Efficient Test Strategy for TDMA Power Amplifiers Using Transient Current Measurements: Uses and Benefits

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Abstract

A novel algorithm for fast and accurate testing of TDMA power amplifiers in a transmitter system is presented. First, the steep cost of high frequency testers can be largely complemented by the proposed method due to its ease of implementation on low-cost testers. Secondly, TDMA power amplifiers usually have a control voltage to operate the device in various modes of operation. At each of the control voltage values, all the specifications of the power amplifier are measured to ensure the performance of each tested device. A new method is proposed to test all the specifications of these devices using the transient current response of their bias circuits to a time-varying control voltage stimulus. This results in shorter test times compared to conventional test methods. The test specification values are measured to an accuracy of less than 5% for all the specifications measured. The proposed test approach can specifically benefit production test of quad-band amplifiers (GSM850, GSM900, PCS/DCS), as a single transient current measurement can be used to compute all the specifications of the device in different modes of operation, over different operating frequencies.

1. Introduction

Testing of high frequency circuits is a much sought after topic in the testing industry today. This can be mainly attributed to the expensive nature of high frequency testers that are required to test high frequency circuits. The testing time of these devices is a determining factor of their cost, since the time spent by each IC in the tester can cause a major impact in their market price. Almost 40 % of the manufacturing cost of these ICs is spent in testing these devices. In particular we focus on testing of RF power amplifiers in wireless networks and cell phones (GSM/PCS/DCS). The goal of this work is to reduce the test time of TDMA power amplifiers (PA) used in any typical transmitter system.

The general block diagram of a transmitter system employed in a communication device consists of a mixer, a PA and a few filters. Ideally, the transmitter is expected to transmit the signal with sufficient spectral purity within the frequency of operation [2]. However, this is not practically possible due to nonlinearities in the system. The embedded power amplifier in this system is an important source of nonlinear behavior. Hence, the specifications of the RF power amplifier are usually critical and any degradation in the above can directly affect the overall transmitter performance. The general transfer function of a power amplifier is shown in Figure 1.

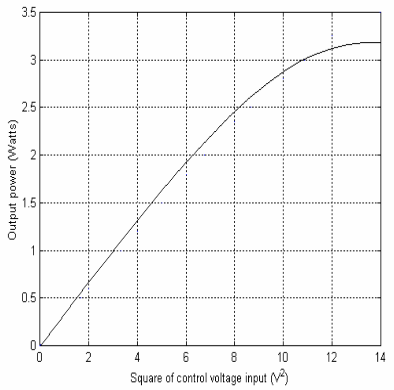

Figure 1 General transfer function of a PA

As shown in the figure the output power is linearly proportional to the square of the control voltage of the bias circuit. The power amplifier used in TDMA applications is operated in different modes (on and low-power). Usually, there is a control voltage terminal provided in these power amplifiers to control the device from drawing excessive current especially in the "low-

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power" mode. The control voltage here refers to the input voltage to the bias circuit of the power amplifier. At each of these control voltage values, all the specifications of the power amplifier are measured to ensure the performance of the device. Certainly, it is time-consuming to measure all specifications at each of these voltage values. In our proposed method, we study the transient current nature of the device under test and use this behavior to measure *all* the specifications of the device at different voltage levels using a single (compact) test.

2. Previous work

In this section, the production test procedure for a TDMA power amplifier used in the industry is explained. To strengthen our argument, we have referred to the data sheets of two such TDMA power amplifiers by Motorola and Texas Instruments (product number MMM5062/D [7] and TRF7610 [6], respectively). The Motorola power amplifier is a quad-band device, which operates in the GSM850, GSM 950, DCS and PCS bands. The power amplifier by Texas instruments is designed for the GSM band of operation. In both of these devices, a control voltage applied to the bias circuit controls the output power to meet the specifications for time-division multiple-access systems in all modes of operation. Usually, the control signal switches to a low voltage for every half time period (if the duty cycle is 50%) to prevent the device from drawing excessive current at low output power. Hence, the requirement to test these devices at different control voltage values.

The power control signal causes the output power of the device to change modes as its amplitude changes. Hence, the control voltage value is varied and all specifications of the device are measured for each value. For example, in the case of the MMM5062 Motorola power amplifier whose typical operating voltage is 3.5V; the circuit is tested at a high value of 3.5V, a nominal value of 2.8V and a low value of 0.8V. This procedure is performed at each of its operating frequencies (since this is a quad-band device). Therefore, twelve pulses (4 bands X 3 control voltage levels) of the required time-period have to be applied to test this power amplifier completely. In this paper, we propose a new method to test all the specifications of the device in a single time-period (device dependent) using the transient current behavior of the circuit.

