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A high-efficiency RF transmitter using VCO-derived synthesis: CALLUM

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Abstract

The combined analogue locked-loop universal modulator (CALLUM) is an RF transmitter topology which produces a linear output through the use of non-linear but highly efficient RF power amplifiers. This is achieved through careful phasing of two constant-envelope vectors, each derived from voltage-controlled oscillators. The system up-converts and amplifies a baseband signal within a closed-loop feedback scheme. The optimal CALLUM system requires complex baseband processing, but a simplified version, known as CALLUM2 can be implemented using simple analogue circuitry. This paper provides some insight into the behaviour of such systems and gives results from an experimental CALLUM2 system in response to a modulating signal compatible with that used in the TETRA standard.

Introduction

The ever-increasing use of mobile communications equipment has necessitated the use of spectrally efficient modulation schemes such as $\pi/4$ -QPSK. Such schemes require a linear transmitter to preserve the trajectory of the complex signal, thereby confining the transmitted power to a well defined bandwidth and not causing interference in adjacent channels. Whilst reasonable levels of linearity can be achieved from class A amplifiers, such arrangements are not power efficient and therefore are unsuitable for use in hand-portable equipment. Existing solutions for producing linear, power efficient transmitters involve using an amplifier stage of increased efficiency such as class C and then attempting to linearize the resulting output. Several linearization techniques exist, the most common of these being Cartesian loop, feedforward and predistortion. A more radical approach to producing a high efficiency, linear transmitter is to use the combined analogue locked-loop universal modulator (CALLUM). Unlike other systems, CALLUM offers the potential of ultra-high power efficiency nearing 100%. Clearly, such a transmitter would find extensive use in hand-portable (i.e. battery-operated) systems.

The CALLUM system produces a linear, high-level RF output signal in the same manner as the LINC (linear amplification with non-linear components) method proposed by Cox [1]. An arbitrary input signal varying in phase and amplitude is decomposed into two constant-envelope signals (fig. 1) which can each be amplified by grossly non-linear, but highly efficient amplifiers and

then recombined at high level to synthesize the required output. The constant-envelope signals are derived from two voltage-controlled oscillators (VCOs). The original LINC system operated in an open-loop configuration and was sensitive to small gain and phase imbalances in the two component arms. The CALLUM system has a closed-loop topology and can continually correct for such imbalances. It is a complete transmitter scheme which both upconverts and linearly amplifies a baseband signal represented in Cartesian form, within a closed-loop system. Due to the closed-loop, high gain nature of this arrangement, the system is inherently narrowband. The bandwidth of the system is defined by the dominant poles and time delay around the loop which will eventually cause instability at higher loop gain levels.

Figure 1: Decomposition of the input signal into two constant-envelope component signals.

System Description

In the generic form of CALLUM proposed by Bateman [2] the two VCOs are driven with the error signal generated by comparing the input and downconverted Cartesian components (fig. 2). This system is not stable for all input phases, however stability can be guaranteed if a sign-switching matrix is employed [3]. Unfortunately, this modified version suffers from discontinuities when the input signal changes from one quadrant of the complex plane to another.

Figure 2: General CALLUM topology

A much improved version of CALLUM was subsequently proposed [4] which is stable for all input phases and does not suffer from discontinuities. The resulting system, known as CALLUM1, performs continual phase rotation and amplitude normalisation for optimal dynamic performance. To implement CALLUM1, the VCOs must be excited with control signals derived from functions of the baseband input signal and error signal vectors (plus known system constants):

$$\begin{aligned} v_1 &= k\Delta x \left[\frac{-x}{cr\sqrt{4R^2 - r^2}} - \frac{y}{cr^2} \right] + k\Delta y \left[\frac{x}{cr^2} - \frac{y}{cr\sqrt{4R^2 - r^2}} \right] \\ v_2 &= k\Delta x \left[\frac{x}{cr\sqrt{4R^2 - r^2}} - \frac{y}{cr^2} \right] + k\Delta y \left[\frac{x}{cr^2} + \frac{y}{cr\sqrt{4R^2 - r^2}} \right] \end{aligned}$$

Eq. (1)

where x and y are the Cartesian components of the input signal, Δx and Δy are the corresponding error signals, c is the VCO sensitivity, k is the loop gain, r is the input signal envelope and R is the magnitude of the two VCO vectors. Implementing these equations is not easy; a practical method of generating v_1 and v_2 might be to employ a DSP. This would be feasible because the bracketed terms of (1) can be generated outside of the feedback loop, thus minimizing the effect of time delay on loop stability. It should be borne in mind however

that although the baseband input signal would typically be of the order of 20kHz, the non-linear nature of (1) can result in terms which have a bandwidth many times this figure. For a $\pi/4$ -DQPSK signal a ten-fold expansion can be expected. The closer to the complex origin that the input signal trajectory passes, the greater the bandwidth expansion.

