A PLL-based BFSK Transmitter with Reconfigurable and PVT-Tolerant Class-C PA for MedRadio & ISM (433MHz) Standards

Karthik Natarajan[1,2], Daibashish Gangopadhyay[1,3], David Allstot[1]

[1]University of Washington, Seattle, WA

[2] Intel Corporation, Hillsboro, OR; [3]Marvell Semiconductors Santa Clara, CA

***Abstract* — An RF transmitter that uses closed-loop PLL-based BFSK modulation and is reconfigurable for both the MedRadio (402-405MHz) and 433 MHz ISM bands is introduced. Innovations include the first reconfigurable class-C PA, the first class-C PA with automatic calibration against PVT variations, and a low-power NMOS delay-based ring-VCO PLL. Several performance records are achieved: (1) The PA realizes a peak efficiency of 47% in the high-power (ISM) (-2 dBm) mode and 43% (33%) in the MedRadio -12 dBm (-16 dBm backoff) modes. (2) The PLL dissipates only 72 µW with a phase noise of -111 dBc/Hz @ 1 MHz, and (3) the overall transmit efficiencies are 29% and 17% for the -12 dBm and -16 dBm backoff levels for the MedRadio band and 44% for the ISM (433 MHz) bands.**

***Index Terms* — Power amplifier, BAN, ultra-low-power, reconfigurable, power amplifiers.**

I. Introduction

Reconfigurable bio-sensor radios promise new opportunities in healthcare. For example, a hospitalized patient may be bedridden with short-haul radios that transmit bio-signals in the MedRadio band to a bedside monitoring station. Because doctors soon encourage patients to move around, reconfigurable sensor nodes that reconfigure from the MedRadio band to the longer-range ISM band enable continuous un-tethered monitoring of recovering ambulatory patients.

Security of healthcare information is an emerging issue [9]: (1) If a bio-sensor is transmitting at high-power and a breach is detected, it switches to a low-power mode and operates in a secure multi-hop peer-to-peer network. (2) If transmitting at low-power and a short-range jammer is detected, it switches to high-power to swamp the jammer. This paper presents the first reconfigurable bio-sensor transmitter for such applications.

Future wireless sensors demand reconfigurability and increased efficiency. The first reconfigurable bio-sensor transmitter is introduced (Fig. 1). It features the first class-C PA that is reconfigurable for a peak output power of -12dBm or -2dBm with auto-calibration to reduce PVT variations. It implements closed-loop BFSK modulation using a low-power ring oscillator-based PLL. [1]

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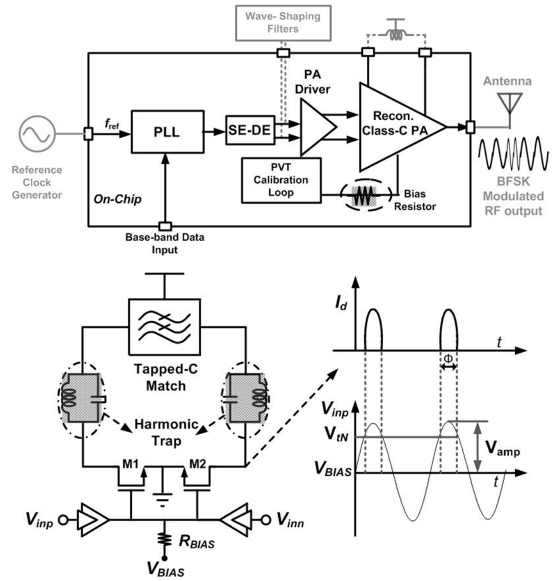

Fig. 1: Architecture of the reconfigurable dual-band MedRadio/ISM (433 MHz) BFSK transmitter (top) and the proposed pseudo-differential class-C PA with operating waveforms (bottom).

MedRadio (402-405MHz) specifies a maximum Effective Isotropic Radiated Power (EIRP) of -16dBm . The maximum EIRP is 30dBm for the 433MHz ISM band, but most applications use medium-haul links with ~0dBm EIRP for high efficiency [5]. Current bio-sensors use antenna interfaces with overall efficiencies of 5-22% at -16dBm [1]-[3]. [1][2] use an injection-locked open-loop oscillator for fast settling with limited tunability; PVT variations cause significant output power variations. [3] uses an open-loop DCO to drive the antenna and eliminates the PA; concerns are inefficient power delivery, temperature drift, and frequency pulling.