In the past, significant amount of research has been performed on current based test of digital circuits. While tests like Iddq, Iddt remain common to digital systems, there is little [5] or no application of this concept to analog circuits. In this work, the proposed algorithm uses transient current behavior to test RF circuits.

3. Proposed test strategy

In this section, the strategy that has been used to reduce the test time of RF power amplifiers is explained. It explains why transient current measurements are used and how the specifications are obtained from the transient current measurements.

3.1 Transient current measurement

As explained in the previous section, the production test procedure of the PA is time consuming due to the different control voltage amplitude values involved. To decrease the test time of these devices, one would ideally want a simple test signal to replace all the control voltage signals of different amplitudes. This signal should be capable of measuring all the test specifications at the different amplitude levels of the control voltage.

To achieve this characteristic, a time varying signal whose amplitude ranges from the low to high value of the control voltages that are involved in the conventional test plan, was used. This is a ramp signal, which is applied to the control voltage terminal of the bias circuit of the power amplifier. The parameters of this ramp signal may be optimized for the measurement capabilities of the tester and circuit parameters of the device. Measurement parameters such as digitizer speed and circuit parameters such as settling time determine the time duration of the ramp, and the high and low control voltages values determine the step size of this ramp. Generating an optimal ramp signal for a device can be done using a similar procedure to that suggested by Variyam et al, in [9]. In [9], fast transient tests are derived for analog circuits. It has been shown in [9] that these fast transient tests can be used to compute the circuit test specifications accurately. Using a similar approach, in this paper, the applied ramp is optimized for the settling time and control voltage values of the power amplifier to be tested.

The general transfer function of a PA, as shown in Figure 1, indicates that the output power is linearly proportional to the square of the control voltage of the bias circuit. When the ramp signal is applied to the control voltage terminal, the output power of the power amplifier increases accordingly. For a PA, the voltage gain produced in each stage of the power amplifier is proportional to the supply current drawn. So, the current drawn by each stage from the power supply changes with the transient control voltage signal applied. To demonstrate this, the transient current behavior of a typical bias circuit used in the power amplifier is presented later. The schematic of the bias circuit used is shown in Figure 2. A short description of the bias circuit is given before discussing the transient current behavior of this circuit

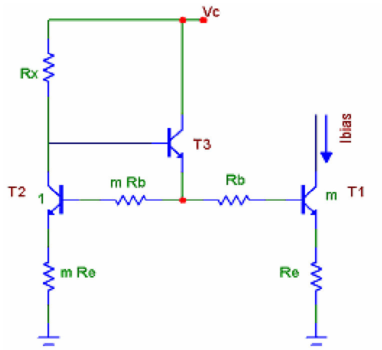


Figure 2 Schematic of bias circuit used

3.2 Bias circuit description

In this circuit, the biasing is provided by the current mirror principle. This circuit is a modification of the simple two transistor current mirror (T1 and T2), which takes into account the β helper (finite β of the BJT) provided by transistor T3. The transistor T1 refers to the transistor in the amplifier gain stage. The circuit differs slightly from the normal β helper circuit in the presence of the resistor "Rb". This resistance is necessary to prevent grounding of the base of the BJT. For close matching, a resistance must be connected to the base of the transistor T_2 also, the ratio of the resistance being the ideal current ratio in the current mirror (i.e. the area ratio of the transistors T_1 and T_2) [3]. In Figure 2 "m" refers to the multiplication factor of the BJT device. The ballast resistor Re is used in the emitter of the amplifier stage to exclude thermal runaway condition. To account for the ballast resistor Re in the emitter of the transistor T1, the emitter degeneration in the transistor T2 is done.

I_{bias} for this circuit is given by,

$$I_{bias} = \frac{V_c - V_{be1} - V_{be3}}{\frac{R_x}{m}\left(1 + \frac{m+1}{\beta(1+\beta)}\right) + \frac{R_e}{\alpha} + \frac{R_b}{\beta}} \qquad \text{Equation 1}$$

From Equation 1, it is clear that *Ibias* (the current in the collector of the amplifier stage) is linearly proportional to the bias circuit control voltage V_c. Hence a linear change in the bias circuit control voltage causes almost a linear change in the amplifier stage collector current. To show this linear relationship, a ramp signal was applied at the input of the control voltage terminal of the bias circuit and the response of the circuit was studied. The waveforms of the transient voltage and current are shown in Figure 3. From the waveforms, it is clear that the control voltage can control the current drawn from the power supply, which is used to produce the output power. For TDMA applications, the specifications are defined for different operating modes of this circuit. Because the control voltage of the circuit controls the switching between different operating modes, there arises the need to test at different control voltage values.

