Output Power-Control Loop Design for GSM Mobile Phones

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Why do we need to control the output power level of mobile phones? There are a number of very good reasons: to prevent intermodulation in base station receivers, to prevent interference with other mobile phones, and to minimize power consumption in the mobile phone -- using the minimum power necessary for reliable communication with the selected base station, based on distance.

The 3GPP (3rd Generation Partnership Project) GSM standards body defines GSM specifications in *TS 45.005 Radio Transmission and Reception*. This document specifies the nominal output power levels, and accepted tolerance of GSM mobile transmitters, under nominal and extreme conditions. Nominal conditions refer to ambient temperature with nominal voltage supply, and extreme conditions to a combination of extreme values of supply voltage and temperature.

The radio transceiver operating voltage for most components in current mobile phone technology is 2.8 V, which is set by voltage regulators. However, the PA needs to be connected directly to the battery, since a higher dc current is required to deliver the necessary output power. The GSM technical specification specifies that, by example, three NiCd battery cells with a nominal 3.6 V should have a lower extreme voltage tolerance of -0.36 V. With regards to temperature variations, the GSM TS specifies extreme conditions between –20°C and +55°C.

Control of nominal output power is done in 2-dB steps. The maximum output power levels for handset mobile station class 4 GSM is +33 dBm (850/900 MHz) and for class 1 DCS and PCS is +30 dBm (1800/1900 MHz). The dynamic range of power control is 28 dB for the 850/900 MHz band and 30 dB for the 1800/1900 MHz band. Table 1 shows power levels and characteristic tolerance values.

GSM Standard: 3GPP TS 45.005 Mobile Station Output Power Levels

Power Control Level			Nominal Output Power (dBm)			Tolerance (dB) for Conditions					
						Normal			Extreme		
900/ 850	1800	1900	900/ 850	1800	1900	900/ 850	1800	1900	900/ 850	1800	1900
	29	22-29		36	Reserved		±2	Reserved		±2.5	Reserved
0-2	30	30	39	34	33	±2	±3	±2	±2,5	±4	±2.5
3	31	31	37	32	32	±3	±3	±2	±4	±4	±2.5
4	0	0	35	30	30	±3	±3	±3	±4	±4	±4
5	1	1	33	28	28	±3	±3	±3	±4	±4	±4
6	2	2	31	26	26	±3	±3	±3	±4	±4	±4
7	3	3	29	24	24	±3	±3	±3	±4	±4	±4
8	4	4	27	22	22	±3	±3	±3	±4	±4	±4
9	5	5	25	20	20	±3	±3	±3	±4	±4	±4
10	6	6	23	18	18	±3	±3	±3	±4	±4	±4
11	7	7	21	16	16	±3	±3	±3	±4	±4	±4
12	8	8	19	14	14	±3	±3	±3	±4	±4	±4
13	9	9	17	12	12	±3	±4	±4	±4	±5	±5
14	10	10	15	10	10	±3	±4	±4	±4	±5	±5
15	11	11	13	8	8	±3	±4	±4	±4	±5	±5
16	12	12	11	6	6	±5	±4	±4	±6	±5	±5
17	13	13	9	4	4	±5	±4	±4	±6	±5	±5
18	14	14	7	2	2	±5	±5	±5	±6	±6	±6
19-31	15-28	15	5	0	0	±5	±5	±5	±6	±6	±6

Table 1: Power Levels And Characteristic Tolerance Values For GSM Mobile Transmitters

How The PA Output Power Level Is Determined

The quest for longer battery life drives mobile phone designers to keep output power levels as close as possible to the nominal values. In the standard transmit architecture the front end of a transmitter will have a minimum loss of around 1.5 dB with an additional 0.5 dB of mismatch loss at the antenna port. It is therefore assumed that the PA output power level needs to be 2 dB higher than the system reference requirements in order to compensate for the loss between the PA and antenna.

Required mobile output signal strength is determined by the distance between the mobile and the base station and, to a certain degree, by environmental conditions. Signal strength information is sent by the base station to the mobile using the BCH (broadcast channel) and the phone controller determines the output power level required at its location. The output power level is set by a voltage-controlled variable-gain PA. The mobile controller checks required output power level against a lookup table containing corresponding PA control voltage levels that have been written during the alignment stage of the phone manufacturing process.