Fig. 1 illustrates operation of a class-C PA with the DC-bias of M1-M2, V_{GS}(=V_{BIAS}) is below V_{tN} [4]. Drain current I_d flows when $|V_{amp}| > V_{tN}-V_{BIAS}$. The conduction angle of $\Phi < 90^\circ$ defines class-C operation. The power drawn from V_{DD} is reduced because I_d flows for a small fraction of the period. On-chip LC filters suppress harmonics. A class-C PA gets high efficiency for EIRP <

0dBm and the PLL-based BFSK modulator minimizes VCO drift and pulling.

II. RECONFIGURABLE TRANSMITTER

a) PVT Tolerant Power Amplifier Design

The reconfigurable class-C PA is shown in Fig. 2. It is configured using a -12dBm PA/output matching network (OMN) for MedRadio or a -2dBm PA/OMN for 433MHz ISM. The -3dB bandwidth is ~80MHz owing to high-Q external inductors. A common driver provides gain from 0dB to 12dB in 4dB steps. The OMN is challenging because only one PA is active at a time. It is easy to disable a PA using switches but parasitics affect the OMN of the selected PA. Efficiency is degraded by any parasitic series resistance—a problem that is exacerbated with large impedance transformation ratios. The output matching networks include a series capacitor, C_D, and selection bits B1 and B2, to decouple the OMN designs.

Because the output power of a class-C PA with fixed $V_{GS} = V_{BIAS}$ varies vs. PVT perturbations, automatic calibration is introduced to reduce these effects. P_{out} is constant if $|V_{amp} -(V_{tN}-V_{BIAS})|$ is constant. Calibration of a class-C PA is implemented using the open-loop design of Fig. 2 which consumes negligible power because it is active only for a short time. Global PVT variations are sensed using a ring oscillator whose free-running frequency determines the time required to count 16 pulses during which a constant current charges a capacitor. If the process is faster than nominal, a smaller value of V_{BIAS} is generated to keep $(|V_{amp} -(V_{tN}-V_{BIAS})|)$ constant and vice-versa. The capacitor is essentially disconnected from the calibration circuit and applied to the PA as V_{BIAS}.

b) NMOS Delay based Frequency Synthesizer

An on-chip PLL provides closed-loop modulation of the baseband data for BFSK transmission. In contrast to cellular standards that require precise frequency control (~1ppm), MedRadio needs only ~100ppm accuracy which allows aggressive design tradeoffs. Fig. 3 employs a low-power integer-N type-II third-order PLL and a novel NMOS delay-based ring oscillator (NDRO). Rather than controlling V_{DD} to set the oscillation frequency, NDRO controls the resistances of switches in series with the gate capacitances of inverters. However, both V_{tune} and (V_{DD}-V_{tune}) signals are required for transmission-gate switches. The latter requires a level shifter that adds area, power,

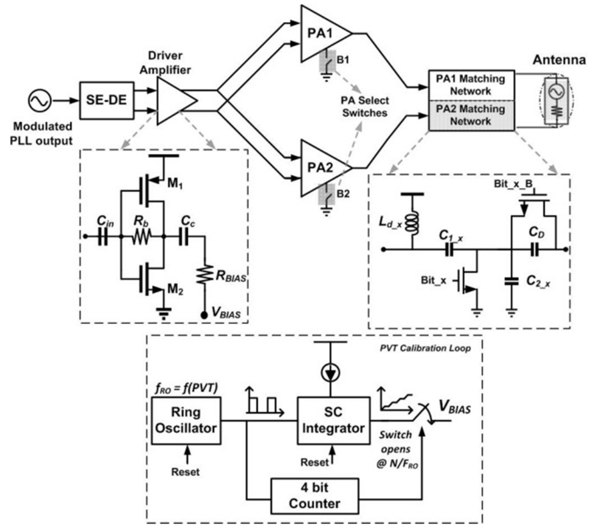

Fig. 2: Architecture of the reconfigurable class-C PA with AC-coupled self-biased inverter driver, reconfigurable on-chip matching network and off-line PVT calibration circuit.

