A +10dBm 2.4GHz Transmitter with sub-400pW Leakage and 43.7% System Efficiency

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<th>Citation</th>
<th>Paidimarri, Arun, Nathan Ickes, and Anantha Chandrakasan. &quot;A +10dBm 2.4GHz Transmitter with sub-400pW Leakage and 43.7% System Efficiency.&quot; 2015 IEEE International Solid-State Circuits Conference (February 2015).</th>
</tr>
</thead>
<tbody>
<tr>
<td>As Published</td>
<td><a href="http://dx.doi.org/10.1109/ISSCC.2015.7063018">http://dx.doi.org/10.1109/ISSCC.2015.7063018</a></td>
</tr>
<tr>
<td>Publisher</td>
<td>Institute of Electrical and Electronics Engineers (IEEE)</td>
</tr>
<tr>
<td>Version</td>
<td>Author's final manuscript</td>
</tr>
<tr>
<td>Accessed</td>
<td>Sun Mar 25 18:29:55 EDT 2018</td>
</tr>
<tr>
<td>Citable Link</td>
<td><a href="http://hdl.handle.net/1721.1/95676">http://hdl.handle.net/1721.1/95676</a></td>
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Arun Paidimarri, Nathan Ickes, Anantha Chandrakasan

Massachusetts Institute of Technology, Cambridge, MA

10.7 A +10dBm 2.4GHz Transmitter with sub-400pW Leakage and 43.7% System Efficiency

Extreme energy constraints inherent in many exciting new wireless sensing applications (such as [1-3]) virtually dictate that such systems operate with extremely low duty cycles, harvesting and storing energy over long periods of time before waking up to perform brief measurement and communication tasks. However, such duty cycling only works if the sleep power of the system is less than the average power available from the power source, which may only be as much as a few nA. In this work, we present an RF transmitter designed to operate in an extremely low duty-cycle industrial monitoring system. The primary challenges are achieving high efficiency in the active mode while transmitting as high as +10dBm and simultaneously minimizing the leakage during the sleep mode. We address these in a +10dBm Bluetooth Low Energy (BLE) transmitter test-chip through 1) low voltage design (0.68V) for switching power and short-circuit power reduction, 2) extensive power gating of unused blocks and 3) a negative-VDD biasing technique for PA leakage reduction without affecting its on-performance.

Typically, high-V$_T$ power switches are used to power gate low-V$_T$ active circuits [1]. But, the switch resistance, which is in the direct path of active current, degrades on-performance. Increasing switch size will in turn increase leakage. Negative gate-biasing of the switching gate has been shown to give significant leakage reduction [3]. However, in this work, we study the effect of negative-gate biasing of the low-V$_T$ active device itself, thereby eliminating a switch in the direct path of active current and simultaneously reducing leakage. This is especially useful for the PA in our work, which operates at +10dBm and is the largest active power consumer.

Fig. 13.7.1 shows the measured drain current (I$_{D,PA}$) and gate current (I$_{G,PA}$) of the NMOS PA transistor as a function of the negative gate bias applied. The 65nm CMOS transistor, because of its thin gate oxide, has significant gate leakage. It is exponential with the gate bias. The drain current, which is the sum of sub-threshold current and gate leakage, decreases exponentially with increasing gate bias while the sub-threshold current is dominant, but increases as gate leakage becomes larger. The red curve (in solid) shows the achievable total PA leakage assuming the negative bias is supplied by an ideal $-\frac{1}{2}$ charge pump ($\pm$0.45V at $-200$mV). The minimum, 430pA, occurs at $-200$mV and represents a 30x reduction in leakage. Fig. 13.7.1 also shows a histogram of the minimum (I$_{D,PA}$−$\pm$0.45V $\pm$0.45V) current for 25 measured chips. Simulations indicate that the minimum leakage points range from $-150$mV to $-300$mV, which implies that a $-\frac{1}{2}$V charge pump generating $V_{NEG} = -\frac{1}{2}VDD$ is sufficient. Low VDD ensures device reliability even with V$_{NEG}$ biasing (V$_{DCC}$=1.2V).