Specifically, individual voltage-controlled PAs have under extreme conditions, and even under typical operating conditions, significant differences between their response to control voltage levels because of variations in operating environment and mass volume manufacturing limitations. The generalized solution is to achieve output power control using feedback circuitry.

GSM Transmit Signal Characteristic

Every time slot or “normal burst” needs to fit in the time/power mask of Fig. 1, with its controlled amplitude level ranging between +5 to +33 dBm in EGSM (Extended GSM) bands. Therefore, the requirement is for 28 dB of effective output power dynamic range. The spectrum of the signal within its bandwidth referred to the noise floor, or residual output power, should be –59 dBc or –54 dBm, whichever is greater.

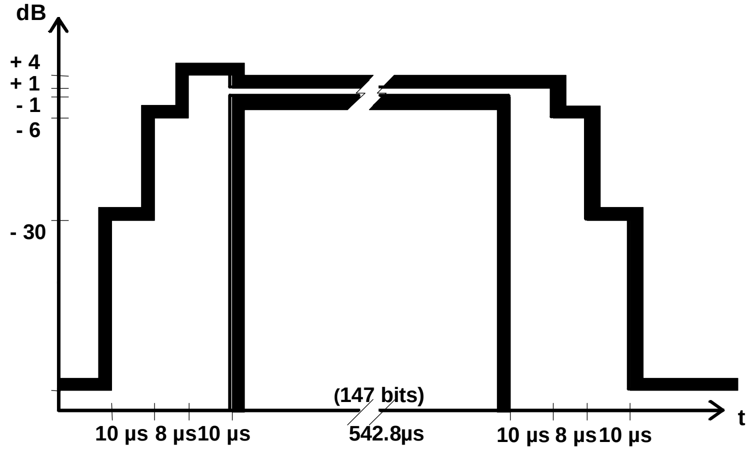
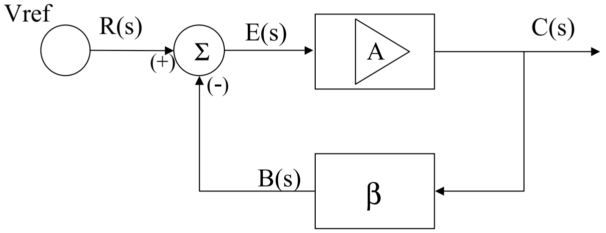


Fig. 1: Time Mask For Normal-Duration Bursts Of GMSK Modulation

Automatic Gain Control (AGC)

AGC is widely used in communication systems to maintain constant signal strength. As mentioned, changes in performance of each individual PA, tolerances in different components of the transmitter chain, supply voltage variations and variations in performance with frequency are all intrinsic to the system at nominal temperature. Mobile phone power level performance under extreme conditions of voltage and temperature is left to guaranteed component tolerances and to the AGC loop circuitry.

A typical AGC loop (Fig. 2) is a feedback system comprising a forward gain stage (A), feedback gain (β) and a signal comparison stage that generates a differential error signal. The AGC loop is analyzed in terms of its closed-loop gain (forward transfer function) and open-loop gain. R(s) is the input amplitude and C(s) represents the output amplitude.



Control loop relevant equations:

Closed-loop gain: $C(s) / R(s) = A / (1+A\beta)$

Open-loop gain: $B(s) / R(s) = A\beta$

Characteristic equation: $1 / (1+A\beta)$

Fig. 2: Typical AGC Loop

The response of an AGC loop to system output amplitude fluctuations -- changes in the C(s) value -- depends on the closed-loop transfer function, since the R(s) reference signal will be fixed (a characterized value at every output power level of the mobile phone system). Variations in the forward gain value, A, due to voltage supply, operating temperature or drive, is what will originate those amplitude fluctuations at the output C(s). Control loop feedback gain β has to be designed to respond to those amplitude fluctuations and correct them in order to obtain a constant steady-state output signal C(s).

The problem for the loop designer is to obtain a model of the response of A in order to determine β so the system keeps C(s) constant while meeting control loop stability criteria (discussed later).

