Chapter 2
Load and Power Conditioning

The parts that form the load of autonomous sensors—sensors, processor and transceiver—plus their power and energy needs, must be considered for a model of the load used in designing the power supply subsystem. The load's power requirements will depend on the quantity to be measured and on the system requirements. For example, ambient temperature is usually a slow-changing quantity that enables small duty cycles. A sensor for presence detection has some parts that are always active and others (*e.g*. transmitter) that are randomly triggered by an event (*e.g*. people walking by).

This chapter begins with analysis of the power consumption of the load's constituent parts. A simple and general model that characterizes the overall load power consumption is then proposed. Measurements of the power consumption of an autonomous sensor were performed to validate the proposed model. The power conditioning stage is also considered here, as some devices that form the load, such as the transceivers, generally contain an internal voltage regulator. The power conditioning stage is used to adapt the electrical characteristics of the power source to that of the load. The different strategies that can be addressed are described and compared.

2.1 Load

Figure 2.1 shows the block diagram of an autonomous sensor. The sensor(s), the processor and the transceiver are considered from hereafter as the *load* to be supplied. This load is usually inactive (in sleep mode) and wakes up to perform some of the following actions: measurement, processing and transmission/reception of data [1].

We analyzed the different parts of the load from the perspective of the power consumption in order to obtain a simple and general model that only provides the relevant information.

To obtain a model of the load, we evaluated the power supply characteristics of several sensors, commercial microcontroller units (MCUs) and transceivers. We also

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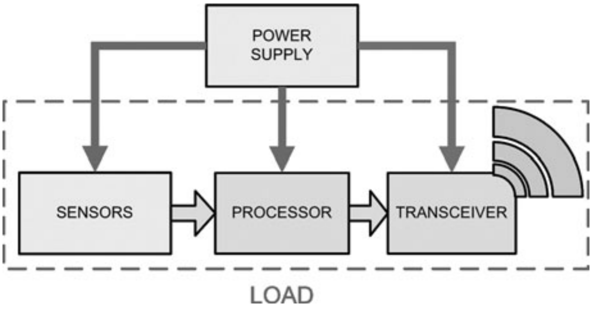


Fig. 2.1 Block diagram of an autonomous sensor

reviewed the relevant literature. However, load design and optimization fall outside of the scope of this thesis.

2.1.1 Sensors and Signal Conditioning

Sensors convert a signal from a physical or chemical quantity into a corresponding signal in the electrical domain. There are many types of sensors, and these vary in their power needs. Nonetheless, regarding the power supply, sensors can be classified as either *modulating* or *self-generating* [2]. In modulating sensors, most of the output signal power comes from the power source. Conversely, in self-generating sensors, output power comes from the input (the quantity to be measured). The output signal of the sensors can be in the millivolt range, and signal-conditioning circuits are used for reaching a suitable signal (units of volts, dc signal) for the analog-to-digital converters (ADCs), which yield a digital code. Signal conditioners can perform any of the following functions: amplification, level shifting, filtering, impedance matching, modulation and demodulation.

Modulating sensors can be resistive, capacitive or inductive. Resistive sensors dissipate energy. Low value resistive sensors are especially prone to high power consumption when used in voltage dividers or bridges. Specific strategies have been proposed to reduce this power consumption [3–5]. A dc voltage or current normally drives the voltage divider or the resistive bridge. For sensors with low resistance, power consumption can be lowered by reducing the driving voltage or current, although at the expense of smaller output and then lower signal to noise ratio. In contrast, there are sensors that require a minimum voltage supply (*e.g.* ultrasonic-based sensors). This voltage supply can be greater than the maximum voltage supply accepted by the other parts of the load; in this case, it would require a dedicated power conditioning stage. The parasitic elements of capacitive and inductive sensors waste some power and additionally these sensors need to be excited with a time-varying voltage or current, which demands specific circuitry that increases power consumption.

Resistive, capacitive and inductive sensors can form part of a variable oscillator that provides an ac signal whose amplitude, period, duty cycle, frequency or phase is proportional to the quantity to be measured. When information is encoded in amplitude, ac signals are typically translated to the dc domain in order to yield a suitable signal for the ADC input. If the phase of the ac signal has to be detected, coherent detection is required. Contrariwise, when the phase carries no information, three basic techniques can be used: peak detection, rms measurement, or mean value measurement after rectification. When information is encoded in either frequency or time, it can be directly measured using an MCU timer. Direct sensor-to-microcontroller techniques [6] have been proposed to directly interface resistive and capacitive sensors to an MCU, which can enable simplification in circuit design and reductions in power consumption. Specific signal conditioners for capacitive sensors built from switched capacitors are also available.

