Towards the improvement of the linearity-efficiency trade-off in TXs for MedRadio

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Abstract. The design trade-offs of a transmitter (TX) for the Medical Device Radiocommunications Service (MedRadio), which encompasses low power consumption in a bandwidth from the 401MHz to the 406MHz, small form factor and robustness, are discussed in this work. The aim is to determine the key factors for linearity and efficiency in a direct-up TX architecture suitable for MedRadio. A solution based on the use of a predriver amplifier preceding the power amplification stage with output power modulation is sketched. Experimental results of the predriver prototype in a double poly, three metal layers, 0.5μm CMOS technology show the effectiveness of the proposed circuit for high efficiency frequency translation.

Keywords: MedRadio, Wireless Direct-Up TX, predriver amplifier.

1 INTRODUCTION

The use of wireless technology in medical devices is nowadays a reality which is turning into a common practice for both, preventive and corrective health care. Some examples of such wireless devices include endoscopes [1], pacemakers [2], fingertip pulse oximeters [3], and diverse sensors for m-Health systems [4]. In order to make easier the employment of wireless in implanted medical devices, the Federal Communications Commission (FCC) has established the MedRadio, whose frequency band lies in the 401 to 406MHz frequency range [5]. In addition, the effective isotropic radiated power (EIRP) is limited to –16dBm and the channel bandwidth restricted to 300kHz maximum. Depending on the application, a MedRadio transceiver has to meet several criteria. Nevertheless, most of the wireless medical applications demand the following [6]: very low power consumption, small form factor, robust link with low Bit Error Rate (BER), and channel selectivity within the MedRadio band.

In general terms, to achieve a low cost and a small form factor in the implementation of CMOS transceivers, commercial vendors as well as researchers have focused

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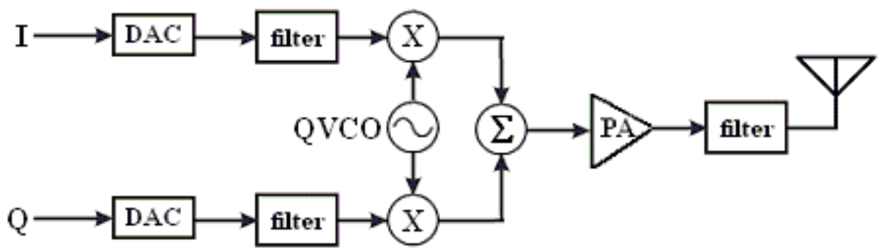

Fig. 1. Zero-IF TX architecture.

on direct conversion architectures [7]. On the other hand, to reach a high spectral efficiency in the TX, digital modulation techniques such as different forms of Quadrature Amplitude Modulation (QAM) are adopted, resulting in a transmit waveform with a high Peak-to-Average Power Ratio (PAPR). This in turn requires a linear Power Amplifier (PA) to drive the antenna and typically, linear PAs exhibit a low-Power Added Efficiency (PAE), resulting in high-power consumption. Thus, the design of an adequate TX architecture for MedRadio still is an open problem which must be assessed.

This paper is organized as follows: in section two, a quick review of the direct-up TX is presented focusing on its most important characteristics as well as pointing out its advantages as well as its drawbacks with respect to the MedRadio system; in section three, the study of the key factors for low power consumption and channel selectivity in the TX is addressed; later in section four, a possible solution is sketched; section five describes a circuit implementation example, with its experimental results, of the proposed solution in a double poly, three metal layers, 0.5μm CMOS technology; finally, the conclusions of the work are drawn in section six.

2 THE ZERO-IF TX ARCHITECTURE

Figure 1 shows the block diagram of a zero-IF TX. As can be seen, the quadrature signals pass through a digital-to-analog converter (DAC) and once filtered those are up converted to RF by the quadrature VCO. Finally, the PA reinforces the output signal, which is filtered again before to reach the antenna in order to suppress harmonic components and intermodulation (IM) products produced by the non-linearities of the PA.

