Control Loop Design for GSM Mobile Phone Applications

White Paper

Control of output power level on GSM mobile phones

Why do we need to control the output power level of mobile phones? There are a number of very good reasons: to prevent intermodulation of base station receivers, to prevent interference with other mobile phones and to minimize power consumption depending on the distance between mobile and base station.

The 3GPP GSM standards body defines GSM specifications in the TS 45.005 Radio Transmission and Reception technical specification. This document specifies the nominal output power levels and accepted tolerance of GSM mobile transmitters under nominal and extreme conditions. The nominal conditions refer to ambient temperature with nominal voltage supply and the latter refers to a combination of extreme values of voltage and temperature. The radio transceiver operating voltage for most components in the current mobile phone technology is 2.8V, set by voltage regulators operating from the phone battery. However, the PA needs to be connected directly to the battery, as a higher level of DC current is required to deliver the necessary output power. Therefore it is battery response that determines the PA extreme voltage conditions. As an example, GSM TS specifies that three NiCd battery cells with a nominal 3.6 V should have a minimum tolerance of -0.36 V. With regards to temperature variations, GSM TS specifies conditions between –20 and +55°C.

Control of output power level is done in 2 dB steps. The normal maximum output levels for GSM handset mobile station are 33 dBm for GSM 850/900 MHz and 30 dBm for 1800/1900 MHz. Dynamic range of power control is 28 dB for the 850/900 MHz band and 30 dB for the 1800/1900 MHz band. See the table below for power levels and characteristic tolerance values.

How the PA output power level is determined

Mobile phone manufacturers, in order to comply with specific network operator demands, may tighten up their internal system specifications for power control. Also the requirement for longer battery life-time drives mobile phone designers to keep output power levels as close as possible to the nominal values.

System specifications such as noise performance and gain need to be partitioned and assigned to the different components of the transmitter chain. With the current transmit architecture and technology; 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. It is therefore assumed that the PA needs to provide an output power level 2 dB higher than the system reference requirements to compensate for the loss between the PA and the antenna.

The required mobile output signal strength is determined by the distance between the mobile and the base station and to a certain degree by the 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 mobile output power level is set by a voltage controlled variable gain power amplifier. The mobile controller checks required output power level against a look up table containing the corresponding PA voltage levels that are written into the look up table at the alignment stage of the phone manufacturing process. Based on the data taken during alignment, different voltage levels are sent by a DAC to the voltage controlled PA. Voltage values are fixed at this stage for nominal conditions.

GSM Standard: 3GPP TS45.005 Mobile station output power specification

Power Control Level (dBm)			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 dB	±2,5	±4	±2,5 dB
3	31	31	37	32	32	±3	±3	±2 dB	±4	±4	±2,5 dB
4	0	0	35	30	30	±3	±3	±3 dB	±4	±4	±4 dB
5	1	1	33	28	28	±3	±3	±3 dB	±4	±4	±4 dB
6	2	2	31	26	26	±3	±3	±3 dB	±4	±4	±4 dB
7	3	3	29	24	24	±3	±3	±3 dB	±4	±4	±4 dB
8	4	4	27	22	22	±3	±3	±3 dB	±4	±4	±4 dB
9	5	5	25	20	20	±3	±3	±3 dB	±4	±4	±4 dB
10	6	6	23	18	18	±3	±3	±3 dB	±4	±4	±4 dB
11	7	7	21	16	16	±3	±3	±3 dB	±4	±4	±4 dB
12	8	8	19	14	14	±3	±3	±3 dB	±4	±4	±4 dB
13	9	9	17	12	12	±3	±4	±4 dB	±4	±5	±5 dB
14	10	10	15	10	10	±3	±4	±4 dB	±4	±5	±5 dB
15	11	11	13	8	8	±3	±4	±4 dB	±4	±5	±5 dB
16	12	12	11	6	6	±5	±4	±4 dB	±6	±5	±5 dB
17	13	13	9	4	4	±5	±4	±4 dB	±6	±5	±5 dB
18	14	14	7	2	2	±5	±5	±5 dB	±6	±6	±6 dB
19-31	15-28	15	5	0	0	±5	±5	±5 dB	±6	±6	±6 dB