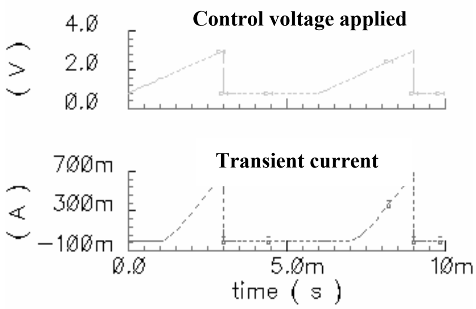


Figure 3 Ramp control voltage input and transient current output waveforms for bias circuit

3.3 Transient current measurement techniques

To reduce the test time of these devices, the different control voltage signals were replaced by a single slow ascending ramp signal with the same time period of the original signal and the transient response of the device was studied. The transient response of the device is measured by monitoring the current drawn from the supplies as the voltage of the ramp changes. The monitoring of the current in the device can be done in two methods. To check the accuracy of these methods, we measured the transient response of a TDMA power amplifier on a HP 84000 RF tester using both these methods.

One method is to use a DC voltage source with an accurate current measuring capability to track the transient response. The input signal to the control voltage terminal was a ramp signal from 0 to 3.5V with a period of 1.2 seconds. The response of the device to the signal was studied using a DC source in the tester with an inbuilt current measuring capability. The transient response of the device is shown in. The transient response shows a spike in its current waveform as soon as the power amplifier turns on.

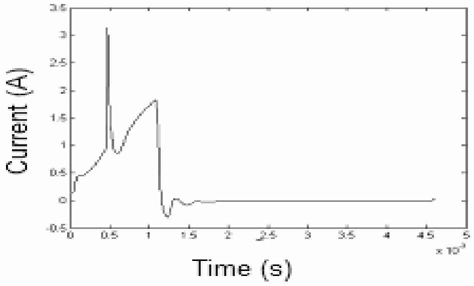
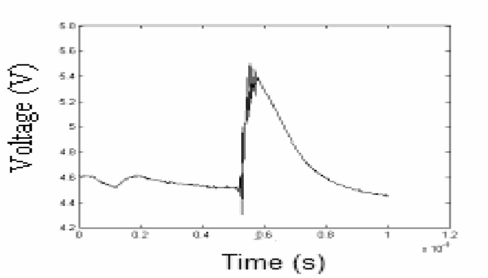


Figure 4 Transient response measured using current measuring capability of a DC source

In the second method, the evaluation circuitry of the device was modified by including a sense resistor in the path of the collector current drawn by the power amplifier from the power supply. The voltage drop across this sense resistor determines the transient current response of the circuit to the slow ascending ramp signal input. Since this resistor should not affect the circuit performance, we used a very small resistance of 0.1ohms (1% tolerance) to measure the potential difference across it. The measured transient voltage responses at the positive and negative terminals of the sense resistor are shown in Figure 5. Using one of the above-mentioned non-invasive methods the transient response of the power amplifier can be studied and this transient response can be stored for further processing. The evaluation board built for the purpose of validation of our test strategy is shown in Figure 6.

1) Positive terminal



2) Negative terminal

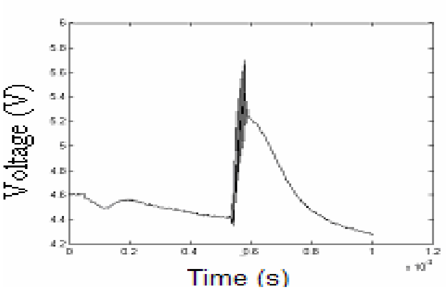


Figure 5 Transient response of the DUT measured at 1) Positive and 2) Negative terminals of sense resistor

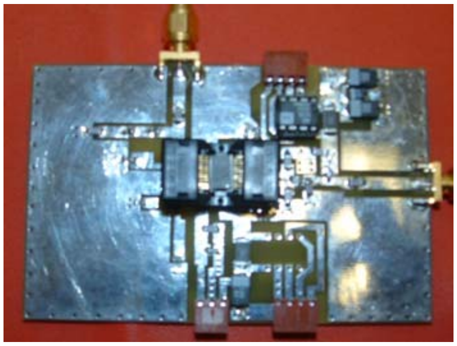


Figure 6 Evaluation board for transient current measurement

3.4 Calculating specifications from the transient current response

Ideally, we would like to have a deterministic expression for computing the output specifications from the discrete tones in the sampled transient response of the power amplifier. Since the relationship of the amplitudes of the sampled transient response to the specifications is not known, it is derived using measurement synthesis done by Variyam et al, in [8] & [10]. The relationship is obtained as a non-linear regression function.

