Dynamic Power Supply Transmitters

Learn how envelope tracking, polar modulation, and hybrid designs using these techniques really work. The first physically based and coherent book to bring together a complete overview of such circuit techniques, this is an invaluable resource for practicing engineers, researchers, and graduate students working on RF power amplifiers and transmitters.

Create more succesful designs:

- Step-by-step design guidelines and real-world case studies show you how to put these techniques into practice
- A survey of various transistor technologies will help you to choose which type of transistor to use for best results
- Details on testing and measurement of all aspects of these designs explain how to measure what the circuit is actually doing and how to interpret measurement results

Earl McCune is a practicing engineer and Silicon Valley entrepreneur. A graduate of UC Berkeley, Stanford University, and UC Davis, he has over 35 years of post-graduate industry experience in wireless communications circuits and systems and more than 70 issued US patents. Now semi-retired, he has founded two successful start-up companies in addition to working in medium and very large corporations. He is also the author of *Practical Digital Wireless Signals* (Cambridge University Press).

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Earl McCune
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Dynamic Power Supply Transmitters

Envelope Tracking, Direct Polar, and Hybrid Combinations

EARL McCUNE

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Dedicated to the outstanding teams I have worked with while learning these details

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Preface

Energy efficiency in all aspects of modern society is now a widespread desire and an active goal. Whether it manifests as driving a high mileage automobile or using a highly rated energy-efficient refrigerator, there is no aspect of modern life that does not benefit from improvement in the energy efficiency used.

Wireless communications are now one of the ubiquitous technological underpinnings of modern society. Mobile communications devices and smart-phones are always at hand and reliably work for the user. As such, it is particularly important for everything involved in wireless communications to be energy efficient. As communication speeds have increased over recent decades, the unfortunate by-product is that the energy efficiency of wireless communications has actually decreased significantly. It is now overdue and important that this gets fixed.

Standards committees have placed the data rate performance of the wireless signals they adopt ahead of any other concern. This means that the energy efficiency of the wireless communication system has not been part of deliberations during the standardization process. The signals adopted years ago are still with us, and there are no plans to change them anytime soon. It is now therefore important to change how these communications devices are made, and to adopt new architectures that will provide the needed energy efficiency while still generating these old signals that are present within the deployed communications standards.

To get full value from this book, the reader should already have a basic familiarity with electrical engineering and wireless communication concepts, including the Fourier transform relationship between time-domain and frequency-domain operations. It is not necessary to have familiarity with the present communications standards.

The contents of this book are drawn from the nearly 20 years of experience I have with dynamic power supply transmitter technology. Being more of a physics-based person than a mathematician, over the decades considerable effort has been given to developing a thorough understanding of the mathematics that underlie the physical relationships being described. Through these pages, I share the results of my efforts with you.

This book is carefully planned so that readers will have a clear understanding of what is being discussed as they work their way through the chapters. This means that the foundations of any topic discussed will as much as possible have already been laid. There are three major parts:

- principles of the dynamic power supply transmitter techniques,
- circuit implementation and special topics for these designs, and
- new issues for testing and calibration of these designs.

The first two major parts start with the 3-port extensions to linear amplifier operation, and then extend the results first to envelope tracking and then to polar modulation. Hybrid designs that use all of the possible techniques in one product have their own chapter. The extensions needed to explain some unusual results experienced when these techniques are applied at multiple stages in the same transmitter also has its own chapter.

Unique contributions in this book include:

- unification of all dynamic power supply operating modes with the inherent characteristics of transistors of any type;
- a specific definition of knee voltage and how this is measured and used;
- direct calculation of what the optimum envelope tracking profile must be for any RF power transistor and selected load line;
- outline of how the concept of matching network design changes significantly when amplifiers are operated in deep compression for polar modulation;
- investigation of the energy efficiency of the various architectures available to implement the dynamic power supply;
- detailed examination of the new interface: connecting the dynamic power supply to the RF PA;
- description of the inherent instabilities in this new interface and what can be done about them;
- clear, unambiguous, and testable definitions of envelope tracking and polar operation, and how these relate to conventional linear operation;
- description of the new transistor specifications needed for polar operation;
- proof that polar operation has higher PA energy efficiency than envelope tracking, and why this must be;
- details of how the concept of amplifier gain must expand into four separate measures that each provide important and different insights;
- identification of the new circuit design rules needed for successful design of polar operation;
- identification of the P-mode amplifier operating region, why this must be avoided by envelope tracking transmitters, and how it can be successfully used by polar operation;
- description of the dynamic power supply feature extensions, including independent automatic compensation at the PA for low battery voltage and/or output impedance mismatch.

Any technology that is involved in multibillion dollar industries, such as wireless communications, is often first published not at a conference or in a technical journal, but rather through the appropriate government patent office. This is certainly true for dynamic power supply transmitter technology. Knowing this fact is particularly important to graduate students who plan on getting doctorate degrees in this technology area, because an idea not seen in the technical journals is not a guarantee that any particular idea is really a new contribution to the technical arts. References in the following chapters do include representative patents that are already published, to aid in accessing that library for further searching.

