio improvement
SONET	synchronous optical network
S_{out}	send out (port of the VQS)
SPC	signal-processing control
SPL	sound-pressure level
SPLR	signal power-level reduction
SPT	signal-processing terminal
STM-1	synchronous transport mode level 1
STS-1	synchronous transport signal level
TBD	to be determined
TC	transcoder (3GPP)
TCE	transcoder equipment
TCH	traffic channel
TDM/P	time-division multiple interface
TDMA	time-division multiple access
TFO	tandem-free operation

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TNLR	total noise-level reduction
TRAU	transcoder unit (2G/3G)
TrFO	transcoder-free operation
TSI	transmitting-subscriber identification: time-slot interchange
UMTS	universal mobile-telecommunication system
UTRAN	3G radio-access network
VAD	voice-activity detector
VED	voice-enhancement device
VLR	visitor-location register
VoATM	voice-over-ATM
VoIP	voice-over-IP
VOP	voice-over-packet (ATM or IP)
VOX	voice-operated transmission
VPA	voice-path assurance
VQ	voice quality
VQS	voice-quality system
VSC	voice-signal classifier
VSELP	vector-sum-excited linear prediction
WAN	wide-area network
W-CDMA	wideband-CDMA
Z-bal	balancing impedance

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