Fig. 13.7.2 shows the complete TX system block diagram. The RF signal path has a 12MHz crystal oscillator feeding a divided 1MHz clock to an integer-N PLL. The PLL provides 2MHz-spaced BLE channels at 2.4GHz. The PLL output is then buffered by a 12MHz crystal oscillator feeding a divided 1MHz clock to an integer-N PLL. The crystal oscillator, PLL and VCO consume 32µW, 132µW and 510µW respectively. The VCO buffer consumes 102µW while the resonant buffer draws 1mW. The PA delivers a wide range of output powers ranging from +10dBm down to -5dBm depending on the supply voltage and bias voltage applied to it. Fig. 13.7.5 plots the overall TX efficiency for various VDD values. At 0.68V, it generates an output power of +10dBm with a PA efficiency of 46.4% and overall TX efficiency of 43.7%. At a lower voltage of 0.25V, the PA has a peak efficiency of 47.2% while delivering 2.6dBm with the TX efficiency at 31.6%. Fig. 13.7.5 also plots the spectrum of 10Mbps GFSK modulation. The adjacent channel power is well below the BLE spec. The TX was able to successfully communicate with a commercial off-the-shelf BLE receiver from Texas Instruments.

Fig. 13.7.6 shows leakage measurements of the full TX. The pie chart breaks down the contribution of the various components with the PA being the dominant one. The total leakage power is around 370µW. Fig. 13.7.6 also shows the measurement of total TX leakage at various temperatures. This experiment was performed bypassing the gate leakage oscillator in order to characterize the true minimum power points. At high temperatures, the effectiveness of the leakage management techniques is better because the sub-threshold current at V$_{NEG}$ = 0 is higher while the gate leakage is relatively constant with temperature. For example, at +80°C, there is a 100× reduction in leakage current at an optimal V$_{NEG}$ of ~300mV.

In conclusion, a 2.4GHz BLE-compatible transmitter architecture for use in ultra-low duty cycle applications has been presented. Low voltage operation, extensive power gating and a negative gate biasing technique help in achieving a peak TX efficiency of 43.7% at an output power of +10dBm while also reaching a leakage power of 370µW, for an on/off ratio of 7.6×10$^6$. Acknowledgements: The authors would like to thank Shell and Texas Instruments for funding and the TSMC University Shuttle Program for chip fabrication.

References:

Fig. 13.7.3 also shows a voltage photo of the TX fabricated in a 65nm LP CMOS process. The die area is 2.5×2.5mm$^2$ while the core area is 1.6mm$^2$. The crystal oscillator, PLL and VCO consume 32µW, 132µW and 510µW respectively. The VCO buffer consumes 102µW while the resonant buffer draws 1mW. The PA delivers a wide range of output powers ranging from +10.9dBm down to -5dBm depending on the supply voltage and bias voltage applied to it. Fig. 13.7.5 plots the overall TX efficiency for various VDD values. At 0.68V, it generates an output power of +10.9dBm with a PA efficiency of 46.4% and overall TX efficiency of 43.7%. At a lower voltage of 0.25V, the PA has a peak efficiency of 47.2% while delivering 2.6dBm with the TX efficiency at 31.6%. Fig. 13.7.5 also plots the spectrum of 10Mbps GFSK modulation. The adjacent channel power is well below the BLE spec. The TX was able to successfully communicate with a commercial off-the-shelf BLE receiver from Texas Instruments.
Figure 13.7.1: Measured drain and gate currents for the PA showing minimum leakage point and its distribution across 25 measured chips.

Figure 13.7.2: Block diagram of the transmitter showing RF signal chain, power gating switches and leakage management blocks.

Figure 13.7.3: RF signal chain from VCO to the antenna showing the VCO buffer running from $V_{DOUB}$, the resonant buffer, the power amplifier and capacitor bank tuning.

Figure 13.7.4: Gate-leakage oscillator that provides the clock for the negative voltage charge pump that generates $V_{NEG}$. All devices are thick-oxide devices except for the gate-leakage current sources.

Figure 13.7.5: RF performance of the transmitter showing overall transmit efficiency at various $V_{DO,PA}$ values. Also shown is the 1Mbps GFSK spectrum from the transmitter.

Figure 13.7.6: Pie chart with the contribution of various blocks to system leakage and variation of the minimum leakage with temperature.
Figure 13.7.7: Die photo of the transmitter fabricated in 65nm LP CMOS. Die size is 2.5×2.5mm² and core area is 1.6mm².