I gratefully acknowledge help with my ability to access transistors and amplifiers using the many semiconductor technologies through the support of Skyworks, Freescale, TriQuint Semiconductor, RF Microdevices, ST Microelectronics, RF Micropower, NXP, Avago Technologies, and Cree. All of these companies have been a huge help in making this story complete. For his particular help, I salute Gray Wong of the RF distributor Richardson RFPD (now Arrow) who tirelessly made good things happen for this project when they needed to.

I want to particularly acknowledge the tremendous help provided by National Instruments, mainly through Haydn Nelson and Takao Inoue, in providing the automated measurement system and software support that allowed me to collect all of the data used for the technology survey in Chapter 10 and in validating the testing requirements presented in Chapter 13. Without this support, the completeness of the technology survey would not have been possible.

The patience of my wife Barbara to the seemingly endless hours spent writing, drawing, rewriting, and editing needed for the preparation of this book is beyond measure. My gratitude to you again is boundless!

I fervently hope that all who read this book, and who may use it as an additional reference, will enjoy the information and approach as much as I have enjoyed writing it.

Earl McCune

Abbreviations

3G	Third generation cellular, standardized by the Third Generation Partnership Project (3GPP)
AC	alternating current
ACLR	adjacent channel leakage ratio
ACP	adjacent channel power
ALBC	automatic low battery compensation
AM	amplitude modulation
AMO	AM offset
AMPR	average to minimum power ratio
APT	average power tracking
β	bipolar transistor current ratio
BJT	bipolar junction transistor
Bluetooth EDR	extended data rate mode for Bluetooth™
BPSK	binary phase-shift keying
BW	bandwidth
BW3	3 dB bandwidth
BWn	n dB bandwidth
CCDF	complementary cumulative distribution function
CCS	controlled current source
CDF	cumulative distribution function
CDMA	code division multiple access
CE	constant envelope
CFR	crest factor reduction
CJTF	constant joint transfer function
CMOS	complementary metal oxide semiconductor
CoE	conservation of energy
dBm	decibels relative to 1 mW
DC	direct current
DC-DC	direct current in to direct current out
D-FET	depletion mode field effect transistor
DP	direct polar
DPS	dynamic power supply
DPST	dynamic power supply transmitter

DQPSK	difference quadrature phase-shift keying
DSB-SC	double sideband with suppressed carrier
DWC	digital wireless communications
EDGE	enhanced data rate for GSM evolution
EDR	envelope dynamic range
EER	envelope elimination and restoration
EF	emitter follower
E-FET	enhancement mode field effect transistor
EFF	envelope flooring and filling
ENB	equivalent noise bandwith
EpHEMT	enhancement mode pseudomorphic high electron mobility transistor
ET	envelope tracking
EVM	error vector magnitude
FET	field effect transistor
FM	frequency modulation
FSK	frequency-shift keying
GaAs	gallium arsenide
GaN	gallium nitride
GMSK	Gaussian minimum-shift keying
GPRS	generalized packet radio service
GSM	global system for mobile communications
HBT	heterojunction bipolar transistor
HD	harmonic distortion
HEMT	high electron mobility transistor
HSDPA	high-speed downlink packet access
HSPA	high-speed packet access
HTOL	high temperature operating life test
IMN	input matching network
InMN	interstage matching network
IQ	in-phase/quadrature phase
IV	current-voltage
KCL	Kirchhoff's Current Law
LDMOS	lateral diffused metal oxide semiconductor
LDO	low dropout voltage regulator
LDVR	linear dynamic voltage regulator
LINC	linear amplification with nonlinear components
LOS	line of sight
LPF	lowpass filter
LTE	long-term evolution
MESFET	metal semiconductor field effect transistor
MOSFET	metal oxide semiconductor field effect transistor
NADC	North American digital cellular

NF	noise figure
NLOS	non line of sight
OBO	output back-off
OFDM	orthogonal frequency division modulation
OMN	output matching network
O-QPSK	offset quaternary phase-shift keying
P1dB	–1 dB compression point
PA	power amplifier
papr	peak-to-average-power ratio (linear)
PAPR	peak-to-average power ratio (dB)
PCDR	power control dynamic range
PDF	probability density function
PEP	peak envelope power
pHEMT	pseudomorphic high electron mobility transistor
PM	phase modulation
PMPR	peak-to-minimum power ratio
PSD	power spectral density
PSR	power supply rejection
PSRR	power supply rejection ratio
pss	power supply sensitivity (linear)
PSS	power supply sensitivity (dB)
QAM	quadrature amplitude modulation
QM	quadrature modulation
QPSK	quaternary phase-shift keying
R	resistance
RBW	resolution bandwidth
RC	resistor-capacitor
RF	radio frequency
rms	root-mean-square
RX	receiver
SF	source follower
SiGe	silicon germanium
SMPS	switch-mode power supply
SR	slew rate
SRC	spectral raised-cosine
SSB	single sideband
SSB-SC	single sideband with suppressed carrier
SSR	stage series resistance
TDM	time division multiplex
TETRA	terrestrial trunked radio
TRC	time raised-cosine
TX	transmitter
UMTS	universal mobile telephone service

UTB	uniform transfer boundary
VSWR	voltage standing wave ratio
WCDMA	wideband code-division multiple access
X	reactance
Z	impedance