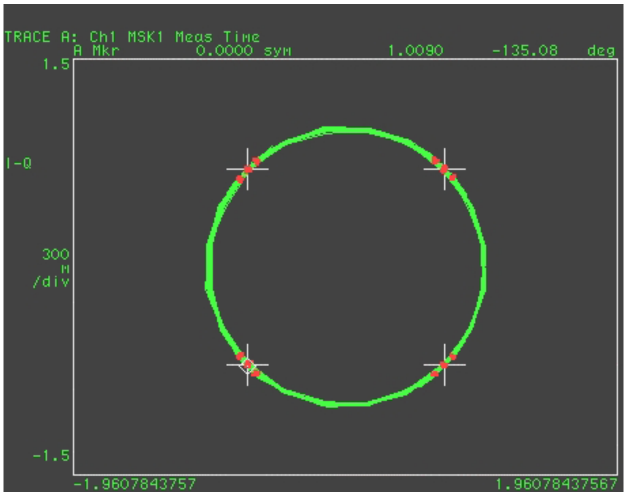
Theoretically, enough statistical knowledge of the performance of the transciever under extreme conditions might enable DSP processing to compensate for all conditions. Accurate sensing of operating temperature and battery voltage, minimal performance variations between component batches and a good understanding of the degradation of component performance during the lifetime of the transceiver would allow such compensation from the DSP routines to be programmed into the phone software.

However, mobile phone design is a very fast paced, evolving environment where components with better performance are continuously being introduced. This makes it almost impossible to compile enough statistical knowledge to build DSP algorithms to compensate for all possible variations. Consequently, software alone cannot possibly control the output power level in extreme conditions and compensate for different transmitter component tolerances. Specifically voltage controlled power amplifiers have, even under typical operating conditions, significant differences between units in their response to voltage control level. The generalized solution is to achieve output power control using feedback hardware circuitry. In order to do to do this, we first need to have good understanding of how a GSM radio transmitter works.

GSM system interface overview with characteristic figures of merit

GSM frequency bands are divided into 200 kHz channels: the European 890 to 915 MHz transmit and 835 to 960 MHz receive band each has 124 channels: each transimission takes place on a 200 kHz-wide Tx and Rx channel spaced at 45 MHz. GSM is a time division multiple access (TDMA) system, where the data in every channel is packed in successive frames lasting for 4.615 ms. Each frame is divided in to eight time slots which can be used by up to eight different mobiles, with each of the mobiles using one out of the eight available time slots in the frame. It is not a full duplex system, meaning that the transmit and receive signals do not happen at the same time. Allocation of time slots to different mobile stations is done making sure that Tx and Rx do not overlap on the same channel. Frequency hopping enables consecutive time slots or ‘bursts’ of the same mobile to be carried on different RF carriers. With the implementation of GPRS, one mobile communication may use a larger number of timeslots in its channel. The system will enable different numbers of timeslots to be used for each mobile on the up link and down link channels, greatly increasing the capacity of the system.

Every time slot lasts for one eighth of the duration of the frame, this is approx 577 µs. The data bit rate of the system is 270.833 kb/s using a Gaussian Minimum Shift Keying, GMSK, modulation scheme. This scheme is a type of FSK where the peak frequency deviation (“mod index” x “modulation frequency”) is one fourth of the data bit rate, hence the modulation will shift the frequency 270.833/4=67.708 kHz above and below the carrier frequency. As the fundamental frequency of a binary square wave is equal to one half of the bit rate, this is will be achieved by having a modulation index of 0.5 rad. Under these conditions, with the modulator sampling phase at the bit rate, the frequency shift can be represented as a phase shift of $\pm\pi/2$. Every symbol in the polar diagram can be represented by one transition bit only. A phase shift of +90 degrees on the carrier represents data bit ‘1’ and a phase shift of –90 degrees represents data bit ‘0’. In order to limit the broad signal spectrum generated by fast phase transitions, GSM uses a Gaussian premodulation filter with BT index 0.3 (BWxT=0.3: filter BW is 0.3/T = 0.3 x Br = 0.3x270.8 = 81.25 kHz). A screen capture of the polar diagram of a GMSK modulation signal is shown below.