Fortunately, CALLUM1 can be simplified and the need to use a DSP removed completely. If the denominators of equation (1) are ignored, then a version called CALLUM2 results. This is also stable, but unlike CALLUM1, its tracking performance degrades as the envelope of the input signal reduces. This is because loop gain (which directly affects tracking performance) is effectively reduced when the envelope becomes small (less than unity). When considering small step changes in the phase (or amplitude) of the input signal, the system can be considered first order and has a time constant equal to $1/k$. In terms of linear control theory, the system may be modelled as an integrator block with a unity-gain feedback path (fig. 3) when considering either phase or amplitude response. The resulting closed-loop transfer function is therefore:

$$G_{CL}(s) = \frac{k}{s + k} \quad (\text{Eq. 2})$$

which gives rise to the time constant of $1/k$. In the case of CALLUM2, the k in fig. 3 is replaced by kr^2 .

Figure 3: Linear model of CALLUM1 in response to a step change in phase

Tracking performance at low envelope levels is increased by the use of more loop gain, but at higher envelope levels the increased loop gain is likely to cause instability. A compromise between expected minimum/maximum envelope levels and loop gain has to be reached to obtain the best performance. In the case of CALLUM1, tracking performance is the same for any input envelope level (so long as the envelope level stays within the *synthesizable range* of $2R$ i.e. when the two components sum together in-phase. This is a fundamental condition for any LINC system). The level of loop-gain applied to the system also defines the maximum frequency component to which the system can lock [4], for CALLUM1 this is given by:

$$f_{\max} = \pm \frac{k}{2\pi r} \sqrt{4R^2 - r^2} \quad (\text{Eq.3})$$

and for CALLUM2,

$$f_{\max} = \pm \frac{kr}{2\pi} \sqrt{4R^2 - r^2} \quad (\text{Eq.4})$$

In the case of CALLUM1, small envelope levels result in high values of $f_{\max}$, the opposite is true for CALLUM2. Although lock may be achieved for frequency components less than $f_{\max}$, a large tracking error may exist and hence poor output linearity.

Hardware Implementation of CALLUM2

The CALLUM2 system can be implemented entirely in the analogue domain, as the two VCO control signals can be generated easily using standard 'linear' components. The structure of CALLUM2 is shown in fig. 4. The system was designed to operate at 220-240 MHz, although the choice of centre frequency is arbitrary as this has no affect on the baseband signal processing design. The core signal processing block is the multiplying matrix which was implemented using four Analog Devices AD-835 wideband multipliers. The error signal is generated using Analog Devices AD-830 differential amplifiers, as are the terms $x+y$ and $x-y$ (the AD-830 can be configured for resistorless summation). The $x+y$ term can be easily inverted to generate $-x-y$ as the AD-835 has differential inputs. The RF section includes the VCOs, non-linear power amplifiers, power combiner and downconverter.

Figure 4: The structure of CALLUM2

Power modules: The PAs are Mitsubishi FM modules which operate at approximately 45% efficiency with a gain of 36dB (maximum output power = 7W).

Power combiner: Wilkinson type, constructed using two quarter wavelength, 75Ω co-axial cables lengths (ideally, this should be 70.7Ω) with a 100Ω load resis-

tor. The resistor must be adequate to dissipate all the power from the two PAs; when the synthesized envelope is very small the component signals sum whilst approaching anti-phase, the unwanted power must be dissipated in this load resistor. The power combining process is problematic, the power loss increases as the phase angle increases, ultimately dissipating all the power in the internal load when the signals are in anti-phase. A solution to this problem might be to use a summing-switching amplifier arrangement or by using a voltage summation method. It may be possible to use an RF operational amplifier if only modest output power is required.

Downconverter: This uses two Mini-Circuits TUF-1 mixers to effect direct quadrature downconversion. The LO is split into quadrature components using a Mini-Circuits PSCQ-2-250. The IF output (baseband in this case), is then amplified using operational amplifiers. These amplifiers have variable gain and a DC offset adjustment so that compensation can be made for any quadrature gain/phase imbalance.

