Pulse-length modulator for analogue-to-digital conversion of radio frequency signals

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Abstract—Modern communication systems require amplifiers with excellent linearity and, at the same time, an efficiency as high as possible, especially for mobile applications. Switch-mode amplifiers seem to be suitable to meet these constraints. Such an amplifier cannot be driven by the radio frequency signal itself, but requires a 1-bit analogue-to-digital conversion. Beside the commonly used sigma delta modulation, pulse-length modulation can be applied, too. In this paper, we present an approach for an all-analogue pulse-length modulator for a working frequency of 250 MHz. Challenges of the design are identified and possibilities for further improvements proposed.

I. INTRODUCTION

Switch-mode amplifiers have commonly been used in power amplifiers at audio frequencies for many years, as they combine very high efficiency (about 90%) and excellent linearity, in contrast to conventional class-AB push-pull amplifiers. These features make the application of a switch-mode architecture very attractive for RF-power amplifiers also, where efficiency rarely exceeds some 30%. Only with class-C, class-D, or even more sophisticated architectures it has been possible to approach efficiencies around 75% at radio frequencies [1]. However, the use of these architectures is limited to RF-signals with constant envelopes, which seriously limits the choice of modulation schemes, especially if high spectral efficiency is required. A class-S-switch mode amplifier enables the amplification of signals with randomly varying envelopes without the application of complex envelope elimination and restoration (EER) techniques, necessary for the use of conventional switch-mode-amplifiers like class-E [2]. On the other hand, a drawback of a class-S-amplifier is that the RF-signal cannot be amplified directly, but has to be digitised in an appropriate way. Until now, bandpass delta modulators (BDSM) have been applied for this purpose. The BDSM concept inherently suffers from stability problems and high quantisation noise levels outside the operating bandwidth. To achieve bandwidths substantially greater than 15 MHz, the loop filter becomes complex. To avoid such difficulties, we have investigated a pulse-length modulator (PLM) at radio frequencies. This concept has been used for a variety of applications at lower frequencies, for several decades. The PLM avoids the above mentioned drawbacks completely, as there are no stability problems and, particularly if implemented as an analogue modulator, no quantisation noise in the output signal. Another advantage of the pulse-length modulator is its relatively simple architecture, which also clearly distinguishes it from a bandpass sigma delta modulator.

II. REALISATION OF THE PULSE-LENGTH MODULATOR

Figure 1 sketches the principle of a classical pulse-length modulator. It consists of a comparator as a key component, driven at one input by a reference signal (e.g., a sawtooth), and at the second input by the signal of interest. At its output, the comparator provides a pulse-length modulated signal, whose polarity depends on the application of the reference signal to the inverting or non-inverting input. In principle, the pulse-length modulator converts the amplitude of the input signal to a corresponding duty cycle of its output signal.

![Fig. 1. Principle of a pulse-length modulator, realised with comparator and sawtooth signal.](Image)

A sawtooth signal has the disadvantage that the steep falling edges occupy a very broad bandwidth, which makes it difficult to generate and handle such signals at radio frequencies. To moderate this problem, it is possible to use a triangle signal instead, which significantly reduces the required bandwidth. The simplest way to generate a triangle signal is the use of the charge function of a RC-network. If the RC-network is driven by a rectangle signal and its time constant $\tau = RC$ is adjusted sufficiently long (typically about ten times the period of the rectangle signal), the voltage across the capacitor assumes a triangular shape. We have adapted this technique to synthesise a triangle signal. The driving rectangle signal was generated by a comparator driven by a sinusoidal signal at 1 GHz, as indicated in Fig. 2 below. It is important that the edges of the triangle signal have good linearity, because distortion of the modulator output signal would occur otherwise. Particularly, if the RC-time constant is too low, the output signal of the RC-network would assume the rounded shape typical of the charge-/ discharge function and would thus cause a phase error in the modulated signal. Therefore, special care has to be paid to the quality of the triangle signal for a good performance of the modulator.

The following figure shows the complete block diagram of the pulse-length modulator realised in this study. The comparator is operated with a triangle signal at 1 GHz and its input signal is a sinusoidal at 250 MHz. The frequency of the reference was chosen four times the signal frequency, to
achieve enough spectral distance between both signals, making the separation of the signals at the amplifier output possible without too much effort in the necessary lowpass filter. In particular, the oversampling ratio has to be high enough to avoid the Bessel spectrum of the pulse-length-modulated signal to interfere with the input signal spectrum. The amplitude of the n-th harmonic of the Bessel spectrum decreases with increasing order n, as illustrated by the following equation [3].

\[ c_{n,q} = \frac{1}{j2\pi n} J_q\left(n\Delta\Phi\right) \left[e^{j\left(n\omega_m + q\omega_m\Delta\Phi\right)} \right. \\
\left. + (-1)^{q} e^{-j\left(n\omega_m + q\omega_m\Delta\Phi\right)} \right], \]

where \( q \) is the order of the Bessel-function \( J_q \), \( \tau_0 \) is the pulse width of the unmodulated output signal, and \( \omega_m \) is the modulating frequency (\( \omega_m = 250 \text{ MHz} \) in our case). Hence, if these spectral components are sufficiently separated from the input signal, harmonic distortion can be avoided. The fourfold oversampling presents a reasonable compromise between accuracy and circuit complexity.