Self-generating sensors provide a voltage or current signal. High amplification is needed for sensors that provide a voltage at the millivolt level (*e.g.* thermocouples). Electrometers, transimpedance amplifiers, and charge amplifiers are used with sensors that provide a relatively high voltage that comes from a high-output impedance source (*e.g.* pH electrodes), or a low current source (*e.g.* piezoelectric sensors) [2]. The operational amplifiers (*op amps*) best suited for building electrometer amplifiers are those whose input stages are based on FET or MOSFET transistors, because these present higher input impedances. Regardless, op amps with low noise, offsets and drifts are required for good resolution and accuracy. Unfortunately, there is a tradeoff between the power consumption and the noise and drift characteristics of op amps. Slew rate and output drive capability also influence their power consumption and performance [3]. Finally, resistances in the megaohm range reduce power consumption, although at the expense of greater thermal noise.

Figure 2.2 shows a generic block diagram of the sensor and signal conditioning stages summarized above, with special emphasis on the power consumption of each part.

Low-pass filters are used to reduce noise for sensors or circuits that employ high resistances, low voltages and/or low currents. The lower the cutoff frequency, the lower the output noise, the higher the resolution, and the longer the response time (and consequently, the energy consumed). Placing the filters right at the sensor's output can reduce the power consumption, as the voltage swing at the filter capacitors will be smaller [4].

If the components of the signal conditioning stage are always active, then they must have ultra-low power consumption. The tradeoff between power consumption and the characteristics of the components must be considered during design. Contrariwise, for components that spend most of their time asleep or powered off, higher-performing units can be employed. Thus, the response and start-up times of the electronic parts involved must be considered. These times sometimes dictate the length of time that the electronics must be activated prior to taking a valid measurement, and therefore, directly affect both the active time and the energy consumption of the autonomous sensor. Finally, the bandwidth of the physical signal to be measured determines the minimum sampling frequency, and consequently, when an autonomous sensor (or at least, its parts required for measurement) must be activated.

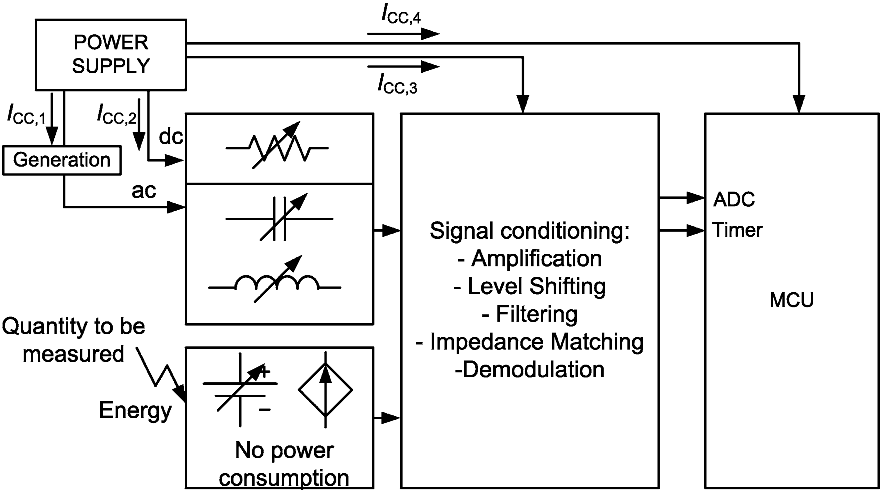


Fig. 2.2 Block diagram of sensors and signal conditioning blocks, illustrating each part's power consumption

2.1.2 Microcontrollers

Low power MCUs are typically used in autonomous sensors to process the digital data and to obtain the measured quantity from a digital code by using additions, multiplications or look-up-tables, among other methods. Most MCUs include ADCs and timers, which enable measurement of dc voltages, frequency or period. Microcontroller units can also implement other functionalities that are not directly related with sensing yet are required for controlling autonomous sensors, including battery protection algorithms, and control of the transceiver or the regulators. Digital signal processors (DSP) are used when high processing capability is needed (*e.g.* for video processing); however, due to their high power consumption, we did not consider them in this work.