According with the results reported in diverse works [7], the direct-up TX architecture is attractive since cost and form factor are good enough and its integrability is high. Moreover, it presents no image problems. Unfortunately, complexity rises by the LO-leakage. The use of techniques such as offset VCO and LO-leakage calibration are somehow necessary to alleviate this problem. It is important to remark that most of the wireless medical applications demand, among others, very low power consumption and channel selectivity within the MedRadio band. Therefore, if direct-up architecture is intended to be employed in a MedRadio TX, it has to exhibit linearity and low power consumption.

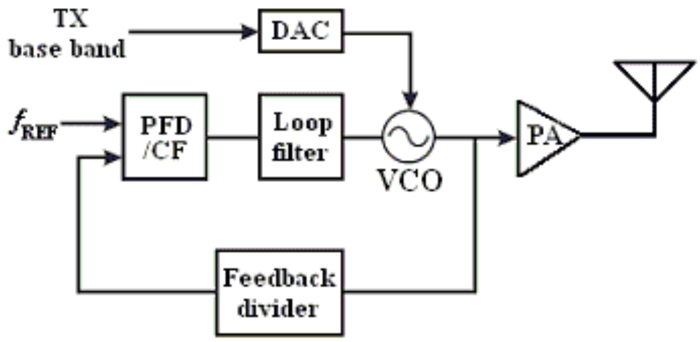

Fig. 2. Zero-IF TX architecture.

One possibility for having both, linearity and low power consumption is to use a zero-IF constant envelope TX [6]. Since it can be driven close to compression, this results in a high PAE of the PA; which means lower power consumption. Fig. 2 depicts the block diagram of the TX proposed in [6] for the Medical Implant Communication Service. It is a constant envelope architecture which utilizes Frequency Shift Keying (FSK) modulation. As can be appreciated, the modulation control of the transmitter is embedded within a Phase Locked Loop (PLL). This yields several benefits. First, it is another step toward lowering power consumption, since this scheme removes the two up converters in Fig. 1. Second, the PLL provides inherent filtering for the modulated signal. Third, the use of direct VCO modulation modifies the control voltage via a DAC and since the transfer function from the VCO-to-PLL is of the high-pass form, the modulation must concentrate most of its power spectral density outside of the PLL bandwidth.

Another possibility for high linearity is the power up converter (PU) proposed in [8] based on the polyphase multipath technique and shown herein in Fig. 3. The differential pairs are driven as transconductors by the corresponding phase shifted base band signal (BB) meanwhile the transistor below acts like a switch driven by the corresponding phase shifted square wave from the local oscillator (LO). The elements labeled as L_{RF} are choke inductors and Z_L is the load of the matching network between the antenna and the driver. A good linearity is achieved with the employment of this circuit, -40dBc worst case harmonic rejection with a six phases system @ 2.4GHz [8]. However, the drain efficiency of the PU is rather low (11% for 9dBm output power) and this implies a high power consumption. On the other hand, the PU does not necessarily require an output filter since unwanted spectral components can be significantly reduced in a flexible manner with the use of multiple paths and multiple phases. This is an attractive characteristic considering that it reduces costs and improves the form factor of the TX since dedicated filters out of chip can be eliminated. Moreover, direct conversion TX with a polyphase multipath scheme provides a flexible architecture for multiple standards [8]. This is a crucial step to TXs for MICS, MedRadio and Wireless Medical Telemetric Service (WMTS) [6].

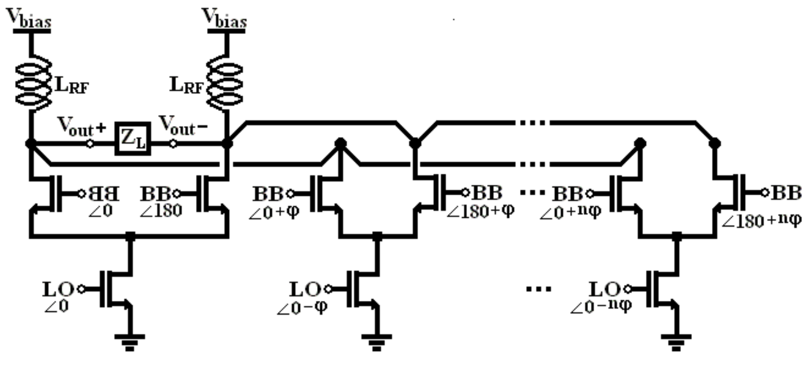

Fig. 3. Power up converter based on the polyphase multipath technique.