To generate such a non-linear regression function, a set of 100 devices are chosen from different production lots. The ramp signal is applied to the control voltage terminal of each of these devices and the resulting transient response of the devices are sampled and stored. Simultaneously the output specifications of these devices are measured using the conventional test set up at the different DC control voltage values. A nonlinear regression function is built from the output specifications measured to the amplitudes of the discrete tones in the transient response for each control voltage value to be measured at. These nonlinear regression functions were built using Multivariate Adaptive Regression Splines (MARS) [1], discussed in the next section.

3.5 MARS model generation

MARS is used for developing the non-linear model that relates the process parameters to the DUT's test specifications. The MARS algorithm mainly depends on the selection of a set of basis functions and a set of coefficient values corresponding to each basis function to construct the nonlinear model. The model can also be visualized as a weighted sum of basis functions from the set of basis functions that span all values of each of the independent variables.

MARS uses two-sided truncated functions of the form *(t-x)+* and *(x-t)+* as basis functions for linear and non-linear relationships between the dependent and independent variables, *t* being the knot positions. The basis function has the form:

$$(x-t)=\left\{\begin{matrix} x-t & x>t \\ 0 & otherwise \end{matrix}\right\} \qquad \text{Equation 2}$$

The basis functions together with the model parameters are combined to generate the predicted values from the values of the independent variables. The MARS model for a dependent variable *y* and *M* independent terms, can be summarized as:

$$y=f(x)=\beta_0+\sum_{m=1}^{M}\beta_m H_{km}(x_{v(k,m)}) \qquad \text{Equation 3}$$

where the summation is over the M independent variables, and β_0 and β_m are parameters of the model (along with the knots *t* for each basis function, which are also estimated from the data). The function H is

$$H_{km}(x_{v(k,m)}) = \prod_{k=1}^{K} h_{km} \qquad \text{Equation 4}$$

where $x_{v(k,m)}$ is the kth independent variable of the k^{th} of the m^{th} product. During the forward stepwise placement, basis functions are constantly added to the model. After this implementation, a backward procedure is applied, when the basis functions associated with the smallest increase in the least squares fits are removed, producing the final model. At the same time, the *Generalized Cross Validation Error* (GCVE), which is a measure of goodness of fit, is computed to take into account the residual error and the model complexity. The above equation can be further decomposed into sum of linear, square products, cubic products and so forth. The accuracy can also be changed by introducing larger or smaller number of basis functions.

Using MARS, we relate the amplitudes of the discrete tones in the output spectrum of the transient response to the measured output specifications from the conventional method. The relationship is of the form

$$(\overline{s}) = \Psi\left(p\right)\cdot\left(p\right) \qquad \text{Equation 5}$$

where, *s* represents the output specifications and *p* represents the amplitudes of the sampled transient response.

Once this nonlinear regression function is built, we can calculate the output specifications from the amplitudes of sampled transient response of the devices directly.

4. Validation of test strategy

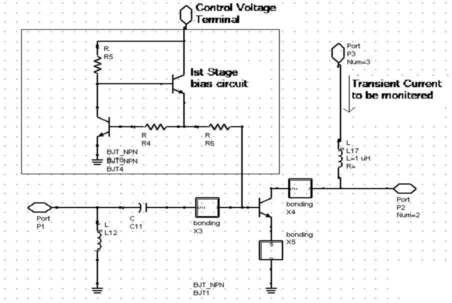
To validate our test strategy we used the transient current measurement technique to measure the specifications of a two-stage power amplifier that we designed. The power amplifier we designed was a SiGe HBT PA used for cellular handsets. Specifications, such as output power, power added efficiency (PAE), Noise Figure (NF), stability factor (K) and, second harmonic were considered in this design. Table 1 describes the design goals and compares them with simulation results obtained using Agilent (HP)'s Advanced System Design (ADS) suite. We used the Silicon Germanium heterojunction bipolar transistor, or SiGe HBT, for the power amplifier design because of its lower knee voltage and higher breakdown voltage as compared to other devices such as CMOS and BJT. The circuit is designed to operate between 820 and 850 MHz.

