MicroNote 703

Silicon PIN Diode and GaAs MESFET Switches and Their Effects On Linearity of Digital Communications Systems

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The RF sections of Analog FM and Digital Radios primarily differ in the required linearity. If the transmitter amplifiers and attendant switching functions are not extremely linear, AM to AM and AM to PM conversion can cause serious deterioration of Bit Error Rate (BER) and an increase in intersymbol interference (ISI). Higher order QAM Systems such as 64-QAM and 256-QAM require even higher levels of linearity. This article discusses the linearity requirements for the RF sections of Digital Communications Links and compares the low-distortion performance of silicon PIN diode and GaAs MESFET switches.

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Introduction

The RF section of a digital communications link consists of the modulator, transmitter, channel medium, receiver and demodulator. The non-linearities and noise, inherent in these analog components of the link, are major causes of link performance degradation. Physical constraints on link inputs and outputs, imposed by limitations in the digital encoder and decoder, may lead to suboptimal operation; but, they produce relatively small degradation in link performance.

In this article, the overall performance parameters of the digital communications link are described. The non-linear distortion characteristics of GaAs MESFETs and Silicon PIN diodes are discussed and related to the problem of optimizing the RF Transmitter linearity. A comparison of the intermodulation performance of Silicon PIN and GaAs MESFET Switches is given and particular system design considerations are listed to aid in the selection of a particular switch type for a specific system application. As an example, the intermodulation of a transmitter chain caused by an interfering station is discussed and some practical values of IP3 are given.

The digital communications link

Deterioration in communications link performance is mainly related to nonlinear noise effects in the RF sections of the transmitter and receiver sections.

The effects of these sources of noise or interference are increased by nonlinear behavior of the transmitter RF power amplifier and the T/R switch.

In evaluating communications system performance the most important quantity is the Signal-to-Noise Ratio (SNR), because the system design depends on the ability to detect a signal in presence of noise, with an acceptable probability of error.

Since the RF output signal is a modulated carrier waveform, it is useful to refer to the average carrier Power-to-Noise Ratio (C/N) as the SNR or interest.

Ultimately we want to retrieve an accurate replica of the input data bit stream. E_b/N_o is that value of bit energy per noise power spectral density (for a digital receiver) needed to achieve a specified probability of error. Overall link performance is analyzed by specifying the SNR needed to achieve an acceptable $(E_b/N_o)_r$ at the receiver, with a specified link margin of safety.

The following sources of signal degradation are shown in the block diagram (Figure 1) of a Satellite Transmitter-to-Receiver link [1,2]

[1] Intersymbol interference (ISI).

[2] Local oscillator (LO) phase noise.

[3] AM/PM conversion.

[4] Multiple-carrier intermodulation (IM) products.

[5] Adjacent channel interference.

[6] Co-channel interference.

Non-linear Distortion Effects

Device Non-linearity

All physical devices have some degree of non-linearity and thus distort the signal transformation process. The elements of a linear equivalent circuit are derived from small variations about the DC operating point. Thus linear of “Small Signal” means that the development is limited to the first order derivative. By extension, a non-linear equivalent circuit is defined by higher order derivatives.

Non-linear distortion may be specified in terms of gain compression, AM-PM distortion, and intermodulation products (specified in terms of intercept point). Very often the relative merits of RF components are compared in terms of their intercept points [Figure2]. For devices with a well-behaved third order IMD performance (3:1 slope) the intercept point definition enables intermodulation performance to specified independently of power level.

Non-linear Effects IN GaAs MESFETs

Major Contributors to device non-linearity in the normal operating range [3] are:

(1) Input Capacitance: C_{gs} varies as a function of gate voltage.

(2) g_s is a non-linear function of gate voltage.

(3) S_{22} varies with gate voltage.

If the device is operated close to its compression point, two additional non-linearities are:

(a) The saturation current limitations as V_g approaches the built-in junction voltage.

(b) The drain current non-linearity caused by V_g reaching pinch-off.

To minimize these large signal effects, the transistor is biased to maximize saturated power. Increasing the FET’s gate width also improves linearity.

GaAs MESFETs are highly linear devices when operated as small to medium signal level devices [4]. However, the third order IMD is no longer well-behaved and departs significantly from the 3:1 slope. IP3 becomes meaningless as a measure of IM performance independent of the two-tone power level. GaAs MESFETs become highly non-linear when driven beyond their small-signal range of operation.