3 POWER SAVING AND LINEARITY

In the previous section we saw that a polyphase multipath direct conversion TX is a good choice for linearity, form factor, and flexibility for multi-standard wireless technologies. Nevertheless, the PU reported in [8] exhibits poor efficiency and therefore its power consumption is rather high. That is an unwanted feature in medical applications. On the other hand, in order to save power the solution proposed in [6] utilizes a constant envelope nonlinear PA. Thus, by using both techniques, an efficient nonlinear PA within a polyphase multipath architecture, a trade-off between power consumption, channel selectivity and form factor can be reached.

There are three parameters which play an important role in the efficiency of any PA: the input power (P_{IN}); the output power (P_{OUT}); and the DC power consumption (P_{DC}). The ratio between P_{OUT} and P_{IN} defines the drain efficiency, η_D, whereas the ratio between the difference of P_{OUT} minus P_{IN} and P_{DC} defines the power added efficiency, *PAE*, which is the most popular measure in industry. An alternative manner to express the *PAE* is as a function directly proportional to η_D and inversely proportional to the power gain (A_P), i.e.

$$PAE = \frac{P_{OUT} - P_{IN}}{P_{DC}} = \frac{P_{OUT}}{P_{DC}}\left(1 - \frac{P_{IN}}{P_{OUT}}\right) = \eta_D\left(1 - \frac{1}{A_P}\right) \quad (1)$$

Hence, η_D and A_P are relevant for a high efficiency performance. In terms of the conduction angle, the η_D for switched (nonlinear) PAs can be expressed as [9]

$$\eta_D = \frac{2\sin^2(\phi)}{\phi(\pi - \phi)} \quad (2)$$

where ϕ is half the total conduction angle, 2π, of the driving signal.

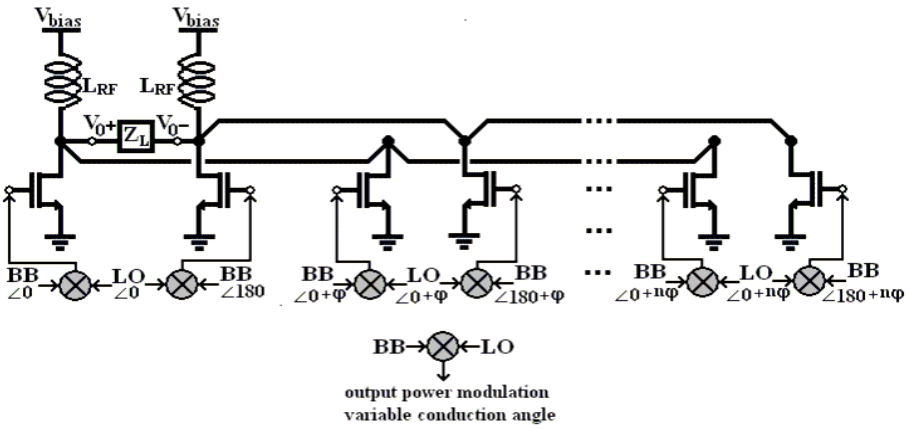

Fig. 4. Direct conversion TX based on the polyphase multipath architecture.

By inspection of (1) and (2) it can be seen that, if sufficient A_P can be attained and a good η_D is exhibited by the driver, then the PAE of the power amplification stage can be high and therefore the power consumption of the TX adequate for medical applications. Probably, one of the simplest manners in which the A_P can be enlarged is to reduce the P_{IN}. Fig. 4 shows the circuit diagram of the proposed direct-up TX within a polyphase multipath architecture. It consists of *n* pseudo differential pairs of switched PAs driven by predriver stages compound by mixers. In this case, the mixer is at the back driving the power amplification stage. In such a way, the power transference of this stage to the load can be improved by modulating the power delivered by the mixer, i.e. the input power of the PA. Besides, if the mixed signal is fed into the PA such that it is capable of modifying the conduction angle of the amplifier, then also the η_D can be controlled. Moreover, the power demands on the BB can be relaxed. In sum, the allocation of the mixer out of the power amplification stage is more convenient for power efficiency and consequently lower power consumption.