Microcontroller units generally lack embedded voltage regulators and accept a wide range of supply voltages (V_{CC}). In order to save power, they are given several power modes (or *states*). There are two main power modes common to all manufacturers: *sleep* and *active*. In sleep mode, all the modules are typically disabled except for a low-power timer (internal or external) to wake up the MCU. In some cases, the MCU can only be woken up by external interruption; this case offers ultra-low power consumption. Data on current consumption (listed on manufacturers' datasheets) in active mode usually accounts for the current consumption of the CPU and the clock; however, if other blocks (*e.g.* ADC, analog comparator, and internal reference) are active, their power consumption must be added to that specified in active mode.

Some tasks, such as writing or erasing flash memory, are power intensive. In addition to active and sleep power modes, manufacturers usually provide several intermediate power modes that may vary widely in current consumption and in

Table 2.1 Power specifications of three low power commercial microcontroller units [7–9], showing typical values

Model	V_{cc} (V)	$I_{MCU,sleep}$ (μA)	$I_{MCU,active}$ (μA)	Wakeup time from sleep	Wakeup time from reset
TI, MSP430x11x2	1.8–3.6 >2.2 @ $f = 4$ MHz > 2.8 @ $f = 8$ MHz	0.1 @ 2.2 V (ram retention)	200 @ 2.2 V; 1 MHz	6 μs @ $f < 3$ MHz	2 ms
Atmel, ATtiny24A	1.8–5.5 >2.7 @ $f > 4$ MHz >4.5 @ $f > 10$ MHz	0.1 @ 1.8 V	210 @ 1.8 V; 1 MHz	750 ns @ $f = 8$ MHz	4 ms
Microchip, PIC16LF72X	1.8–3.6 >2.3 @ $f > 16$ MHz	0.02 @ 1.8 V	110 @ 1.8 V; 1 MHz	7 μs	65 ms

the components that are active. To minimize consumption, the input/output pins must be handled carefully, and all the unnecessary parts should be disabled. Table 2.1 shows the current consumption in sleep ($I_{MCU,sleep}$) and active ($I_{MCU,active}$) modes at 25 °C for three similar commercial MCUs. As observed in the table, a difference of three to four orders of magnitude can be expected from $I_{MCU,sleep}$ to $I_{MCU,active}$.

Figure 2.3 shows how $I_{MCU,active}$ increases with increasing voltage supply (Fig. 2.3(a)) and operating frequency (Fig. 2.3(b)). These plots are based on an Atmel MCU [8], but data for devices from other manufacturers are similar [7]. As observed in Fig. 2.3(a), $I_{MCU,active}$ increases linearly with increasing supply voltage. Consequently, the dissipated power depends on the square of the supply voltage [10]. Thus, working at the minimum possible supply voltage is recommended. Alternatively, temperature appears to only slightly affect $I_{MCU,active}$. Figure 2.3(b) shows that $I_{MCU,active}$ also increases linearly with increasing oscillator frequency (f). However, as the frequency increases, the time needed for executing instructions decreases, leading to similar overall energy consumption for the MCU. Nonetheless, working at the lowest supply voltages in order to save power is only possible at the lowest clock frequencies ($f < 4$ MHz for $V_{CC} = 1.8$ V in Fig. 2.3(b)).

Dynamic voltage scaling (DVS) [1] is a power-saving technique that instantaneously adapts the supply voltage to the needs of the autonomous sensor. For example, when the autonomous sensor runs at maximum frequency, the supply voltage is set at a high value, whereas when the autonomous sensor sleeps, the supply voltage is reduced to its minimum value. This technique exploits all the available resources at a minimum energy cost, but leads to more complex circuits and control.

In sleep mode, the MCU works with a low-power timer at a fixed frequency; consequently, $I_{MCU,sleep}$ is not frequency dependent, but does vary with temperature and voltage (Fig. 2.4). As observed in the figure, the variation of $I_{MCU,sleep}$ with supply voltage is not linear under these conditions, in which temperature has a greater effect. The $I_{MCU,sleep}$ in this figure is roughly three orders of magnitude lower than the $I_{MCU,active}$ in Fig. 2.3(b).