All real amplifiers have a number of internally-compensated poles, meaning that they can be represented as having a single pole above the higher operating frequencies. The PA in the loop can therefore be modeled as having a transfer function with variable gain and a dominant pole above the operating frequencies -- somewhere above 1 GHz in the case of a GSM power amplifier.

$$\textit{Typical PA gain in the frequency domain}: \quad \frac{Vs(w)}{Ve(w)} = \frac{A(Vapc)jw}{1+j\dfrac{w}{w_a}}; \quad \textit{with its pole at } w = w_a$$

The design of β, in addition to the linear gain required to optimize the response of the different components used in the control loop (the GSM system will require an attenuator, comparator and reference voltage source), might require an integrator, depending upon the loop type. Each integrator within the loop will add a pole:

$$\textit{In the frequency domain}: \quad \frac{Vs(s)}{Ve(s)} = \frac{1}{1+RCs} = \frac{1}{1+RCjw}; \quad \textit{with its pole at } w = \frac{j}{RC}$$

In control theory the number of poles of the transfer function is what determines its type. Poles are values of *s (jω)* that make the denominator of the closed loop transfer function equal to 0 (note: this would be the same as making the open loop transfer function equal to -1). The loop "type" refers to the order of the open-loop transfer function pole. The number of poles required in the open-loop transfer function (*Aβ*) to obtain constant output signal will be determined by the way the output signal amplitude changes. The amplitude will generally follow a step, ramp or parabolic function.

A loop with an amplitude variation following a step function is of type 0 and needs no integrator in the open-loop transfer function. Amplitude variations following a ramp function will characterize a loop type 1 which needs one integrator in the open loop transfer function. Amplitude variations following a parabolic function will characterize a loop type 2 which would need two integrators.

With a non-continuous (due to the characteristic TDMA time multiplexing) fast response control loop, all changes in amplitude in the control loop input can be regarded as instantaneous, hence can be explained as following a step function model. In such cases, no integrator is required in the feedback transfer function (*β*).

The loop design exercise will then be fundamentally about the implementation of the error correction or comparator. Once the transfer function of the comparator is determined, an adequate op amp implementation can be selected to meet the characteristic loop gain and speed requirements.

Voltage-Controlled PA

The output of the transmit voltage-controlled oscillator (TxVCO) will typically have an amplitude tolerance of ±2 dB with a nominal output power of around +5 dBm. At this stage the RF carrier with the modulation information is ready to be amplified by the PA. With a PA input power level of around 0 dBm, the power control loop is required to control that power level following the GSM specified output power level steps from +5 dBm to +33 dBm.

To illustrate the response of a GSM PA we have plotted (Fig. 3) the actual response of the Agilent ACPM-7891 PA against control voltage for the GSM, DCS and PCS bands. The input to the PA would be a GMSK modulated RF carrier of constant power level at 0 dBm and the PA maximum output level is around +35 dBm. Input RF carrier and Vcontrol are both pulsed following the GSM TDMA characteristic response. This is a period of 4.615 ms with a duty cycle of 12.5% for standard GSM (1/8). The graph clearly reflects the characteristic output power response of the PA against voltage control with a high slope at lower power levels and flat gain response as the PA saturates.

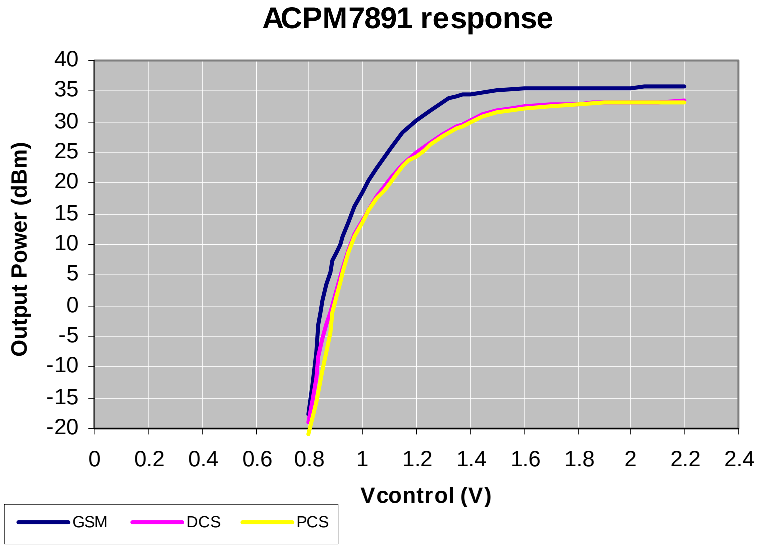


Fig. 3: Response Of Agilent ACPM-7891 PA Vs. Control Voltage In GSM/DCS/PCS Bands

Power Sampling In GSM Mobile Phone Control Loop

Control loop designs need to be linked to specific mobile transmitter radio design architectures. The first step, therefore, should be to identify the ideal control loop model based on the components of the radio transmitter. There are three main factors than need to be taken into account:

1. Output and feedback mobile radio signals are at RF while the voltage reference signal is dc. Feedback monitoring signals can be also obtained by PA current sampling, which should be proportional to the PA output power level
2. The control loop system requires a mechanism to convert the RF feedback into dc to be compared against the reference. Typical power-sampling schemes use diode detectors, which are intrinsically nonlinear (linear techniques such as logarithmic detection can also be used, although with added complexity)
3. Gain nonlinearity of the power amplifier under different Vreference control conditions and the nonlinearity of a Schottky diode detector

The block diagram of Fig. 4 shows control loop components used in a mobile phone. There is a gain stage in the comparator (C) and temperature compensation at the detector diode stage (T) to compensate for diode detector forward voltage, Vf, variation with temperature.

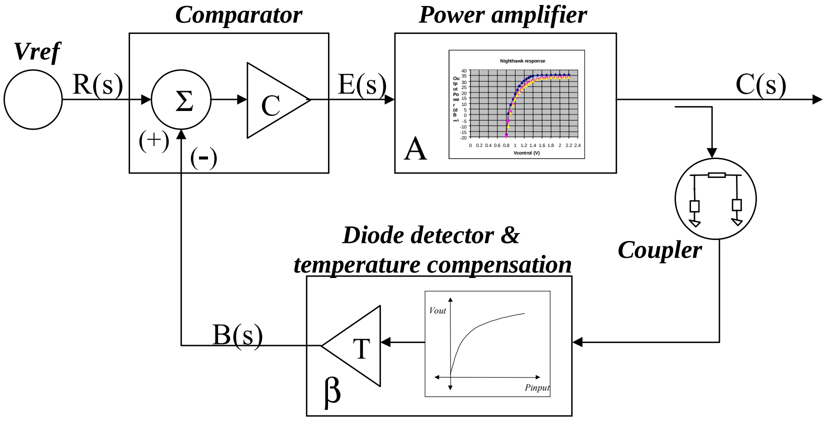


Fig. 4: Control Loop Components Used In Mobile Phone

Loop Gain and Bandwidth

The objective of the control loop is to compensate for any variations at the PA (A) due to changes in performance, temperature or voltage supply with a fixed-voltage reference level, ensuring that the output power level C(s) is constant. This has to be achieved for each power step or fixed Vref levels. The nonlinear PA and detector diode response causes a variation of the closed-loop gain C(s)/R(s) at different output power levels: a factor of 1 for an output power level of +5 dBm to a factor of 6 for an output power level of +33 dBm. These nonlinearities in the detector and PA dictate a high level of discrimination at Vref for high power levels, and a very low level of discrimination for lower power levels. The accuracy of the Vref voltage control source needs to be sufficient for the system to meet the tolerance requirements in the GSM output power level specifications. The GSM standards have taken this into account and the tolerance at low power levels in extreme conditions is ±6 dB.

We have previously seen that another requirement of GSM systems is for the carrier to meet a certain time mask specification. The rising and falling envelope of any switched RF carrier will generate transient spurious response. These need to be kept under certain limits; hence it is necessary to “shape” the profiles to minimize spurious emissions. The Vout reference DAC splits the 28 µs of allocated time for the profiles into a number of amplitude registers. The common number of registers is 16, each lasting for 1.75 µs, corresponding to a minimum DAC speed in the region of 600 kHz.

A loop bandwidth of 1.0 MHz to 1.2 MHz is commonly accepted since the design rule will be the use of a bandwidth of approximately twice the sampling speed (2 x 571 kHz). This needs to be taken into account in the loop design to limit the loop bandwidth and consequently reduce feedback signals to the PA control input. For this reason a loop filter is generally added to the system.