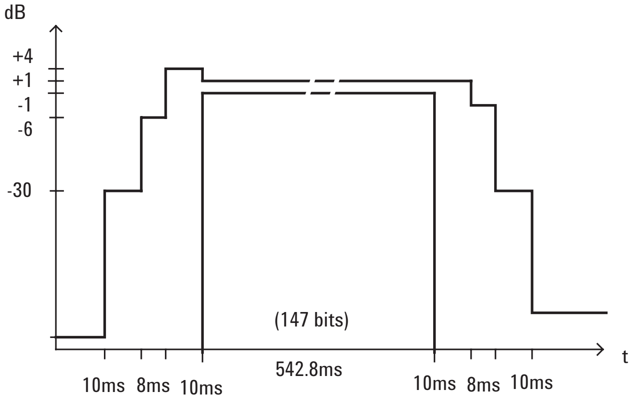


Speech and signaling data is encoded and interleaved to partition the data into the TDMA structure. Every 20 ms of speech is digitized and coded with an effective bit rate of 13 kb/s. The data is then is convoluted and interleaved into the corresponding TDMA timeslot. At the end, the effective GSM data rate will be of 9.6 kb/s after discounting all the coder configuration overheads of around 27%. With the introduction of GPRS the system has the capability of using variable coding schemes ranging from 8.8 kb/s to 17.6 kb/s. This, together with the characteristic multi slot operation with up to five timeslots used in the same frame, has enabled GPRS to achieve data rates of up to 80 kb/s.

It is also relevant to mention that effective data rate and channel BW are not the only factors that determine the capacity of a cellular mobile communications system. Its performance will also be dependent on the required C/I (carrier-to-interference) ratio for required system BER (Bit Error Rate) and the cellular system frequency reuse factor of the network.

GSM Transmit signal characteristic

Every timeslot or 'normal burst' needs to fit in the following time/power mask, with its controlled amplitude level ranging between +5 to 33 dBm, at EGSM bands. Therefore the requirement is for 28 dB of effective dynamic range at the different output power levels. The spectrum of the signal within its BW, referred to the noise floor or residual output power, should be –59 dBc or –54 dBm, whichever is the greater.



Time mask for normal duration bursts at GMSK modulation.

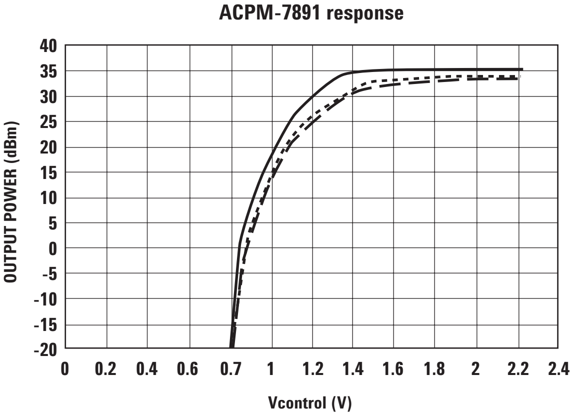
GSM Transmiter architecture: Offset Phase Locked Loop (OPLL)

The GSMK constant envelope modulation scheme, together with today's more-efficient saturated power amplifiers, enables the use of a relatively simple offset PLL transmit architecture. The carrier frequency is modulated without the need for an up conversion mixer. Modulation information is on the phase content of the IQ modulator output. The phase detector output of the offset phase locked loop is a phase modulated constant amplitude signal with a fixed offset voltage (corresponding to the VCO RF carrier frequency). This signal contains the phase modulation information and drives the TX VCO. Input to the PA is a noise 'clean' signal from the low phase noise VCO. The noise floor of the system is therefore determined by the intrinsic PA noise performance. Noise limiting band pass filtering at the PA input or output is not required. This allows the use of a low-loss post-PA output architecture, the only filtering requirement is for a LPF to prevent harmonics from affecting receivers in nearby mobile phones. A block diagram of an OPLL circuit is shown below.