When switching between power modes, time is spent on waking up the components or on storing the MCU current state. Therefore, power (and consequently,

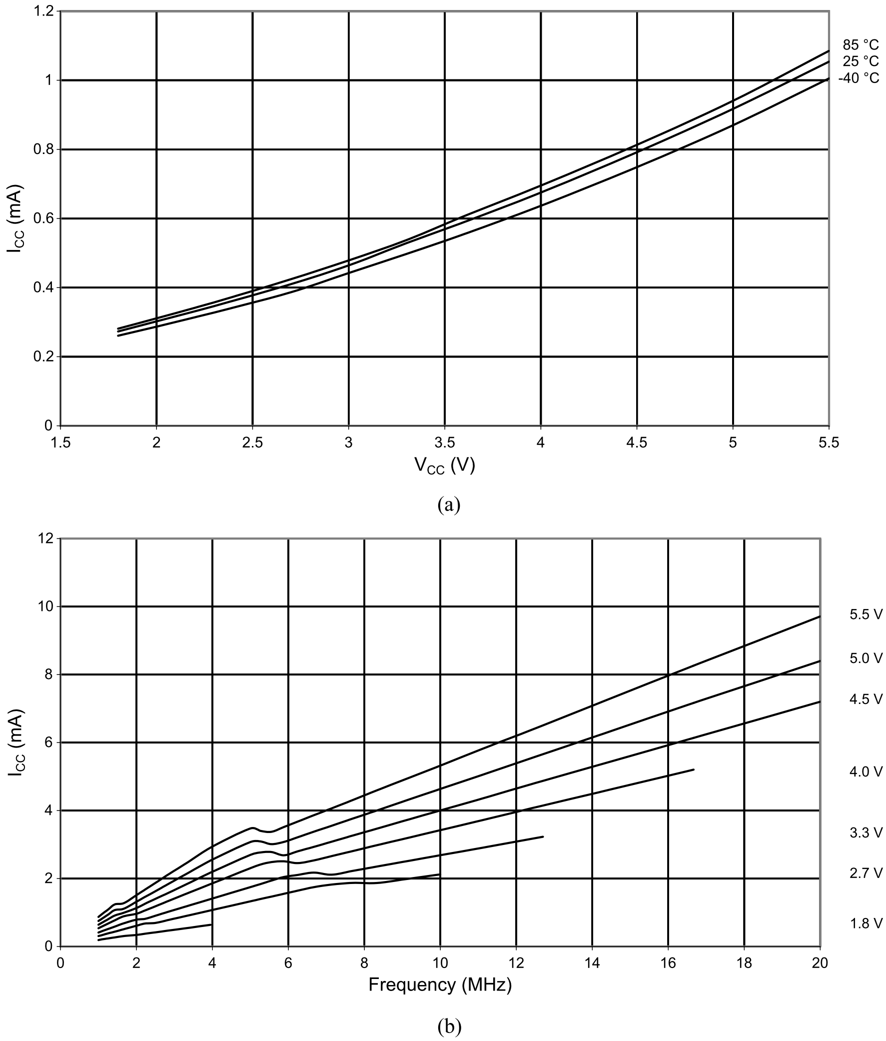


Fig. 2.3 $I_{\mathrm{MCU,active}}$ versus (**a**) supply voltage at several temperatures and 1 MHz, and (**b**) frequency at several supply voltages. Data from the ATtiny24A Atmel microcontroller unit [8]

energy) is wasted during this time. Usually, as the power consumption of a state decreases, the time required to wake up from this state increases, resulting in non-negligible energy consumption [11]. Moreover, every component that can be switched on and off has a stabilization time that must be accounted for in every specific application. Thus, if the amount of energy saved by a component while sleeping is similar to that wasted in its stabilization time, thus no energy will be saved. For this scenario, the component should probably be kept awake.

Table 2.1 presents the wake up times from the sleep state and from reset for each MCU. As observed in the Table, the values differ by model; thus, these times can

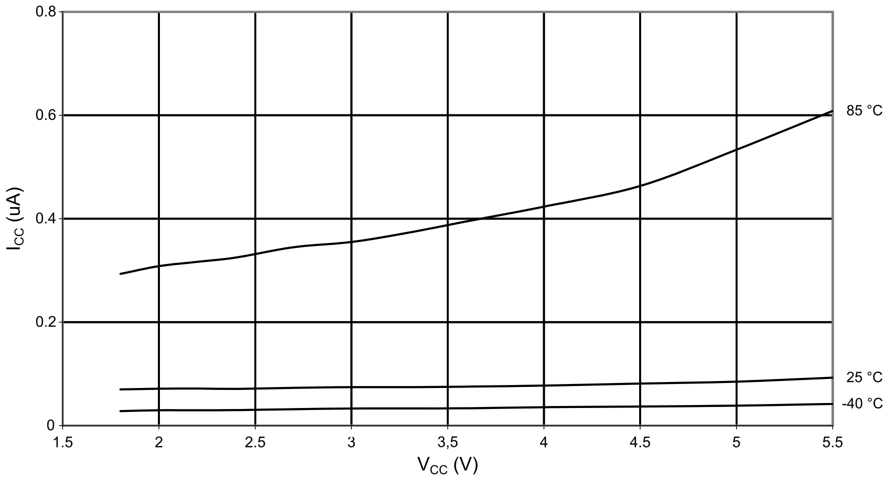


Fig. 2.4 Variation of $I_{MCU,sleep}$ with voltage supply and temperature for the ATtiny24A Atmel microcontroller unit [8]

