A 13.56/402 MHz Autonomous Wireless Sensor Node with -18.2 dBm Sensitivity and Temperature Monitoring in 0.18 μm CMOS

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Abstract—A multi-band autonomous wireless sensor node (AWSN) with temperature monitoring is designed in a standard 0.18 μm CMOS technology. The AWSN comprises a high efficiency energy harvester, a power management module, a temperature-to-time converter (TTC) and a passive 402-MHz MICS band OOK transmitter for backscattering transmission. The AWSN demonstrates a sensitivity of -18.2 dBm at 13.56 MHz. The energy harvester achieves an RF-to-DC power conversion efficiency (PCE) of 11.5 %. From 0 to 100 °C, the temperature conversion and temperature accuracy of the TTC are 1.5 μV/°C and 0.21 °C, respectively. The active area of the AWSN is 0.72 mm². It consumes 1.5 μW (RMS).

I. INTRODUCTION

Until recently, power consumption was thought of as a hindrance towards the wider adoption and development of wireless sensor network (WSN) technology. Proven to be a sustainable energy source, the advancement of RF energy harvesting technologies has spurred considerable interest in reliable, cost-effective, low-power WSNs envisaged to monitor our environment. WSN nodes embedded with multiple functionalities are often deployed to monitor and control process variables like temperature, pressure, flow, level, etc.

Today’s single-band/channel solutions for personal and body area networks rely on digital logic, ADCs, embedded memory for data management, and often require external elements (capacitors) for energy storage and power management [1-4]. This classical design methodology is relatively inflexible with respect to sensor accuracy and the required power budget tends to exceed what is permissible for autonomous operation. To overcome shortcomings of the classical design, this paper proposes an ultra low-power, general-purpose multi-band (MICS and ISM) autonomous wireless sensor node with temperature monitoring.

The paper is organized as follows. Section II presents the design of the AWSN. Measurement results are presented in Section III. Conclusions are drawn in Section IV.

II. MULTI-BAND AUTONOMOUS WIRELESS SENSOR NODE

As shown in Fig. 1, the AWSN comprises a passive high efficiency energy harvester, a power management module, a temperature-to-time converter and a 402 MHz (MICS band) OOK backscatterer data transmitter. The multi-band approach is chosen to exploit the maximum permissible power transmission at 13.56 MHz, the wide bandwidth for data transmission at 402 MHz, thus providing simultaneous data communication and energy harvesting.

The theoretical model and analysis of the energy harvester is presented in [5]. The harvester comprises a passive volt-boosting network (VBN) (Fig. 2(a)) and an orthogonally switching passive charge pump rectifier (OS-CPR) (Fig. 2(b)).

To adequately drive the OS-CPR, the VBN delivers large swing control ($V_{dd}$ and $V_{cc}$) and energy signals ($V_{+}$ and $V_{-}$). The resonant circuit of the VBN is modeled by the self-inductance of the antenna, $L_A$ (9.5 μH), its series resistance, $R_A$ (12 Ω) and capacitance $C_{VT}$ (14 pF) (being the sum of the tuning and parasitic capacitances). An inductive choke $L_C$ provides a DC short at the input terminals of the rectifier to ensure a zero DC offset error at the input of the OS-CPR. A single rectifier stage comprises PMOS transistors as voltage-controlled switches ($M_1$ and $M_2$) and capacitors for AC coupling ($C_C$) and energy storage ($C_{DD}$ and $C_{EQ}$). To reduce the unwanted flow-back current, capacitances $C_{DC}$ and resistors $R_{DC}$ set the optimal values of the gate voltages of $M_1$ and $M_2$. From a -18.2 dBm 13.56 MHz RF signal, a 5-stage OS-CPR sets the power supply voltage ($V_{DC} = V_{0N}$) at 1.2 V.

Fig. 3 presents the all CMOS-based power management module. It includes a nanopower voltage reference, a linear voltage regulator and a low-voltage detector (LVD) with hysteresis (0.15 V). The reference produces a sub-1V stable and temperature-independent voltage. With all the MOSFETs biased in weak inversion and the op-amp $A_1$ creating a virtual ground at $V_{out}$, the current through $R_1$ is PTAT. Proper selection of $R_{C1}$, $R_2$ and $V$ sets temperature-independent voltage $V_{out}$ at 0.54 V, which is derived by combining PTAT ($V_{T2}$)
and CTAT ($V_{g,s}$) voltages. Current $I_{ref}$ is steered into $M_{10}$, generating $V_s$ used to generate $m_{I_{ref}}$, $m_{I_{ref}}$ and $p_{I_{ref}}$.

The linear regulator employs a unity gain buffer configuration to set the power supply ($V_{DD}$) of the AWSN at $V_{ref}$. Power supplies $V_{DC}$ and $V_{DD}$ are filtered using on-chip decoupling capacitors.

The low-voltage detector, which comprises switches $S_1$, $S_2$ and comparator $CM_1$, monitors the $V_{DC}$ voltage level. During power-up $V_{DC}$ initially is 0V and increases with time, until it reaches 1.2V. Also $V_{ref}$ initially is 0V. The LVD operates as follows:

1) During power-up: $S_1$ is closed and the voltage divider formed by $M_{11}$ and $M_{12}$ sets $p_{V_{DC}} < q_{V_{DC}}$. To reduce static power consumption, $q_{V_{DC}}$ is generated from the capacitive divider formed by $C_1$ and $C_2$. Voltages $q_{V_{DC}}$ and $p_{V_{DC}}$ are compared by $CM_1$ and as long as the latter is smaller, the output voltage of the LVD ($V_{LVD}$) equals $V_{DC}$.

