PRACTICAL RF SYSTEM DESIGN

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Lecturer in Electrical Engineering
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To those from whom I have learned:
Teachers, Colleagues, and Students

CONTENTS

PREFACE

This book is about RF system analysis and design at the level that requires an understanding of the interaction between the modules of a system so the ultimate performance can be predicted. It describes concepts that are advanced, that is, beyond those that are more commonly taught, because these are necessary to the understanding of effects encountered in practice. It is about answering questions such as:

- How will the gain of a cascade (a group of modules in series) be affected by the standing-wave ratio (SWR) specifications of its modules?
- How will noise on a local oscillator affect receiver noise figure and desensitization?
- How does the effective noise figure of a mixer depend on the filtering that precedes it?
- How can we determine the linearity of a cascade from specifications on its modules?
- How do we expect intermodulation products (IMs) to change with signal amplitude and why do they sometimes change differently?
- How can modules be combined to reduce certain intermodulation products or to turn bad impedance matches into good matches?
- How can the spurious responses in a conversion scheme be visualized and how can the magnitudes of the spurs be determined? How can this picture be used to ascertain filter requirements?

- How does phase noise affect system performance; what are its sources and how can the effects be predicted?

I will explain methods learned over many years of RF module and system design, with emphasis on those that do not seem to be well understood. Some are available in the literature, some were published in reviewed journals, some have developed with little exposure to peer review, but all have been found to be important in some aspect of RF system engineering.

I would like to thank Eric Unruh and Bill Bearden for reviewing parts of the manuscript. I have also benefited greatly from the opportunity to work with many knowledgeable colleagues during my years at Sylvania-GTE Government Systems and at ESL-TRW in the Santa Clara (Silicon) Valley and would like to thank them, and those excellent companies for which we worked, for that opportunity. I am also grateful for the education that I received at Santa Clara and Stanford Universities, often with the help of those same companies. However, only I bear the blame for errors and imperfections in this work.

WILLIAM F. EGAN

Cupertino, California
February, 2003

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SYMBOLS LIST AND GLOSSARY

The following is a list of terms and symbols used throughout the book. Special meanings that have been assigned to the symbols are given, although the same symbols sometimes have other meanings, which should be apparent from the context of their usage. (For example, A and B can be used for amplitudes of sine waves, in addition to the special meanings given below.)

$\equiv$	is identically equal to, rather than being equal only under some particular condition
$\triangleq$	is defined as
$\sim$	(superscript) indicates rms
$X\rvert_{y}$	variable X with the condition y or referring to y
$X\rvert_{y1}^{y2}$	variable X with y between $y1$ and $y2$
$\angle x$	angle or phase of x
$\begin{smallmatrix}\sim\\ \not\sim\end{smallmatrix}$	low-pass filter
$\begin{smallmatrix}\not\sim\\ \sim\\ \not\sim\end{smallmatrix}$	band-pass filter
acceptance band	band of frequencies beyond the passband where rejection is not required; used to indicate the region between the passband and a rejection band
contaminant	undesired RF power
passband	band of frequencies that pass through a filter with minimal attenuation or with less than a specified attenuation

rejection band	band of frequencies that are rejected or receive a specified attenuation (rejection)
sideband	signal in relation to a larger signal

Generic Symbols (applied to other symbols)

*	complex conjugate
$\lvert x\rvert$	magnitude or absolute value of x
$\breve{x}$	x is an equivalent noise factor or gain that can be used in standard equations to represent cascades with extreme mismatches (see Section 3.10.4)

Particular Symbols

A	voltage gain in dB. Note that G can as well be used if impedances are the same or the voltage is normalized to R_0.
a	voltage transfer ratio.
$\lvert a\rvert$	voltage gain (not in dB)
AM	amplitude modulation
a_n	nth-order transfer coefficient [see Eq. (4.1)]
a_{RT}	round-trip voltage transfer ratio
B	noise bandwidth
B_r	RF bandwidth
B_v	video, or postdetection, bandwidth
BW	bandwidth
$\mathrm{c}(n, j)$	jth binomial coefficient for $(a+b)^n$ (Abromowitz and Stegun, 1964, p. 10)
cas	subscript referring to cascade
CATV	cable television
cbl	subscript referring to cable
CSO	composite second-order distortion (Section 5.2)
CTB	composite triple-beat distortion (Section 5.2)
dB	decibels
DBM	doubly balanced mixer
dBm	decibels referenced to 1 mW
dBc	decibels referenced to carrier
dBV	decibels referenced to 1 V
dBW	decibels referenced to 1 W
e	voltage from an internal generator
F	noise figure, $F = 10\ \mathrm{dB}\log_{10} f$ or fundamental (as opposed to harmonic or IM).
f	noise factor (not in dB) or standard noise factor (measured with standard impedances) or frequency
$\hat{f}$	theoretical noise factor (measured with specified driving impedance) (see Sections 3.1, N.1)