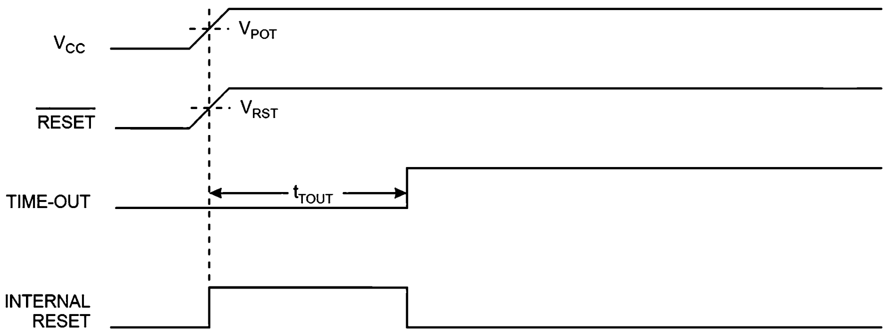


Fig. 2.5 Power on reset timing for the ATtiny24A Atmel microcontroller unit [8]

be used as criteria for selecting the MCU that offers the lowest power consumption for a given autonomous sensor. However, these data must be interpreted with caution, as manufacturers differ in their specifications and characterization methods.

Waking up from reset takes much longer than waking up from sleep. Figure 2.5 shows that each time an MCU is powered up from its off state (no supply voltage), a reset (*power on reset [POR]*) is performed to generate a suitable supply voltage. Therefore, the time that an MCU takes to be completely operational from reset must be considered when powering the node for the first time or whenever the power supply is removed between measurements (t_{TOUT} in Fig. 2.5).

2.1.3 *Transceiver*

A transceiver transmits and receives data wirelessly via RF waves, according to a proprietary or standard protocol. The Zigbee specification [12] is optimized for networks with a very low data rate and low power consumption. Bluetooth low-energy technology, recently included in Bluetooth version 4.0, offers minimal power consumption at high data rates (1 Mbit/s) [13].

This section only covers ZigBee transceivers, as Bluetooth low-energy technology was not available during the development of this work. It begins with a brief summary of the remarkable characteristics of the Zigbee specification, and then analyzes the power supply characteristics of some commercial models.

2.1.3.1 The Zigbee Specification

The Zigbee specification is based on IEEE 802.15.4 standard and defines a series of protocols for efficient, facile communication of multiple devices. It can operate at 2.4 GHz (16 channels), 915 MHz (10 channels, US free band) and 868 MHz (1 channel, Europe free band). The modulation used is direct-sequence spread spectrum (DSSS) and the medium access protocol is Carrier Sense Multiple Access with Collision Avoidance, (CSMA/CA), which directly impacts power consumption, as the channel must be listened to before a packet can be sent. Several network topologies can be implemented, including tree, star or mesh. In most commercial ZigBee transceivers this process is done automatically and is transparent to the user. The network is established as follows: the first ZigBee device present in the environment establishes a network and names itself as parent device; then, as new nodes arrive, they add as children to this network [12]. The ZigBee protocol defines three types of devices:

- Full function devices (FFD): These route messages between ZigBee devices. When they are allocated in large networks, they should remain active as long as possible. Alternatively, if these nodes are allocated in small networks, then they can be periodically woken up, always in synchronization with the nodes they have to route. These devices can also incorporate sensors.
- Reduced-function devices (RFD): These are end devices that periodically poll their parent for any message addressed to them. They are typically the sensor nodes of the network. There are two types:
  - Sleepy end device (SED): These are always joined to the same parent device and are unable to leave the network. They are used for static networks.
  - Mobile sleepy end device (MSD): After being inactive for three seconds, these devices are erased from the network; upon reactivation, they search for a new parent device from the same network or another one.
- Coordinator (COO): This node is the FFD that initiates the network and parent of all other devices in the network. A network can only have one COO.