Non-linear Effects In PIN Diodes

A p-i-n diode is a pn-junction with a doping profile tailored in such a way that an intrinsic layer, “I-region”, is sandwiched between a p-layer on n-layer [5]. The idealized i-region is approximated by a high-resistivity p-layer or n-layer. A p-π-n diode has a p-π junction and a π-n junction in series.

Under forward bias conditions, the i-region resistance is given by

$$R_1 = (W^2/2\mu\tau)\ 1/I_F \qquad (1)$$

μ = ambipolar mobility of minority carriers

τ = effective lifetime of minority carriers

W = effective width of the i-region

I_F = forward bias current

Equation (1) is the defining relationship for PIN diodes used as Current Controlled Resistors. The PIN diode presents a linear resistance to flow-of RF current through the diode when it is d-c biased in the forward direction. The forward biased resistance vs bias current curve for the UPP9401 is given in Figure (3).

PIN diodes are designed and manufactured to enhance the linear forward biased resistance vs forward bias current characteristics, equation (1). But if $f < \tau^{-2}$ and/or I_{RF} ♍ 20 I_F the PIN diode will begin to rectify and this effect can be seen experimentally [7 & 8]. Equation (4) is really a “small-signal” condition on PIN action. If the r-f induced charge is nearly equal to the (d-c) stored charge, the forward biased resistance is no longer determined solely by the forward bias current.

Optimization of RF Transmitter Linearity

The important performance parameters for optimizing the P/A-T/R Switch combination are shown in Figure 4. Each RF component makes its own contribution to the overall system’s intermodulation distortion level. In hand-held transceivers, the power amplifier may be a “linearized” class AB amplifier to achieve the desired CNR or IM3, Carrier-to-Noise Ratio (CNR), and power-added efficiency.

Often a GaAs MESFET Switch is chosen for the T/R switching function because of convenience and apparent cost saving. Their catalog specifications can be misleading, especially regarding IM3 performance at power amplifier’s output level. Since the switch’s IM3 level is a function of the input power, the P/A-T/R combination is optimized by backing-off the P/A output power until the transmitter distortion specification is met.

The optimum solution is improve the T/R switch:

- C/N and BER improve because $[IM3]_s$ is lower.
- P/A output power can be increased conservatively by 3-4 dB, or until $[IM3]_s \approx [IM3]_A$. This solution can be quite cost effective because the use of a silicon PIN diode switch dramatically improves the system without resorting to more expensive alternatives to raise the carrier to noise ratio. The IM3 of a Silicon PIN Switch is 70 dBc at the 1 Watt level. For new designs, a silicon switch can be combined with a more highly linearized P/A to achieve a CNR improvement of 8 to 10 dB, without the cost of increasing the system’s carrier power level.

Table I shows some typical T/R Switch specifications from manufacturer's catalogs. The choice would depend on the specifics of the system application. Some critical issues are:

- Peak and average modulated output power.
- End-to-end Bit Error Rate for Voice or Voice and Data Transmission.
- Complexity of Signal Constellation needed to satisfy bandwidth efficiency requirements.
- Constant envelope or linear modulation.
- Random traffic density experienced by a particular station.
- Proximity of high power interferers.
- Switch bias conditions available, etc.

Battery-operated hand-held transceivers have a very low current budget and designers often choose a GaAs MESFET Switch driven from a voltage source. The trend toward chip sets for high volume applications favors the use of GaAs MESFET Switches.

But Base Station, Fixed-Mobile, and Bag phones operate at higher transmitter levels and have the bias current available to take advantage of the improved IP3 performance of the Silicon PIN Switch.

The trend is toward the manufacture of transceivers supporting voice and data transmissions. Higher values of CNR are needed to support the systems' BER specification. It is usually cheaper to reduce the RF Channel distortion level than to increase the linear power level.

Summary

Silicon PIN diodes are inherently higher power, lower distortion devices than GaAs MESFETs. In the forward biased "ON" State, the effect of conductivity modulation by the RF signal is minimized by the stored charge, $Q_S = I_F\tau$, in the diode's I-region [6]. If the transmitter power is increased, forward bias current can be increased to obtain the same IM3 as specified [7]. In comparison, GaAs MESFETs are inherently lower power switching devices. The gate source junction of a MESFET device is a rectifying schottky junction with higher distortion properties than a PIN diode.