4 LINEAR AND EFFICIENT TX SCHEME FOR MeDRadio

Typically, the usual metrics to evaluate the performance of a mixer are: conversion gain/loss, noise figure, port isolations, linearity, and power consumption [10]. From those, noise figure and port isolations are of major concern in case that the mixer is intended to be used in a receiver circuit. In addition, with the use of the multipath polyphase technique, linearity is, in principle, not a major issue. Instead, the demands on the performance of the mixer used as a predriver stage just like depicted in Fig. 7 in multipath polyphase architecture with improved efficiency can focus in the following aspects:

- Output power modulation.
- Capability of modifying the conduction angle of its output signal, i.e. the driving signal of the PA.

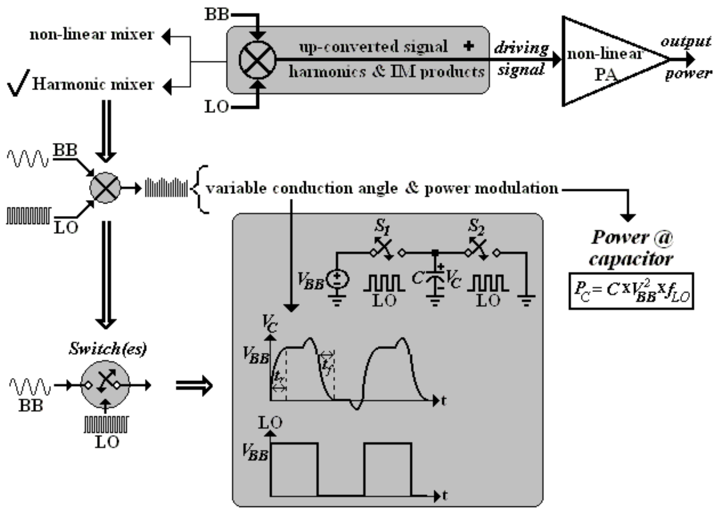

Fig. 5. Switched circuit used as a mixer.

From the many mixer architectures available, it is difficult to find one which exhibits these features. There are basically two ways to accomplish the frequency translation of two signals. The first method is by means of a nonlinear circuit whose nonlinearities generate harmonics and IM products, and the second possibility is with the use of a time variant circuit. Switching circuits known as harmonic mixers are used in zero-IF TXs to up convert the BB to RF. Since harmonic mixers possess a low self-mixing DC offset, they result attractive for zero-IF TXs, with the drawback of having a conversion gain usually small [7].

Fig. 5 depicts the action of a simple switching circuit with two switches, S_1 and S_2, and one capacitor, C. The LO signal controls the action of S_1 and S_2 such that they operate in turn. When LO is at a high value S_2 is open and S_1 is closed leading to the charge of capacitor C at voltage V_{BB} which is provided by the voltage source on the left. Assuming there is some resistance value between the terminals of S_1 when it is closed then there is an RC circuit given by the series connection of C and the resistive value of the switch. The time constant of the RC circuit establishes a rise time, t_r, in which C is charged at approximately V_{BB}. On the other hand, when LO is at a low value S_1 is open meanwhile S_2 is closed; again, assuming there is an series RC circuit given by the resistive value between the terminals of S_2 when it is closed and the capacitor C, the time constant given by this RC circuit establishes a fall time, t_f, in which C is discharged completely. Note that if there are different rise and fall times in the circuit it is possible to alter the duty cycle of the resulting signal. In other words, we can modify the conduction angle of the signal at the output by changing the time constants in the circuit, which can be done easily by changing the resistive value of the switches. Moreover, the power at the output of circuit such as the one depicted in Fig 5 is given by [11]