Table 2.2 Power specifications of ZigBee transceivers [14–17]

Model	V_{cc} (V)	$I_{RF,sleep}$ (μA)	$I_{RF,rx}$ (mA)	$I_{RF,tx}$ (mA)	Wakeup time from sleep	Wakeup time from reset
Atmel, AT86RF230 (system-on-chip)	1.8–3.6	0.02	15.5	16.5 (@ 3 dBm)	880 μs	3 ms
Ember, EM 250 (system-on-chip)	2.1–3.6	1	36	36 (@ 5 dBm)	Not specified	Not specified
TI, CC2520 (transceiver only)	1.8–3.8	<1 @ full V_{CC} range	18.5 @ full V_{CC} range	33.6 (@ 5 dBm and full V_{CC} range)	300 μs	≥ 0.3 ms (clock dependent)
TI, CC2430 (system-on-chip)	2–3.6	0.3	26.7	26.9 (@ 0 dBm)	120 μs	1.7 ms @ 32 kHz

The type of ZigBee device configured will influence the power consumption of the node. Network management overhead (*e.g.* acknowledgements) can also strongly influence power consumption if not carefully designed.

2.1.3.2 Commercial ZigBee Transceivers

The main characteristics of the four marketed ZigBee transceivers that we studied are listed in Table 2.2. Of these devices, three are system-on-chip (SOC) integrated circuits that combine an RF transceiver and an MCU. They offer several power modes, and every part of the system can be independently powered on or off by setting a specific register. All the transceivers have an internal linear low dropout regulator (LDO) to supply a stable voltage for some of the system parts (*e.g.* the radio). Consequently, the current consumption in active states barely changes with voltage supply variations (Fig. 2.6(a)) and is quite higher than that of MCUs (Sect. 2.1.2). The transmit current ($I_{RF,tx}$) is slightly influenced by the transmitted power. Table 2.2 displays this current for the maximum transmitted power allowed, and shows the reception ($I_{RF,rx}$) and sleep ($I_{RF,sleep}$) currents as well. In most cases $I_{RF,tx}$ is four to five orders of magnitude higher than $I_{RF,sleep}$. Current consumptions are specified at $V_{CC} = 3$ V. Wakeup time varies among different commercial transceivers and depends on the power-down mode from which they stem. As with MCUs, this time is not negligible.

Figure 2.6 shows how $I_{RF,tx}$ (a) and $I_{RF,sleep}$ (b) depend on the supply voltage for a CC2520 transceiver [16]. The variation in $I_{RF,tx}$ above 2 V is very low (<5%); thus, $I_{RF,tx}$ can be considered a constant current. As such, the power consumption in this mode is directly proportional to the supply voltage. In contrast, $I_{RF,sleep}$ almost triples when the supply voltage varies by 2 V (in sleep state the LDO is disconnected). Thus, working at the minimum possible supply voltage is desirable for both MCUs and transceivers in order to reduce power consumption.

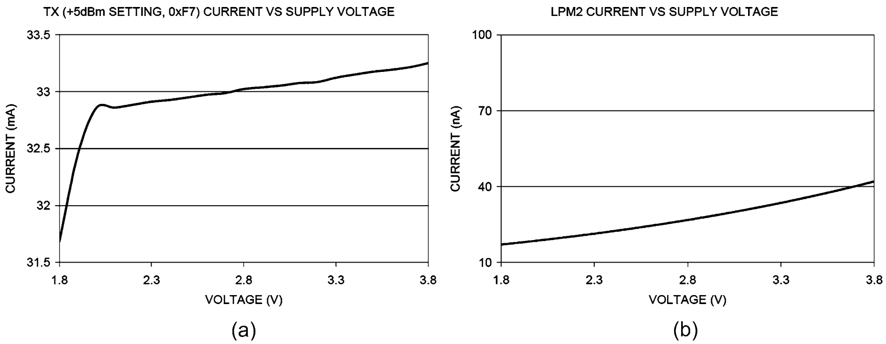


Fig. 2.6 (**a**) $I_{RF,tx}$ @ +5 dBm versus supply voltage and (**b**) $I_{RF,sleep}$ versus supply voltage. Data from a CC2520 transceiver [16]. Courtesy Texas Instruments