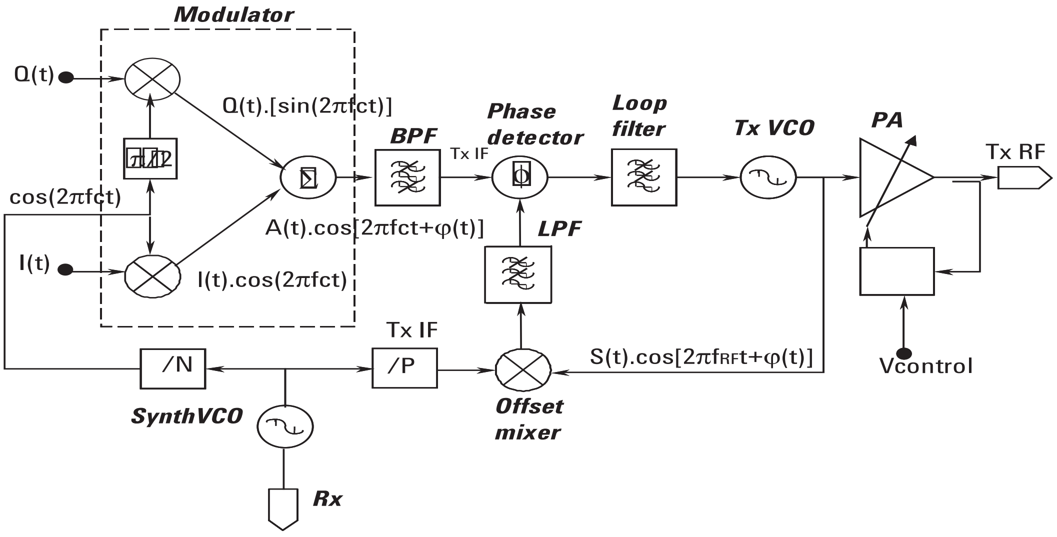
The output of the TxVCO will typically have a tolerance of ±2 dB with typical nominal output power level of around +5 dBm. At this stage the RF carrier with the modulation information is ready to be amplified by the PA. With a PA input power level of around 0 dBm, the power control loop requirement is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

Voltage controlled PA

In order to illustrate the response of a GSM PA, we have plotted the actual response of the Avago Technologies ACPM-7891 Tri-Band PA for the GSM, DCS and PCS bands versus control voltage. The input to the PA would be a GMSK modulated RF carrier of constant power level of 0 dBm and the PA maximum output level is of around 35 dBm. Input RF carrier and V_{apc} 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 graphs clearly reflect the characteristic output power with the output power response of the PA against voltage control demonstrating a steeper slope at lower power levels and flat gain response when the PA enters saturation.



A relevant characteristic of the Avago Technologies ACPM-7891 is the dynamic range of approx 0.8 V between 0 and +35 dBm output power level. Any control loop system will require a high level of discrimination in V_{apc} in order to accurately set the correct output power level. This is a challenge for the design of the power control loop as a few millivolts may well represent a change of power level. Further more, at low power levels the discrimination of Schottky diode power detectors is at its lowest making the resolution even smaller.



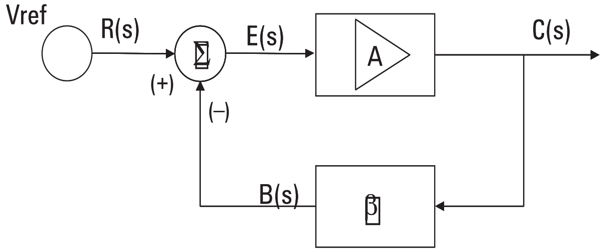
Control loop theory

Automatic gain control (AGC)

AGC is widely used in communication systems to maintain constant signal strength. As mentioned previously, changes in performance of each individual PA, tolerances in different components of the transmitter chain, supply voltage variations and changes in performance across frequency, are all intrinsic to the system at a nominal temperature. Some of these factors will be taken into account when the phone is being aligned during production. However, the main purpose of the alignment is to set a look up table of voltage values corresponding to different controlled power levels. Generally changes of power level across supply voltage and frequency range will *not* be calibrated in the phone alignment process. Mobile phone power level performance under extreme conditions of voltage and temperature is left to guaranteed component tolerances and to the automatic gain control loop circuitry.