Control Loop Components Definition

The required dynamic range of the control loop, wide nonlinearity of the response at block level (PA and power detector) and variation with temperature of Vf at the diode detector, make the control loop design an interesting challenge. Three elements need to be correctly specified:

- Diode detector: To assure that its dynamic range covers the required input power range, adequate selection of the diode's biasing conditions and input power level needs to be made. The selection of the best-suited coupling factor and adequate 50 Ω RF termination needs to be provided at the diode input. The output load should assure optimum functionality of the diode by setting its bias current. RF decoupling capacitors at the diode output will remove any RF signal harmonic energy
- Temperature Compensation: There is a strong dependency with temperature of the detector diode junction resistance (Rj) and consequently with the forward voltage drop (Vf). This difference in voltage drop with temperature may add to the rectified RF signal with the consequent detection of the wrong power level. The solution is to use an identical diode working in the same way that the one used for RF detection biased identically. Temperature compensation of the offset term (RF detected) is obtained if the bias current of each diode is equal. Different compensation schemes circuits can be used with those diodes, but the basic concept for compensation is to use the identical Vf variation in temperature of one diode to compensate for the variation in the other

  {Agilent has used two different temperature compensation schemes experimentally. One control loop uses a differential model (900-MHz control loop) and the other one uses a feedback model (1800-MHz control loop). Both temperature compensation schemes worked well, maintaining the maximum variation from nominal condition below ±1 dB at maximum power levels and meeting also the extreme condition specifications at power levels 17 - 19}
- Comparator stage: The desired response of the comparator corresponds to an error amplifier with variable positive reference input voltage. This is a circuit that will try to dynamically correct by increasing or decreasing the PA control voltage of any performance variation that may cause a deviation from the wanted output power level

The linear expression that corresponds to that wanted response can be obtained by using an inverting op amp with a non-inverting positive reference. Its transfer function is:

Vout = (Vref*Rf/Rn)+Vref-(Vinput*Rf/Rn).

Appropriate values given to Rf and Rn achieve the required gain. Fig. 5 is a proposed design.

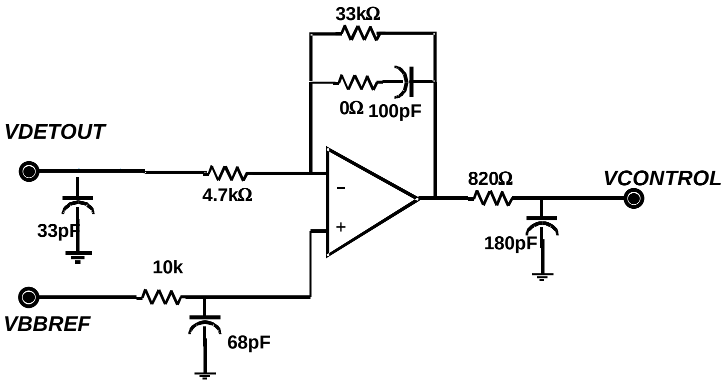


Fig. 5: Proposed Design For GSM Comparator

Conclusions

A GSM transmitter system has been explained together with a description of closed-loop gain control theory and practical implementation of a power control circuitry in a GSM mobile phone transmitter. Loop type, gain, bandwidth and stability have been discussed linked with a number of specific mobile radio design considerations. The proposed control loop design has been implemented using an Agilent ACPM-7891 E-pHEMT PA. Output power is controlled in 2-dB steps across the required range and power level variations under extreme conditions are well within specified tolerances.

The following table summarizes the results under nominal and extreme conditions:

SAMPLE_#1
Frequency = 900MHz
Nominal Vbatt = 3.6V
Use of feedback temperature compensation design

	Pout (dBm)			
Temp	**Vbatt: 3V**	**Vbatt: 3.6V**	**Vbatt: 4.2V**	**Max dB variation**
+55	33.1	34	34.22	0.9
	25	25.15	25.24	0.15
	9	9.7	10.2	0.7
+25	33.22	34.01	34.18	0.79
	24.8	24.94	25.01	0.14
	7.8	7.4	9	1.6
-20	33.36	33.97	34.09	0.61
	24.3	24.44	24.52	0.14
	3.5	4.7	5.3	1.2

SAMPLE_#1
Frequency = 1800MHz
Nominal Vbatt = 3.6V
Use of differential temperature compensation design

	Pout (dBm)			
Temp	**Vbatt: 3V**	**Vbatt: 3.6V**	**Vbatt: 4.2V**	**Max dB variation**
+55	30.14	30.91	31.2	0.77
	21.96	21.91	21.98	0.07
	2.2	4.1	4.7	1.9
+25	30.24	31.04	31.35	0.8
	22	21.98	22.05	0.07
	2.9	4.6	5.1	1.7
-20	30.38	31.33	31.69	0.95
	22.07	22.02	22.1	0.08
	3.2	4.9	5.4	1.7

Table 2: Measured Performance Of Demonstration GSM Mobile Transmitter Designs: Using Feedback And Differential Temperature Compensation