$$P_C = C \times V_{BB}^2 \times f_{LO} \tag{3}$$

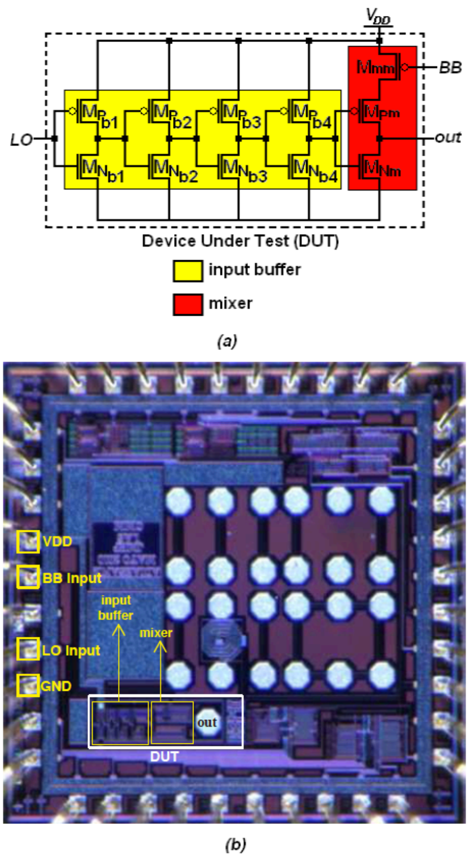

Fig. 6**.** Proposed predriver CMOS circuit: (a) circuit diagram and (b) prototype die photo.

where f_{LO} is the frequency of the LO. According with this expression, the output power is proportional to the quadratic value of the V_{BB} voltage. Thus, the output power can be controlled by changing the value of V_{BB}. Therefore, it is convenient to use a switched RC network as a pre-driver mixer for the PA stage of the TX since it allows to modulate the power at its output and to change the duty cycle of the output waveform.

5 EXPERIMENTAL RESULTS

A prototype of the predriver stage was designed and fabricated in a double poly three metal layers 0.5μm CMOS technology from MOSIS foundry. Fig. 6 (a) shows the circuit diagram of the fabricated circuit. As can be seen, it consists of an input buffer which turns the input sinusoidal signal from the LO into a square wave signal with 50% duty cycle followed by the mixer. A total of 11 transistors are used. From those, only three belong to the mixer. The *(W/L)* ratios used for the devices in the

Table 1. Experimental results of the predriver stage.

LO Frequency	393.5MHz
BB Frequency	10MHz
Power Supply, V_{dd}	3.3V
Tuning control	1.0V – 1.8V
Maximum Power Consumption	88.2μW
Minimum Power Consumption	68.2μW
Maximum Output Power	-13dBm
Minimum Output Power	≈-19dBm
Maximum Duty Cycle	50%
Minimum Duty Cycle	≈30%
Maximum Pulse Amplitude	2.5V
Minimum Pulse Amplitude	0.4V

buffer were (19.8μm /0.6μm), (66μm /0.6μm), (115.5μm /0.6μm) and (264μm /0.6μm) for the transistors M_{Pb1}, M_{Pb2}, M_{Pb3} and M_{Pb4}, respectively; whereas the ratios for the transistors M_{Nb1}, M_{Nb2}, M_{Nb3} and M_{Nb4} were (15μm /0.6μm), (30μm /0.6μm), (45μm /0.6μm) and (120/0.6), respectively. For the case of the switches in the mixer, the ratios occupied were (180μm /0.6μm) for transistors M_{Pm} and (540μm /0.6μm) for transistors M_{Nm}. Finally, the ratio of transistors M_{mm} was (480μm /0.6μm). The prototype area is 0.472μm X 0.148μm including the output pad. The prototype die photo is depicted in Fig. 6(b). As can be appreciated, the bias input, V_{DD}, the BB input, the LO input and the ground are fed to the bond pads of the chip meanwhile the output node must be taken from an inner-pad labeled as out.

Table 1 summarizes the most important characteristics of the prototype. The LO frequency was 393.5MHz meanwhile the BB frequency was 10MHz. The power supply for the circuit was of 3.3V. The tuning control was of 800mV ranging from 1.0V to 1.8V. The maximum power consumption was 88.2μW and the minimum power consumption was 68.2μW. The maximum output power was -13dBm meanwhile the minimum output power was -19dBm approximately. The duty cycle of the prototype was modifiable in a range of 20% from 50% to 30%. Finally, the maximum pulse amplitude of the output signal was 2.5V whereas the minimum was 400mV.