Gain Control loop theory

A typical AGC loop is a feedback system comprising a forward gain stage (A), feedback gain (β) and a signal comparison stage that generates a differential error signal. 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:
Close loop gain: $C(s)/R(s) = A/(1+A\beta)$
Open loop gain: $B(s)/R(s) = A\beta$,
Characteristic equation: $1/(1+A\beta)$

Response of an AGC loop to the system output amplitude fluctuations –changes in C(s) value- depends on its closed loop transfer function since the R(s) reference signal will represent a fixed characterized value at every output power level. Variations in the forward gain value (A) due to voltage supply, operating temperature or drive 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 question for the loop designer is to obtain a model of the response of A in order to determine β so that the system keeps C(s) constant while meeting control loop stability criteria (those criteria are discussed later).

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

Typical PA gain in the frequency domain:

$$\frac{Vs(w)}{Ve\ (w)} = \frac{A(Vapc)jw}{1+j\,\frac{w}{w_a}}\ ;$$ with its pole at $w = w_{a.}$

The design of β, in addition of 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 of the loop type. Each integrator within the loop will add a pole:

In the frequency domain:

$$\frac{Vs(s)}{Ve(s)} = \frac{1}{1+RCs} = \frac{1}{1+RCjw};$$

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' (jw) that make the denominator of the closed loop transfer function equal to '0' (notice that 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, it can 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 *type 1* loop which needs one integrator in the open loop transfer function and amplitude variations following a **parabolic** function will characterize a *type 2* loop which would need two integrators.

It is important to note that 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 described with a step function model. In such cases, no integrator is required in the feedback transfer function (β).

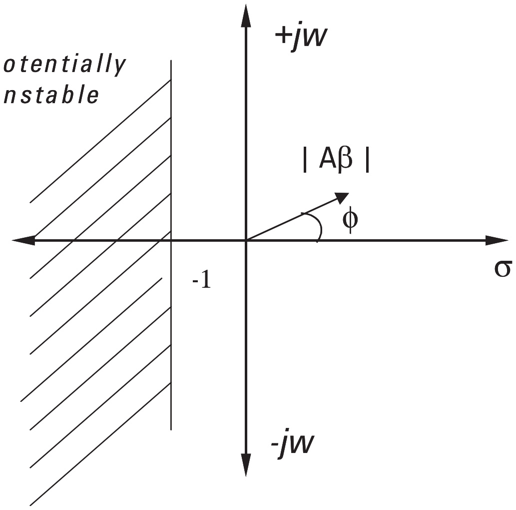
The loop design exercise will then be mainly about the implementation of the comparator. Once the transfer function of the comparator is determined, an adequate op-amp implementation can be selected to meet the characteristic loop gain and speed requirements.

Basic stability theory

Some basic principles of stability theory are described below.

Control theory uses the root locus plane to represent the zeros and poles of the open loop transfer function Aβ: it can be represented as module and phase components $A\beta = (\sigma + jw)$. Vector positions across the frequency spectrum will determine whether the system is potentially unstable at any frequency. The control loop system will be unstable when the following conditions are met:

$$\left.\begin{array}{l} |\sigma| > 1 \\ \phi \cong \pi \end{array}\right\}; \quad \phi = \text{arctn}\,(w/\sigma)$$



Graphically represented in the locus plane

The criterion for unconditional stability is that the module of the open loop gain Aβ must be less than unity (0 dB) when the phase of the open loop gain is equal to π. This is the Nyquist stability criterion. However it is difficult to obtain reflect transfer function of non-linear elements as power amplifiers and power detectors. We may get S_{21} figures of a PA at a certain V_{apc}, but a mathematical model of gain against frequency can only be obtained by mathematical curve fitting models. Control loop theory traditional analysis is therefore somewhat unpractical.

Bode diagrams are used in telecommunications in order to determine how close a system is to being unstable. This represents the logarithmic module and phase against frequency of the open loop transfer function by giving a graphical representation of Phase and Gain Margins.