FDM	frequency division multiplex
f_c	center frequency
f_{osc}	oscillator center frequency
f_I or f_{IF}	intermediate frequency, frequency at a mixer's output
f_L or f_{LO}	local oscillator frequency
FM	frequency modulation
f_m	modulation frequency
f_R or f_{RF}	radio frequency, the frequency at a mixer's input
G	power gain, sometimes gain in general, in dB.
g_k	power gain of module k, sometimes gain in general, not in dB.
g_{pk}	power gain preceding module k
H	subscript referring to harmonic
I, IF	intermediate frequency, the result of converting RF using a local oscillator
i	subscript indicating a signal traveling in the direction of the system input
IF	intermediate frequency, frequency at a mixer's output
IIP	input intercept point (IP referred to input levels)
IM	intermodulation product (intermod)
IMn	nth-order intermod or IM for module n
in	subscript indicating a signal entering a module (1) at the port of concern or (2) at the input port
int(x)	integer part of x
IP	intercept point
IPn	intercept point for nth-order nonlinearity or for module n
ISFDR	instantaneous spur-free dynamic range (see Section 5.3)
$\overline{k}$	Boltzmann's constant
$\overline{k}T_0$	approximately 4×10^{-21} W/Hz
L	single-sideband relative power density
L, LO	local oscillator, the generally relatively high-powered, controllable, frequency in a frequency conversion or the oscillator that provides it
L_φ	single-sideband relative power density due to phase noise
$\mathbf{M}$	a matrix (bold format indicates a vector or matrix)
m	modulation index (see Section 8.1)
$\tilde{m}$	rms phase deviation in radians
ma	subscript for "maximum available"
MAX$\{a, b\}$	the larger of a or b
$m \times n$	m refers to the exponent of the LO voltage and n refers to the exponent of the RF voltage in the expression for a spurious product; if written, for example, 3×4, m is 3 and n is 4
N_0	noise power spectral density
N_T	available thermal noise power spectral density at 290 K, $\overline{k}T_0$
o	subscript indicating a signal traveling in the direction of the system output.

OIP	output intercept point (IP referred to output levels)
out	subscript indicating a signal exiting a module (1) at the port of concern or (2) at the output port
P	power in dB.
p	power (not in dB).
$p_{\text{avail},j}$	available power at interface j (preceding module j)
PM	phase modulation
$p_{\text{out},j}$	output power at interface j (preceding module j)
PPSD	phase power spectral density
PSD	power spectral density
R, RF	radio frequency, the frequency at a mixer's input
R_0	agreed-upon interface impedance, a standard impedance (e.g., 50 Ω); characteristic impedance of a transmission line
RT	subscript for "round trip"
S	power spectral density or S parameter (see Section 2.2.1)
$\hat{S}$	sensitivity (see Section 2.5)
S_{ijk}	S parameter of row i and column j in the parameter matrix for module (or element) number k
SF	shape factor, ratio of bandwidth where an attenuation is specified to passband width
SFDR	spur-free dynamic range (see Section 5.3.1)
S/N	signal-to-noise power ratio
SSB	single-sideband; refers to a single signal in relation to a larger signal
SWR	standing wave ratio (see Section F.2)
T	absolute temperature or subscript referring to conditions during test
T_0	temperature of 290 K (16.85°C)
T_{ijk}	T parameter (see Section 2.2.3) of row i and column j in the parameter matrix for module (or element) number k
T_k	noise temperature of module k (see Section 3.2)
UUT	unit under test
$\mathbf{V}$	a vector (bold format indicates a vector or matrix)
v	normalized wave voltage (see Section 2.2.2) or voltage (not in dB.)
V	voltage in dB
$\hat{v}$	phasor representing the wave voltage (see Section 2.2.2)
$\tilde{v}$	phasor whose magnitude is the rms value of the voltage $\tilde{v} = \hat{v}/\sqrt{2}$ (see Section 2.2.2)
v_i, v_{in}, v_o, v_{out}	see Fig. 2.2 and Section 2.2.1
$\Delta_{\pm}$	maximum ± deviation in dB of cable gain A_{cbl}, from the mean
Δf	peak frequency deviation or frequency offset from spectral center
ρ	reflection coefficient (see Section F.2)
σ	standard deviation