There are two trends that will be interesting to track. To accommodate data transmission and multimedia capabilities, there is need to increase RF Signal Bandwidth efficiency which ultimately means a significant improvement in end-to-end BER or system SNR. On the other hand, high volume applications tend toward chip set implementation with the switching function integrated onto the transmitter chip. Silicon and GaAs devices will be needed for their own unique characteristics.

Source: Reference [2]

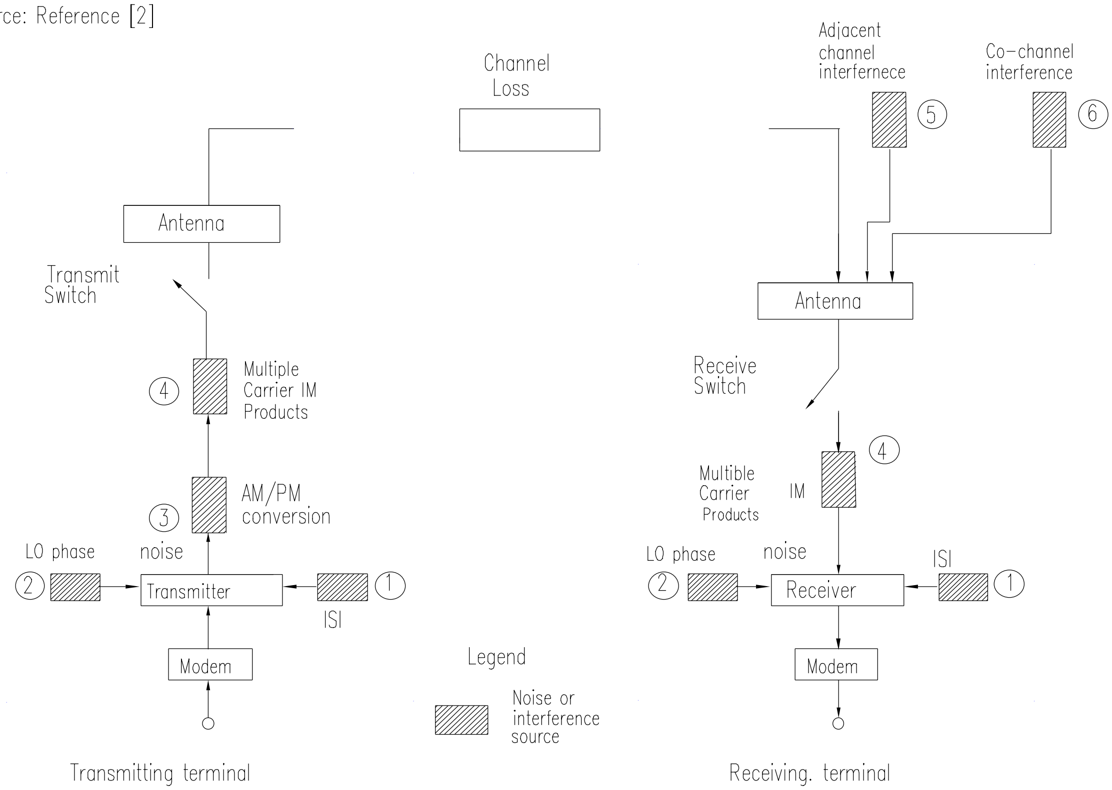
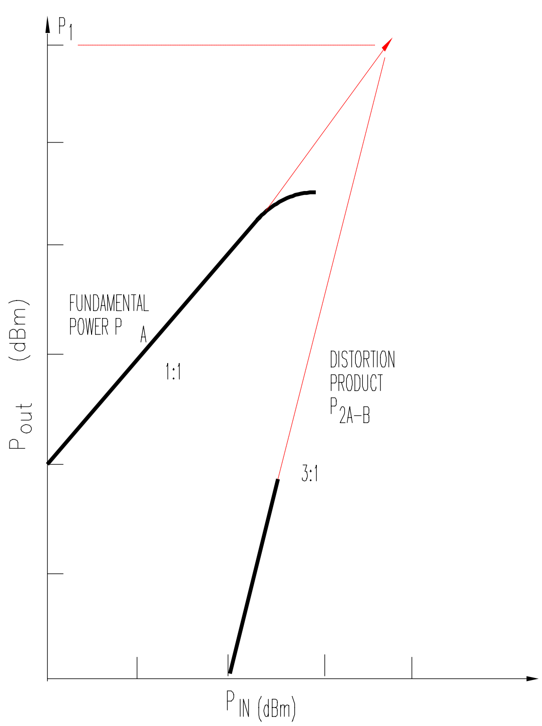