2) Steady-state: $S_1$ opens, $S_2$ closes and $V_{ref}$ is connected to the input of $CM_1$. Once $p_{V_{DC}}$ equals $V_{ref}$ (i.e. $V_{DC}$ settles to 0.96 V), $V_{LVD}$ goes from $V_{DC}$ to 0 V, thereby enabling the temperature-to-time converter (TTC).

The TTC and the 402 MHz (MICS band) OOK transmitter are shown in Fig. 4. Derived from the circuit design presented in [6], the temperature-to-time encoded clock signal is generated by steering a weighted PTAT current ($m_{I_{ref}}$) into an integrating capacitor ($C_T$). The slope of the resulting ramp-like analog waveform is compared to two voltage references, $V_1=0.35$ V for the rising and $V_2=0.15$ V for the falling edge transitions. The resulting output square wave signal of the TTC with a time period $T_{TTC}$ is defined as

$$T_{TTC} = \frac{C_T \Delta V}{m_{I_{ref}}},$$  \hspace{1cm} (1)

Fig. 3. Power management module of the AWSN.

Fig. 4. Temperature-to-time converter and the 402 MHz (MICS band) OOK transmitter.
where \( m = 2 \), \( \Delta V = V_1 - V_2 \). A backscattering return link is formed at 402 MHz when the TTC clock signal drives switches transistor \( M_{12r} \), thereby modulating the signal power.

### III. Measurement Results

The AWSN is mounted on a double-sided, copper-clad FR-4 laminate substrate with a high quality factor coil (antenna) etched on the back plate (see Fig. 5). The physical and electrical properties of the customized antenna coil are presented in Table I. The coil is modeled using ADS Momentum.

![Antenna Coil (back plate)](image)

**Fig. 5.** The AWSN and the antenna coil on a 1/2 oz. 1.55 mm thick, double-sided FR-4 laminate substrate.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>PHYSICAL AND ELECTRICAL PROPERTIES OF THE ANTENNA COIL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical</td>
<td>Physical</td>
</tr>
<tr>
<td>( L_A ) (( \mu )H)</td>
<td>9.5</td>
</tr>
<tr>
<td>( R_A ) (( \Omega ))</td>
<td>12</td>
</tr>
<tr>
<td>( C_A ) (pF)</td>
<td>2.4</td>
</tr>
<tr>
<td>( f_{3dB} ) (MHz)</td>
<td>33</td>
</tr>
<tr>
<td>Q-Factor</td>
<td>67</td>
</tr>
</tbody>
</table>

At 13.56 MHz, the measured real and imaginary impedance components of the antenna coil are 12.7 \( \Omega \) and 0.81 \( k\Omega \), respectively (see Fig. 6). Simulation and measurement results show less than 5% discrepancy.

The microphotograph of the AWSN fabricated in AMS 0.18 \( \mu \)m CMOS technology is shown in Fig. 7. The total and the active chip area are 2.64 mm² (1.2 x 2.2 mm²) and 0.72 mm² (0.4 x 1.8 mm²), respectively.

![Energy Harvester](image)

**Fig. 7.** Microphotograph of the AWSN in 0.18 \( \mu \)m CMOS.

Superior to traditional topologies, the energy harvester operates over a large range of resistive loads (0.1 \( M\Omega \) to 0.82 \( M\Omega \)). As shown in Fig. 8, the maximum PCE is 11.5% for a 0.82 \( M\Omega \) load. Note that PCE equals the ratio of the electrical power delivered to the load and the incident electromagnetic power at the antenna.

![PCE Efficiency](image)

**Fig. 8.** PCE of the energy harvester as a function of resistive load.

The temperature conversion, jitter and temperature accuracy of the TTC are 1.5 \( \mu \)s/°C, 320 ns and 0.21 °C, respectively, from 0 to 100 °C (see Fig. 9). The temperature accuracy (\( T_{TTC_{acc.}} \)) is calculated as the ratio of the jitter to temperature conversion and equals:

\[
T_{TTC_{acc.}} = \left( \frac{320 \text{ns}}{1.50 \mu \text{s/°C}} \right) = 0.21 \text{ °C} \tag{2}
\]

In compliance with MICS, the minimum clock period of the TTC is set to 20 \( \mu \)s. Fig. 10 shows the backscattering signal from the AWSN.
Table II compares the proposed AWSN to recently published designs. This work demonstrates superior design characteristics, such as high sensitivity, PCE and TTC accuracy with ultra-low power consumption. Moreover, the AWSN is both technology and frequency scalable.

IV. CONCLUSIONS

The proposed multi-band (13.56/402 MHz) autonomous wireless sensor node with temperature monitoring is fabricated in a standard 0.18 \( \mu \)m CMOS process. Scavenging a -18.2 dBm RF signal at 13.56 MHz, the energy harvester achieves a maximum power conversion efficiency of 11.5 %. From 0 to 100 °C, the temperature conversion and accuracy of the TTC are 1.5 \( \mu \)m/°C and 0.21 °C, respectively. The total RMS power consumption is 1.5 \( \mu \)W.

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REFERENCES