σ^2	variance
τ	voltage transfer ratio of a matched cable (i.e., no reflections at the ends)
$\varphi(t)$	$\omega t + \theta$

CHAPTER 1

INTRODUCTION

This book is about systems that operate at radio frequencies (RF) (including microwaves) where high-frequency techniques, such as impedance matching, are important. It covers the interactions of the RF modules between the antenna output and the signal processors. Its goal is to provide an understanding of how their characteristics combine to determine system performance. This chapter is a general discussion of topics in the book and of the system design process.

1.1 SYSTEM DESIGN PROCESS

We do system design by conceptualizing a set of functional blocks, and their specifications, that will interact in a manner that produces the required system performance. To do this successfully, we require imagination and an understanding of the costs of achieving the various specifications. Of course, we also must understand how the characteristics of the individual blocks affect the performance of the system. This is essentially analysis, analysis at the block level. By this process, we can combine existing blocks with new blocks, using the specifications of the former and creating specifications for the latter in a manner that will achieve the system requirements.

The specifications for a block generally consist of the parameter values we would like it to have plus allowed variations, that is, tolerances. We would like the tolerances to be zero, but that is not feasible so we accept values that are compromises between costs and resulting degradations in system performance. Not until modules have been developed and measured do we know their parameters to a high degree of accuracy (at least for one copy). At that point we might insert the module parameters into a sophisticated simulation program to compute the expected cascade performance (or perhaps just hook them together to see how the cascade works). But it is important in the design process to ascertain the range of performance to be expected from the cascade, given its module specifications. We need this ability so we can write the specifications.

Spreadsheets are used extensively in this book because they can be helpful in improving our understanding, which is our main objective, while also providing tools to aid in the application of that understanding.

1.2 ORGANIZATION OF THE BOOK

It is common practice to list the modules of an RF system on a spreadsheet, along with their gains, noise figures, and intercept points, and to design into that spreadsheet the capability of computing parameters of the cascade from these module parameters. The spreadsheet then serves as a plan for the system. The next three chapters are devoted to that process, one chapter for each of these parameter.

At first it may seem that overall gain can be easily computed from individual gains, but the usual imperfect impedance matches complicate the process. In Chapter 2, we discover how to account for these imperfections, either exactly or, in most cases, by finding the range of system gains that will result from the range of module parameters permitted by their specifications.

The method for computing system noise figure from module noise figures is well known to many RF engineers but some subtleties are not. Ideally, we use noise figure values that were obtained under the same interface conditions as seen in the system. Practically, that information is not generally available, especially at the design concept phase. In Chapter 3, we consider how to use the information that is available to determine system noise figure and what variations are to be expected. We also consider how the effective noise figures of mixers are increased by image noise. Later we will study how the local oscillator (LO) can contribute to the mixer's noise figure.

The concept of intercept points, how to use intercept points to compute intermodulation products, and how to obtain cascade intercept points from those of the modules will be studied in Chapter 4. Anomalous intermods that do not follow the usual rules are also described.

The combined effects of noise and intermodulation products are considered in Chapter 5. One result is the concept of spur-free dynamic range. Another is the portrayal of noise distributions resulting from the intermodulation of bands of noise. The similarity between noise bands and bands of signals both aids the analysis and provides practical applications for it.

Having established the means for computing parameters for cascades of modules connected in series, in Chapter 6 we take a brief journey through various means of connecting modules or components in parallel. We discover the advantages that these various methods provide in suppressing spurious outputs and how their overall parameters are related to the parameters of the individual components.