Using the HPADS simulator, the number of power cells for each stage, the impedances for adequate power outputs, and the corresponding passive networks for input, inter-stage, and output matching were determined [4]. The schematic of the input and output stages of the power amplifier are shown in Figure 7.

Table 1 Design specifications and the Simulation results of the Power amplifier

Linear Gain	>30 dB at 0 dBm input	35.48dB
PAE	> 35%	~ 42.885%
Noise Figure(NF)	>2	1.433
Stability factor	Unconditionally Stable, K > 1	K > 1 (200 MHz – 2 GHz)
Second harmonic($2f_o$)	<20	19.45dB

1) Input stage



2) Output stage

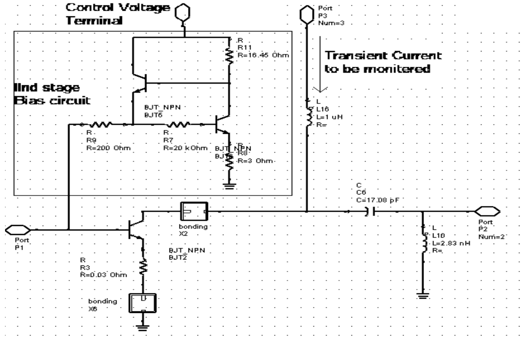


Figure 7 Schematic of 1) Input stage, and 2) Output stage

4.1 Transient Current measurement

The circuit parameters of the power amplifier designed are perturbed to generate different "instances" of the circuit. A set of hundred such instances were created. The test ramp signal was applied to the control voltage terminal of these hundred devices. Simultaneously the output specifications of these devices were measured using the conventional method at three different control voltage values (3V, 2V and 0.8V). The nonlinear regression function was built from the output specifications to the sampled transient current data using MARS.

We then measured the accuracy of measurement of the specifications of the device under test using the proposed test strategy by testing another set of 20 instances. We applied the ascending ramp signal to the control voltage terminal and monitored the transient current response. Using the nonlinear regression function built in the previous step we calculate the output specifications from the amplitudes of the sampled transient current response.

5. Results

The test stimulus applied to the control signal is shown in Figure 8. The stimulus initially operates the device in low-power mode, and then applies the ramp, finally resetting it to low power mode again. The current responses for a set of 100 devices are shown in Figure 9.

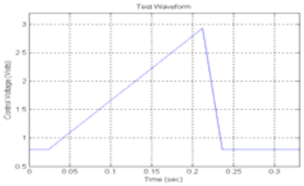


Figure 8 Test waveform applied to the control voltage input

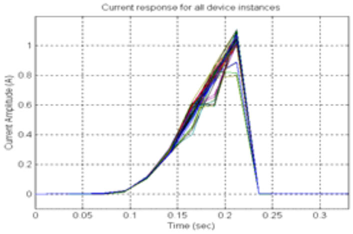


Figure 9 Current responses for all device instances

A study was performed to find out how the model can predict the specifications of the PA by monitoring the current waveform when the test stimulus was applied. Table 2 shows the accuracy achieved using the model generated and compares with the standard specification measurement technique. Also a comparison of total test time for both cases has been presented to obtain the speedup using this approach.

Table 2 Performance comparison

	Proposed method	Conventional method
Test time	330ms	1450ms
Measurement error	2.3%	~1% (digitizer)

To strengthen our argument we wanted to compare the prediction accuracy of the transient current measurement to a method of predicting the specifications from the sampled voltage measurements made on the RF output pin of the same device. To strengthen our argument we wanted to compare the prediction accuracy of the transient current measurement to a method of predicting the specifications from the sampled voltage measurements made on the RF output pin of the same device. The prediction error associated with different specifications in each case is shown in Table 3. It is very clear from the error values that the transient current generates a very accurate model for predicting the specifications.

Table 3 Comparison of prediction error

	Gain (%)	PAE (%)	Noise figure (NF) (%)	Stability Factor (K) (%)	$2f_o$ (%)
Current prediction	0.7	4.2	1.5	2.2	1.9
Voltage prediction	1.5	10.3	8.1	3.3	1.9

6. Conclusion

A novel test strategy for power amplifiers used in TDMA applications has been presented. The proposed approach uses the transient response of the power amplifier bias circuit to a slow ascending ramp signal to measure all the specifications of the device using non-linear regression equations. A test time reduction of a factor more than *three* was achieved. Overall, the measurements could be made to an accuracy of 4% of the actual value.

7. References

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