and noise coupling from V_{DD} to the output. These concerns are eliminated in Fig. 3 where only NMOS switches are tuned. Compared to conventional RO-based PLL designs, this approach saves power, reduces K_{VCO} for higher stability, and reduces phase noise at the expense of reduced tuning range. The frequency of oscillation is approximated by eqn. (1) where C_g is the effective capacitor across each stage and R_{NMOS} is the effective resistance of the NMOS switch

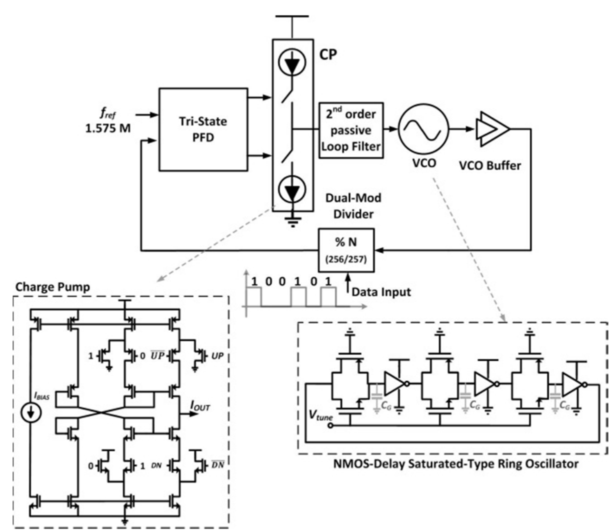

Fig 3 : Architecture and circuit topologies of the NDRO-based type-II third-order integer-N PLL. The BFSK modulation data is input to the dual-modulus divider.

$$f_{NDRO} = \frac{1}{2N\tau} = \frac{1}{2NC_g(R_{NMOS} + \frac{1}{Gm})} \qquad (1)$$

The baseband digital data modulates the PLL output frequency through the dual-modulus divider. The BFSK-modulated output of the PLL drives a digital single-ended-to-differential converter followed by an (off-chip) LC filter that ensures a sinusoidal PA input. The reference frequency (f_{ref}) of the integer-N PLL sets the BFSK frequency offset (f_{offset}) which should be maximized to minimize the transmission bit-error rate given the limited bandwidth of the MedRadio/ISM standards, number of non-overlapping MedRadio channels for multi-sensor coexistence and PLL power consumption. This work uses a low-power TSPC DFF-based 256/257 divider and a reference frequency of 1.575 MHz for the MedRadio band. Although the high divide ratio and low reference frequency further reduce the dynamic power consumption of the PLL, a charge pump (CP) with high linearity is required because of the limited low-pass filtering of the reference spur. The high-linearity low-power CP of Fig. 3 easily meets the dual-standard specifications.

III. Measurement Results

An experimental prototype is fabricated in a 0.13µm CMOS process with eight metal layers including a thick layer for high-quality passives. For testing, the transmitter was chip-on-board bonded to a four layer PCB with high-Q ceramic inductors. The measured output power transfer characteristics for reconfigurable operation in the low-power (LP) and high-power (HP) modes are shown in Fig. 4. The power saturates at -12 dBm (LP) and -2 dBm (HP) with peak drain efficiencies of 43% and 47%, respectively. The output power drift over temperature and supply variations, with and without calibration, are shown in Fig. 5. Uncompensated power variation of 49% with a standard deviation 10.63 µW is reduced to 20% with standard deviation of 4.34 µW signifying a 59% decrease in Standard deviation (σ). The PVT calibration technique reduces output power variations by about 2.5X compared to conventional class-C PA designs. The NDRO consumes 42 µA and exhibits a tuning range of 100 MHz centered at about 385 MHz. The PLL consumes 72 µW and achieves a closed-loop bandwidth of 80 KHz, a phase noise of -111 dBc @ 1 MHz offset and -133 dBc @ 10 MHz offset with a reference spur of -48 dBc (Fig. 6). The overall transmitter efficiency is 44% (@ -2dBm) in the ISM mode and 17% (@ -16 dBm) and 29% (@ -12 dBm) in the MedRadio mode.

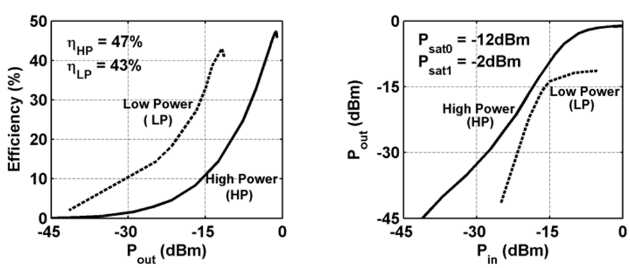

Fig. 4: (L-R) Measured performance of the reconfigurable class-C PA Efficiency vs. output power; P_{out} vs. P_{in}.