Phase Margin (PM) = $\pi + \phi(w_0)$

Gain Margin (GM) = $-20 \log |A\beta\ (\phi=\pi)|$

Stability requires PM > 0 and GM > 1. It is generally accepted that any system needs to be designed in principle with a minimum GM = 10 dB and PM = 45 degrees. In *Type 1* control loops, the presence of two poles in the transfer function with no zeros compensating each pole phase shift, will add two $\pi/2$ degrees of phase shift. At certain frequencies the PM will therefore be $\pm\pi$ and make the system unstable. It has to be remembered that although the mobile phone control loop is of *Type 0*, the presence of a LPF to limit the loop BW will add an integrator to the system. Stability needs therefore to be monitored as the power amplifier transfer function may have phase shift across some specific frequencies that could potentially cause instability.

It is possible to represent S_{21} magnitude and phase values across frequency and to determine graphically the phase margin at GM=1. Values below $\pi/4$ will indicate that in higher frequencies the system is potentially unstable.

Power Sampling in a GSM mobile phone control loop

Control loop design issues need to be linked to a specific mobile transmitter radio design architecture. The first step therefore should be to identify the ideal control loop model with the components of the radio transmitter used in mobile phone applications. There are three main factors than need to be taken into account:

a) Output and feedback mobile radio signals are at radio frequency while 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. Those models are not discussed in this document.)

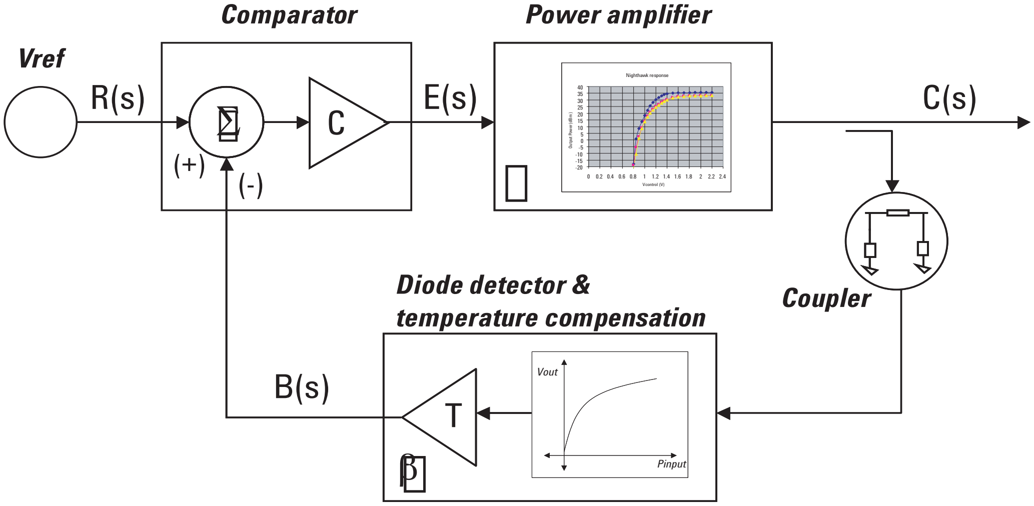
b) The control loop system requires a mechanism to convert the RF feedback into a DC signal to be compared against the reference. A typical power sampling schemes use diode detectors that are intrinsically non-linear (other linear detector techniques like logarithmic detection can also be used with added complexity).

c) Gain non-linearity of the power amplifier under different $V_{reference}$ control conditions and Schottky diode detector non-linear characteristic performance.

The block diagram below identifies the ideal control loop components with those used on a mobile phone. There is a gain stage in the comparator (*G* in diagram*)* and temperature compensation at the detector diode stage (*T* in diagram) for the diode detector V_f variation against temperature.