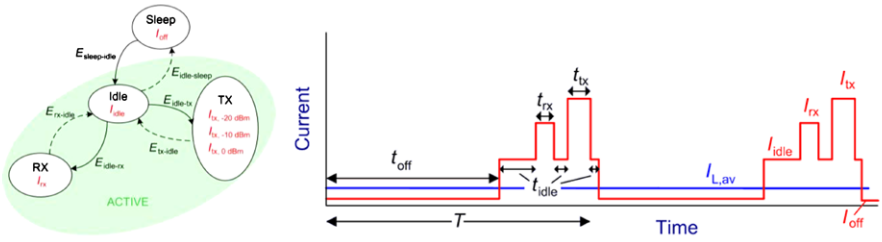
2.1.4 Load Model

The literature contains various models for wireless sensor nodes or networks. Some researchers have extensively analyzed MAC or network protocols to obtain a Markov Chain that describes the nodes [1, 18] or the network [19] from the perspective of power consumption. These studies are mostly used for simulation of network lifetime. Other researchers have evaluated the sensor node as a single element that does not interact with the rest of the network; they use a load model to test proposed models for other parts of the autonomous sensor, such as a supercapacitor [20] or an energy harvester [21]. In contrast, we sought a simple model that easily describes the load power profile.

Dynamic power management (DPM) is a power-saving strategy based on the connection or disconnection of the parts of a system that are not used, which generates several power consumption states. It has been applied to wireless sensor networks since their onset [1]. Most authors [1, 18, 19] have dealt with four or five active states (depending on the blocks of the load that remain active; see Fig. 2.1).

We considered a model with just three active states, which represent the main functions (transmit, receive and idle), plus one sleep state (Fig. 2.7) [19]; nonetheless, a different number of states can be considered. Because not all the functionalities are always done, not all the active states need to be visited when the load wakes up. In sleep state, all the parts remain inactive, except for some timers or the circuitry required for waking up the node. In idle state, only the sensing parts and the processor parts remain active. In the transmit or receive state, the transceiver is encoding and then sending packets, or receiving and then decoding packets. The MCU and the transceiver are both active at this time; hence, the total power consumption in these states is equal to the sum of the current consumption of both components. The energy spent to switch between states (*e.g.* $E_{\text{sleep-idle}}$ in Fig. 2.7(a)) can be considered by simply extending the time spent in the initial or destination state. The average current consumption ($I_{L,av}$), assuming a periodic performance of the node, gives:

$$I_{L,av} = \frac{t_{tx} \cdot I_{tx} + t_{rx} \cdot I_{rx} + t_{idle} \cdot I_{idle} + t_{off} \cdot I_{off}}{T}, \tag{2.1}$$



(a) (b)

Fig. 2.7 (**a**) State diagram when considering three active states plus one sleep state. (**b**) A generic current profile of the load. Both adapted from [11]

whereby $T = t_{tx} + t_{rx} + t_{idle} + t_{off}$; t_{tx}, t_{rx}, t_{idle} and t_{off} are the time intervals that the node is transmitting, receiving, in an idle state and sleeping, respectively; and I_{tx}, I_{rx}, I_{idle} and I_{off} are the current consumptions in the corresponding states (Fig. 2.7(b)). A state diagram can be drawn (Fig. 2.7(a)). Autonomous sensors usually wake up to the idle state, and then may transmit or receive. They then return to the idle state prior to sleep. Nonetheless, if no information has to be transmitted (*e.g.* when recording a measurement), the autonomous sensor simply wakes up to the idle state.

As stated in Chap. 1, the average current consumption is necessary for sizing the power supply. As later explained in Chap. 4, the peak value of the current can influence the voltage behavior of the power supply, especially at relatively high values of output resistance.

2.1.4.1 Measurements

To assess our model, we measured the current consumption of an autonomous sensor that used an EM 250 transceiver. We configured the autonomous sensor to send a data packet every 5 min and disabled all the other network default functionalities. The sensor node measured battery voltage and ambient temperature. The sensors and signal conditioning circuits functioned at 1.8 V, so they were powered from the internal regulator of the transceiver, which produced this voltage.