VCO: This is the main element of the CALLUM system. At first, the VCOs were implemented using the DC-FM facility of two RF signal sources. The limited modulation port bandwidth of these sources (approximately 100 kHz) resulted in a low frequency pole in the feedback loop, causing instability at modest loop-gain levels. The onset of oscillation was signalled by an increase in the noise skirt at ± 90 kHz either side of the centre frequency. To improve the bandwidth of the system and to allow the use of more loop-gain, the signal sources were replaced by Z-COMM 930MHz VCOs. The output of the VCO is divided by a factor of 4 using a prescaler, this decreased the tuning sensitivity from 8 to 2 MHz/V and also improved phase noise performance. The sensitivity of the VCO directly affects loop gain; 2 MHz/V is equivalent to a loop-gain of 2,000,000. To set the free-running frequency and to allow a bipolar control voltage, the VCOs were biased by summing in a DC level. During set-up, this level is adjusted so as to have a free-running frequency which is the same as that of the intended LO. It is essential that the VCOs are DC-coupled for the system to operate. The tuning port bandwidth of these VCOs is in excess of 50 MHz and so shouldn't limit system stability. The output of the VCO is adequately buffered (to prevent undesired loading effects) by a series attenuator followed by a MMIC amplifier stage. The overall output power of the complete VCO blocks (including prescaler) is -6 dBm. The output of each PA is therefore approximately 1W.

A source of low frequency poles are the operational amplifier stages in the downconverter. Devices with high gain-bandwidth product were used so that the bandwidth

of the system could be made as large as possible. Loop gains twenty times greater could now be achieved, until oscillation at ± 3 MHz ensued.

The entire system is locked to the LO reference, therefore changing the transmit channel becomes a simple matter of changing the LO frequency to the new channel. The new channel must, however, be well within the linearization bandwidth of the system. For example, if a 1kHz tone was being transmitted, the tone would appear at $f_c + 1\text{kHz}$. If the LO was changed to $f_c + 10\text{kHz}$, then the system is then effectively attempting to track a tone of 11kHz which demands more loop gain for the same tracking performance. If the VCO free-running frequency were also changed to the new channel frequency then the system would revert back to tracking a 1kHz tone and have the associated benefit of better tracking performance.

Results from the hardware system show that linearity is good enough to achieve the transmission masks for most modulation formats including TETRA (trans-european trunked radio) so long as adequate stable loop gain can be provided. TETRA employs $\pi/4$ -DQPSK modulation at a data rate of 18kBaud with a filter alpha of 0.35. When excited by a TETRA modulation signal, the output spectrum shown in fig. 5 results. This figure also shows the spectrum of one of the two wideband, phase-modulated component signals. When these signals are summed, frequency components outside of the complex modulation bandwidth combine in anti-phase and cancel, leaving the desired linearly amplified output.

Figure 5: CALLUM2 output and component spectrum for a TETRA-type modulation input ($\pi/4$ -DQPSK, 18kHz, $\alpha=0.35$)

Conclusions

The CALLUM system provides a method by which highly efficient, switching-type non-linear RF power amplifiers can be used to generate a linear output. The potential of very high power efficiency from these sys-

tems makes them particularly suited to battery-operated, mobile applications. Overall system efficiency is however limited at present by power combining methods. Due to its closed-loop nature, CALLUM is particularly suited to narrowband systems such as TETRA or D-AMPS. The optimal CALLUM1 system requires non-linear calculations to be performed to obtain the ideal VCO control voltages. If these non-linear operations are ignored, a simplified system known as CALLUM2 results. This version can be implemented using simple analogue components, but suffers from poor tracking performance at low envelope levels. This is due to the dependence of loop gain on envelope level. If the envelope of the modulation signal does not vary over a wide range (as is the case with $\pi/4$ -DQPSK) then CALLUM2 can be particularly effective. The optimal CALLUM1 system has constant loop gain over the entire permissible envelope range and is therefore capable of tracking input signals whose envelope drops to very low values. If the envelope falls to zero, as is the case with a standard two-tone test then a discontinuity will occur, resulting in wideband distortion products. This applies to LINC systems in general, apart from those which use more than one component signal.

Further Work

To fulfil the potential of the CALLUM technology, a power efficient combining method must be sought, this is currently being researched. The optimal CALLUM1 system is currently under development by the authors and should give improved linearity, particularly with input signals with large envelope variations.

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