Loop Gain and Bandwidth

The objective of the loop is to compensate for any variations at the power amplifier (A) due to changes in performance, temperature or voltage supply under the presence of a fixed voltage reference level ensuring that the output power level C(s) is constant. This has to be achieved for a number of power steps or fixed V_{ref} levels. The non-linear PA and detector diode response causes a variation of the closed loop gain C(s)/R(s) at different output power levels: from a factor of 1 for output power level of +5 dBm to a factor of 6 for output power level of +33 dBm. Those non-linearities of detector and power amplifier 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 V_{ref} voltage control source (DAC on the mobile phone controller) needs to be enough for the system to meet tolerance requirements in 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 fall within a defined time mask. The rise and fall of the envelop of any RF carrier will generate transient spurious responses. These need to be kept under certain limits, hence it is necessary to 'shape' those profiles in order to minimize the spurious emissions. The V_{out} reference DAC output splits the 28 µs of allocated time for the profiles into a number of amplitude 'towers' or registers. Commonly there are sixteen registers, each lasting 1.75 µs. Therefore the system will require a bandwidth of approximately twice the sampling speed of 571 kHz. Loop bandwidth of 1–1.2 MHz are commonly accepted. This needs to be taken into account by the loop design because there is a need for limiting the loop BW and consequently reducing feedback signals to the PA control input. A loop filter will therefore be added to the system.

Control Loop components

The required dynamic range of the control loop, wide non-linearity 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 a interesting challenge. Three elements need to be correctly specified:

- **Diode detector**

To maximize its dynamic range over the required power input level, it is necessary to determine a diode's optimum bias, and to select an optimum coupler-coupling factor and adequate 50Ω termination at the diode input. The output load should set the optimum diode current. RF decoupling capacitors at the diode output will remove any RF signal and its harmonics.

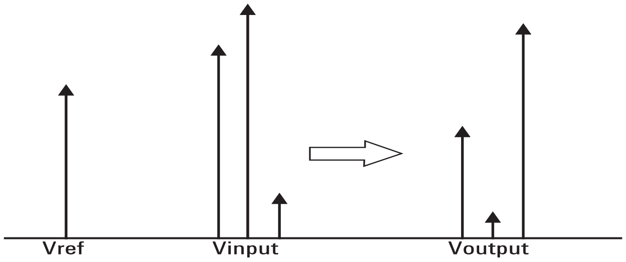
- **Temperature compensation**

There is a strong temperature dependency of the detector diode junction resistance (R_j) and consequently with the forward voltage drop (V_f). 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 a second identical diode operating under the same bias conditions as the RF detector. Temperature compensation of the offset term (RF detected) is obtained if the bias current of each diode is equal. Different compensation circuits can be used with those diodes, but the basic concept for compensation is to use the identical V_f variation in temperature of one diode to compensate for the variation in the other diode.

Two different temperature compensation schemes have been used experimentally in an Avago Technologies control loop demo board. One control loop uses a differential model (900 MHz control loop) and the other one use 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 level 17–19.

- **Comparator stage**

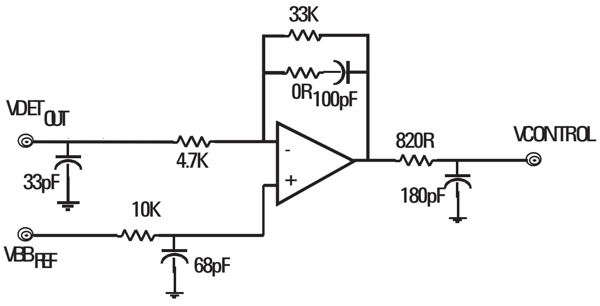
The desired response of the comparator can be easily understood by using a graphic example. For a given V_{ref} and three possible comparator voltage input signals, the output wanted signals should correspond one to each other as per the diagram:



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

$V_{out} = (V_{ref} * R_f / R_n) + V_{ref} - (V_{input} * R_f / R_n)$.

Appropriate values are given to R_f and R_n to achieve the required signal gain. Below is a proposed design for a GSM comparator used in a discrete control loop demoboard designed at Agilent.



Conclusion

GSM transmitter system has been explained together with a description of gain control closed loop theory and practical implementation of power control circuitry for a 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 with excellent results using Avago Technologies E-pHEMT power amplifier ACPM-7891. 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 tables summarize the results under nominal and extreme conditions.

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

	Pout(dBm)			
Temp.	V batt: 3V	V batt: 3.6V	V batt: 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 feedback temperature compensation design

	Pout(dBm)			
Temp.	V batt: 3V	V batt: 3.6V	V batt: 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

5989-0047EN - May 9, 2006