Chapter 5

LOW-POWER PRECISION VOLTAGE REFERENCES

Temperature-insensitive precision voltage references are critically needed for passive wireless microsystems. Although bandgap voltage references are widely studied and numerous designs are available, the rapid reduction of supply voltages, the need for precision voltage references, and the low-power consumption requirement of passive wireless microsystems impose stringent constraints on the design of voltage references. This chapter deals with the principles and design of CMOS voltage references. The chapter starts with a brief examination of the figure-of-merits that characterize the performance of voltage references in Section 5.1. It is followed by an in-depth investigation of the temperature-dependent characteristics of semiconductors and MOS devices in Section 5.2. First-order voltage references are studied in Section 5.3 while high-order voltage references are dealt with in Section 5.4. The performance of recently reported first-order voltage reference and that of high-order voltage references such as temperature coefficient, power consumption, power supply rejection ratio, and minimum supply voltage are compared. Section 5.5 focuses on the design of ultra low-power voltage references where devices operate in weak inversion. These voltage references are of particular importance to passive wireless microsystems. The chapter is concluded in Section 5.6.

5.1 Characterization of Voltage References

There are a number of metrics that are often used to quantify the performance of a voltage reference. These metrics provide a quantitative measure of the effect of temperature variation and supply voltage fluctuation on the output of the voltage reference. In this section, we examine some of these metrics, specifically temperature coefficient, power supply rejection ratio, and the minimum supply voltage.
5.1.1 Temperature Coefficient

The temperature coefficient (TC) of a voltage reference quantifies the effect of temperature on the output voltage of the reference. Two temperature coefficients, namely normalized temperature coefficient, also known as fractional temperature coefficient, and normalized average temperature coefficient, also known as effective temperature coefficient, are often used. The fractional temperature coefficient is defined as

$$TC_f = \frac{1}{V_{\text{ref}}(T)} \frac{\partial V_{\text{ref}}(T)}{\partial T},$$

where $V_{\text{ref}}$ is the output voltage of the reference and $T$ is temperature. The fractional temperature coefficient quantifies the dependence of $V_{\text{ref}}$ on temperature at a specific temperature. Since $V_{\text{ref}}$ usually varies with temperature in a nonlinear fashion, to effectively quantify the dependence of $V_{\text{ref}}$ on temperature over a specific temperature range, the normalized average temperature coefficient defined as

$$TC_{\text{eff}} = \frac{1}{V_{\text{ref,avg}}(T_{\text{max}} - T_{\text{min}})} \int_{T_{\text{min}}}^{T_{\text{max}}} V_{\text{ref}}(T) dT$$

should be employed. Here $V_{\text{ref,avg}}$ is the average value of $V_{\text{ref}}$ over the specified temperature range, $T_{\text{min}}$ and $T_{\text{max}}$ are the minimum and maximum temperature of the temperature range, respectively. Since we usually do not know the analytical expression of $V_{\text{ref}}(T)$, the following approximation is used to estimate the normalized average temperature coefficient

$$TC_{\text{eff}} \approx \frac{1}{V_{\text{ref,avg}}} \left( \frac{V_{\text{ref,max}} - V_{\text{ref,min}}}{T_{\text{max}} - T_{\text{min}}} \right),$$

where $V_{\text{ref,min}}$ and $V_{\text{ref,max}}$ are the minimum and maximum output voltages of the reference over the temperature range, respectively. Note $V_{\text{ref,avg}}$ in (5.3) is often replaced with the desired reference voltage.

Both the fractional temperature coefficient and effective temperature coefficient have the unit ppm/$^\circ$C (ppm is the abbreviation of parts per million). Often, the maximum variation of the reference voltage over a specific temperature range is used to quantify the effect of temperature on reference voltages in engineering reports and scientific publications. It can be easily converted to ppm/$^\circ$C. For example, if the maximum variation of the output voltage of a voltage reference over $-20\sim100^\circ$C is 5 mV and the average reference voltage over the temperature range is 1.2 V, the effective temperature coefficient of the reference voltage is calculated from