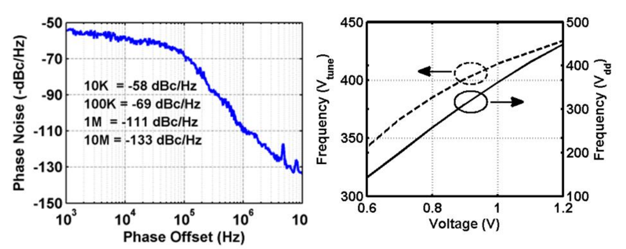

Fig. 6: (L-R) Measured Phase noise; tuning range vs. V_{DD} (K_{VDD} = 500 MHz/V @ V_{tune} = 0V) and V_{tune} (K_{VCO} = 140 MHz/V @ V_{DD} = 1.1 V).

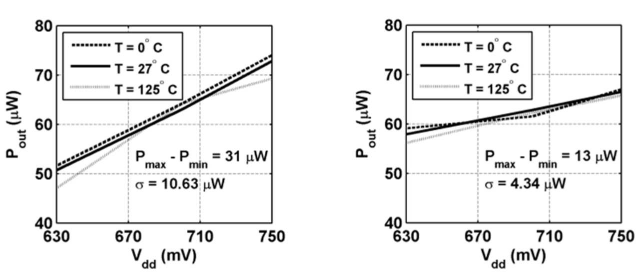

Fig. 5: (L-R) Uncompensated output power (P_{OUT})variation; Compensated PVT loop, output power variation.

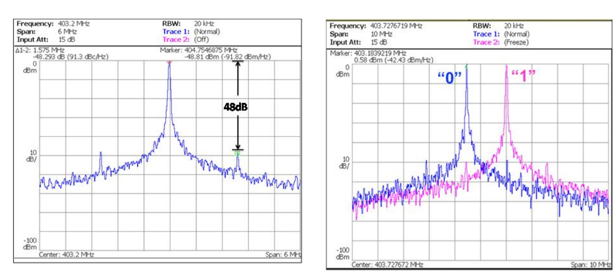

Fig 7: (L-R) Reference spur level (-48dBc); PLL outputs for BFSK data modulation.

TABLE I: Performance Summary

TX	This Work	[1]	[2]	[3]
Supply (V)	0.7-1.2	1.2	1.2	1
Area (mm^2)	0.41	0.04	2.5	0.5
Architecture	NDRO-PLL-PA-MN-ANT[1]	Edge-combing PA-MN-ANT	Edge-combing PA-MN-ANT	DCO-ANT
Reconfigurable PA	Yes	No	No	N/A
Modulation Clock Gen.	PLL	ILVCO	DLL	DCO (open loop)
On-chip PVT calibration	Yes	No	No	No
Power Consumption (µW)	150	90	400	350
Output freq. (MHz)	400/433	400	400	400
Max. Data-rate (Kbps)	80	200	100	120
PA efficiency (%) @ o/p pwr.				
-16 dBm	33	30	16	N/A
-12 dBm	43	29	N/A	
-2 dBm	47	N/A	N/A	
TX efficiency (%) @ o/p pwr.				
-16 dBm	17	23	5	7.14
-12dBm	29	26	N/A	N/A
-2dBm	44	N/A	N/A	N/A

PLL	This Work	[6]	[7]	[8]
Power Consumption (mW)	0.072	0.440	0.400	10
Output freq. (MHz)	400/433	400/433	400	5000
PN @ 1MHz(dBc/Hz)	-111	-91.5	-87	-115
FOM (dB)	174.5	147.1	143.0	178.9

VII. Conclusion

A reconfigurable transmitter achieves overall efficiencies of 17% and 44% in the MedRadio and ISM bands. The first-reconfigurable class-C PA is reported which outputs -16 dBm (-2 dBm) with 33% (47%) efficiency. PVT calibration reduces output power variations by 2.5X versus conventional class-C designs. The BFSK modulator uses NMOS delay-based ring-VCO (NDRO) PLL achieves PN of -111 dBc/Hz @ 1 MHz.

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