Fig. 7 (a) shows the waveform obtained at the output of the prototype for a voltage value of the tuning control of 1.2V. On the other hand, Fig. 7 (b) depicts the spectrum at the output of the prototype within the MedRadio band. It can be seen that the frequency components $\omega_{LO} \pm 4\omega_{BB}$, $\omega_{LO} \pm 3\omega_{BB}$, $\omega_{LO} \pm 2\omega_{BB}$, $\omega_{LO} \pm \omega_{BB}$, are present with enough power to be taken into account ($\omega_{LO} = 2\pi f_{LO}$). Nevertheless, further cancellation of the intermodulation distortion in the transmitter chain can be performed by using a band pass filter to select the frequency of interest, $\omega_{LO} + \omega_{BB}$.

6 CONCLUSIONS

The design issues of TXs for MedRadio circuits have been discussed. Due to the requirements of medical applications such as low power consumption, small form

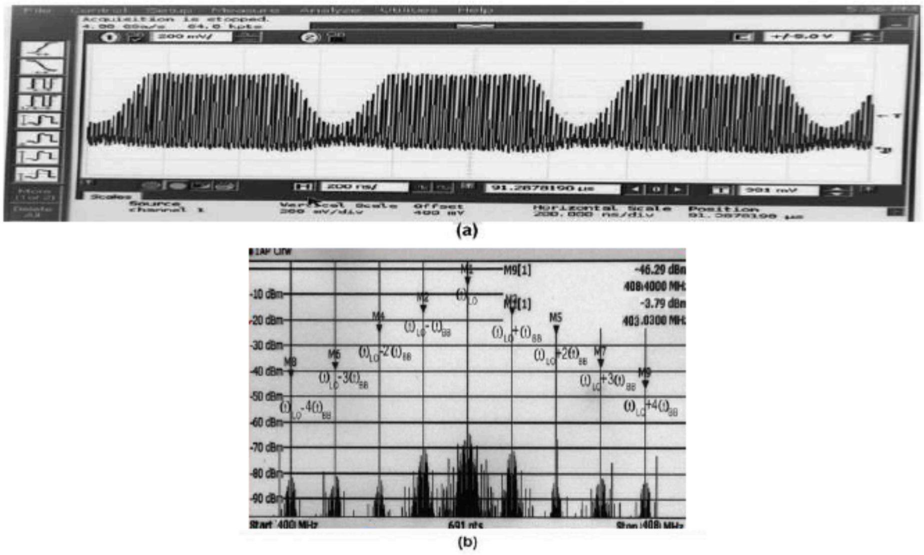

Fig. 7. Output signal of the prototype: (a) waveform in time domain and (b) spectrum within the MedRadio band.

factor and channel selectivity, a direct-up approach intended to exhibit a good efficiency within a polyphase multipath architecture have been sketched as an alternative to satisfy those demands. The key aspects for power saving lies in the pre-driver stage which must perform two actions: mixing the LO and BB and driving the PA with variable conduction angle and modulated output power.

The experimental results were: a tuning control of the predriver of 800mV ranging from 1.0V to 1.8V; a maximum power consumption of 88.2μW and a minimum power consumption of 68.2μW; a maximum output power of -13dBm meanwhile the minimum output power was -19dBm; a duty cycle modifiable in a range of 20% from 50% to 30%; a maximum pulse amplitude of the output signal of 2.5V whereas the minimum was 400mV. In addition, the frequency components $\omega_{LO} \pm 4\omega_{BB}$, $\omega_{LO} \pm 3\omega_{BB}$, $\omega_{LO} \pm 2\omega_{BB}$, $\omega_{LO} \pm \omega_{BB}$, are present with enough power to be taken into account. However, further cancellation of the intermodulation distortion in the transmitter chain can be performed by using a band pass filter to select the frequency of interest, $\omega_{LO} + \omega_{BB}$.

According to the results obtained in the characterization of the prototype, we conclude that the behavior of the predriver stage follows the course anticipated in the synthesis of the mixer performed in section 4.

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