Figure 2. Satellite Transmitter-to-Receiver Link With Typical Interference And Noise Sources.



Definition of the intercept point

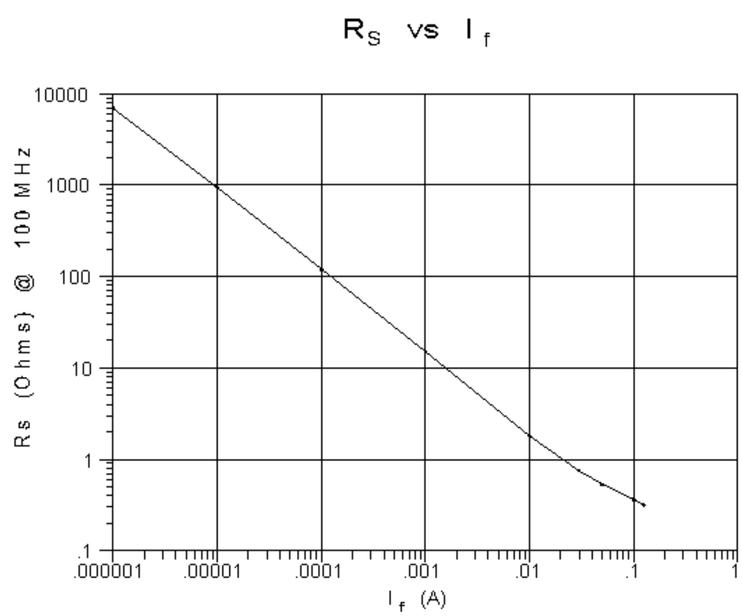


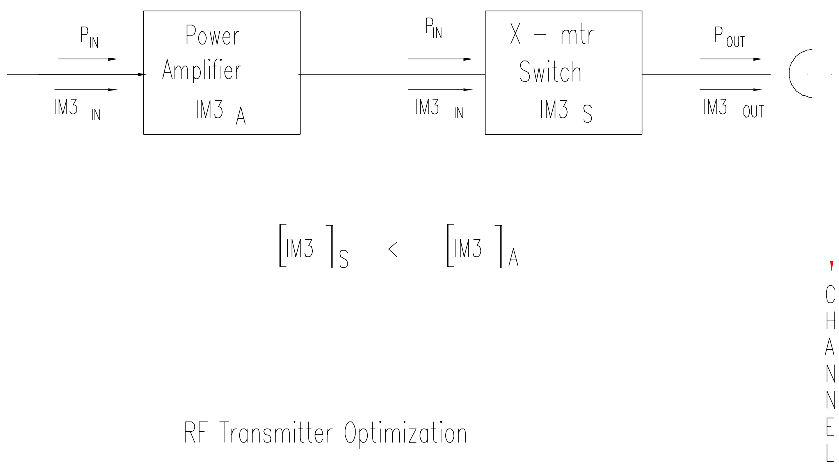
Figure 3

TABLE I

Typical T/R Switch Specifications

	Silicon	**GaAs MESFET ***
IL	0.25 dB Typ	1.0 dB Typ
ISO	40 dB Typ	40 dB Typ
IP3	65 dBm Typ	45 dBm Typ *
"ON" State	10 W Typ	2 W Typ
"ON" State		-10 V
Test Tones	1 W	10 mW Max

* +10 dBm IP3 Calculated From IM3 Measured With Two Input Tones



RF Transmitter Optimization

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[6] Microsemi's PIN Diode Designers Handbook.

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[8] "Solid_State Antenna Switching", P.C. Basile & R.G. Erdman, RCA Review, Vol 42, December 1981, pp 752-769.