We found out that it is advisable not to feed the triangle signal and the input signal to separate inputs of the comparator, but to combine them by a directional coupler and feed them to a single input, to obtain lower nonlinear distortion of the comparator. The remaining input was grounded, or tied to a DC-offset voltage. The comparator used in our study was a very fast type in SiGe-technology, the ADCMP580 from Analog Devices. It exhibits output rise/fall times of typically 35 ps and a low RMS-Jitter of 200 fs. This is important in several respects. First, the rise/fall time of the output signal determines the minimum pulse width, which consists of the sum of one rise time and one fall time, and which sets the minimum output power of the amplifier driven by the PLM. Secondly, very steep pulse edges are necessary to achieve a high efficiency in a switch-mode amplifier, which is limited mainly by losses during the switching cycles. To keep these low, the amplifier output stage has to be switched as quickly as possible.

III. MEASUREMENT RESULTS

A parameter of particular interest is the linearity of the pulse-length modulator. Therefore, we have carried out a classical two-tone frequency intermodulation measurement with two test signals of identical power at 250 MHz and 251 MHz. A typical result for third-order intermodulation is shown in figure 3. An intermodulation distance of about 44 dB was observed. To check if the intermodulation follows the cubic power law expected for a memory-less nonlinearity of third order, the power of the test signals was decreased by 10 dB. Interestingly, the intermodulation distance hardly changed. Similar results were obtained for second-order intermodulation measurements, with test signals at 120 MHz and 130 MHz, where the intermodulation product at 250 MHz was observed. Again, the intermodulation distance remained essentially unaffected by the power at the fundamental tones. These results indicate that the intermodulation is dominated by hysteric processes in the comparator. Further studies are under way to understand this behavior in greater detail.

Another figure of interest is the signal-to-noise ratio (SNR) of the modulator. Within an estimated bandwidth of 25 MHz, the PLM shows a SNR of approximately 31 dB was derived from a spectral analysis of the PLM, corresponding to an average of 17 dB per MHz bandwidth. One reason for this relative small value can be associated with the quality of the triangle signal, which is depicted in figure 4.

It can be observed that there is some ripple superimposed to the triangle signal, probably caused by parasitic inductances of the RC-network in conjunction with the very fast rise time of the rectangle signal driving it. The ripple leads to additional
jitter of the comparator output signal, which adds to the noise level at the output and deteriorates the SNR.

Furthermore, the noise figure of the modulator was derived from measured data to amount to about 34 dB, in fair agreement with the performance expected from numerical simulations. Although this value appears high at first glance, it has to be noted that the triangle signal and the input signal were added by means of a directional coupler, which had a coupling attenuation of 20 dB. Hence, if the directional coupler were omitted from the circuit by feeding the triangle signal and the input signal to separate comparator inputs, the noise figure would amount to 14 dB only. Nevertheless, we used the directional coupler on purpose, because we wanted to minimise distortion as mentioned above.

Figure 5 shows the output signal of the modulator achieved for 1 GHz clock frequency, as monitored by a fast sampling oscilloscope. The variation of the duty cycle over one period of the sinusoidal input signal and the fourfold oversampling can be clearly observed. Because the oscilloscope was DC-coupled, the logic levels at the comparator output with 50 Ω-termination are also visible, which are specified for 0 V for the high-level and -400 mV for the low-level (CML-levels). For a good efficiency of the entire RF-power amplifier system, the power consumption of the modulator block is also of importance, particularly at low RF-output power levels. The described modulator circuit has primarily been designed to demonstrate the principle-of-operation of pulse-length-modulation at RF-frequencies, with less attention on the power consumption. The DC power required for this modulator amounts to 500 mW, which is not yet suited for an application in a mobile device like a cell-phone, but which could be reduced in advanced designs. In addition, in a base station power amplifier, this DC power demand would be negligible, with almost no influence on the overall efficiency. More generally, reliable estimations of the efficiency (or the power-added efficiency) can be made only in terms of the complete amplifier system. In particular, the architecture of the final power stage has dominant impact on the overall efficiency.

**IV. DISCUSSION AND CONCLUSION**

We have investigated the possibility to use a pulse-length modulator for 1-bit analogue-to-digital conversion of a switch-mode amplification of radio frequency signals. While the principle-of-operation could be successfully demonstrated at 250 MHz with a fourfold oversampling, the performance of the realised modulator can be improved further. This holds especially for the noise level, which results from several sources. First of all, the jitter of the comparator is important, as this directly increases the noise level of the output spectrum. Another problem may arise if the input signal continues to vary after having set the comparator at the rising edge of the reference signal. In such a case, the reset of the comparator at the falling edge of the reference signal may occur at a different time than the one which corresponds to the amplitude of the input signal at the instant of setting. This effect can be called an “aperture error”, as the pulse-length is not determined at one sampling instant, but within a time window depending on the input signal [4]. This contributes significantly to the noise level. A solution to this problem could be the application of a track-and-hold stage at the modulator input, which samples the input signal within a very short time interval and then holds the amplitude through the converting cycle of the modulator. Unfortunately, the realisation of an appropriate track-and-hold stage would be a challenging task, because of the demand for very high operating speeds. A more general problem is the quality of the triangle signal. In our setup, the edges of the triangle signal showed some ripple, probably caused by the parasitic inductance of the capacitor in the RC-network. This ripple leads not only to additional noise from a random shifting of the switching moments, but also degrades the linearity of the modulator. In total, we have successfully illustrated pulse-length modulation with a simple circuit architecture and with promising performance at RF frequencies. In addition, we have identified several approaches to improve the performance of the pulse-length modulator. With the availability of faster and faster comparators on the market, it seems to be possible to extend the operation of pulse-length modulation to frequencies that are of interest for mobile communication systems.

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**REFERENCES**