We computed the average current consumption of the sensor node at 3 V by measuring the current consumption when packets are sent and the current consumption when in sleep mode. For these measurements, the sensor node was powered from a dc power supply. Firstly, we used a DSO8104A oscilloscope and a 10 Ω resistor, placed in series with the dc power supply, to measure the time intervals and the current when the sensor node woke up (Fig. 2.8). Despite the fact that we had disabled all the network functionalities, every approximately 32 s the sensor node woke up for just 2 ms. These network functionalities cannot be disregarded. Figure 2.8(b) offers a more detailed illustration of the time at which the packet was sent (every 300 s, which corresponds to $t = 142$ s in Fig. 2.8(a)). As observed in the figure, the sensor node woke up three times during a period of 1.5 s. This phenomenon

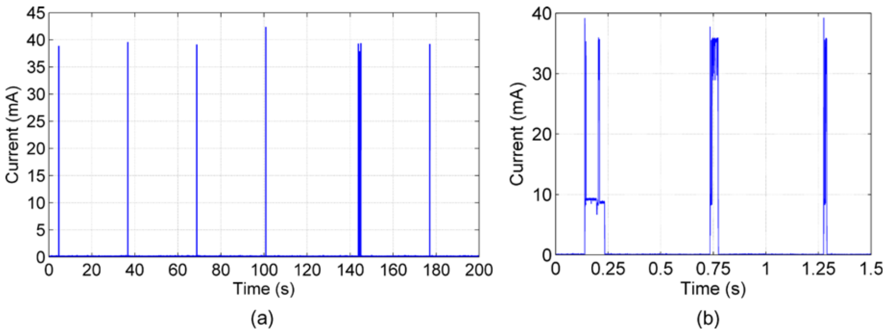


Fig. 2.8 Power consumption of a sleepy end device. (**a**) 200 s acquisition; and (**b**) magnified area of plot at the time when a packet was sent

Table 2.3 Times and currents in every state of the load working as a sleepy end device

State	Time (ms)	Current (mA)	Average current (μA/%)	
Idle	101.6	9.3	3.224	20.68
Transmit (data + ACK)	32.7	36	3.924	25.17
Transmit (network functionalities)	17.1	36	2.052	13.16
Receive (data + ACK)	13.7	34.9	1.594	10.22
Sleep	299831.8	0.0048	4.797	30.77
TOTAL	300000	–	15.59	100

of waking up more than once each time a packet had been sent was due to polling the parent for acknowledgement (ACK) [22]. The current behavior in Fig. 2.8(b) is similar to that described in Fig. 2.7.

We next measured the current while the node was sleeping, using the 34401A (Agilent) multimeter in the 10 mA scale: the value was 4.8 μA at 3 V. This current consumption was mostly due to a resistor divider used to measure the supply voltage. Table 2.3 summarizes the times and currents spent in every state of the load every 5 min. We distinguished between network functionalities and data packets in order to determine if the ZigBee network functionalities consumed a significant amount of power. We were able to easily compute the value of $I_{L,av}$ by using (2.1): the result was 15.59 μA. We also computed the average current of each state. For this T (5 min), network functionalities corresponded to 13% of $I_{L,av}$. The greatest contribution was from the sleep state. The network functionalities and the sleep state consume an even greater share of power in applications with a larger T. Thus, in these cases, minimizing the power consumption in sleep state and disabling all unnecessary network communications are essential.

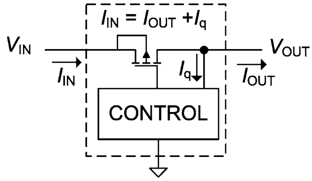


Fig. 2.9 Linear regulator using a MOSFET

2.2 Power Conditioning

Power conditioning is used to adapt the power delivered by the power source to the load's power needs (Fig. 1.2). The power source can be either a primary battery or an energy harvester, which nearly always includes a storage unit (*i.e.* a secondary battery or supercapacitor). The supply voltage needs of autonomous sensors are described earlier in this chapter and the electrical characteristics of primary batteries and storage units are described in Chap. 4.

Power conditioning is mainly achieved through the use of voltage regulators. Three main types can be outlined [23]: *linear regulators*, *switching regulators*, and *charge pumps* (or *non-inductive switching regulators*). Regulators can be skipped whenever the voltage range of the power source fits within that of the load. However, as we have seen, the power consumption of the load is reduced by working at the minimum supply voltage. When using a regulator to achieve this, its power waste should be less than the power gain. Whenever the load or some of its parts go to sleep, the corresponding voltage regulator should be disabled or put into shutdown in order to save power. Regardless, designers must assure that the MCU (or the circuit that controls the power conditioning stage) never loses its own power supply—otherwise, the load will not be able to restart.

In a voltage regulator, efficiency (η) is defined as the ratio of power output ($P_{OUT} = V_{OUT} I_{OUT}$) to power input ($P_{IN} = V_{IN} I_{IN}$), as observed in (2.2), where V and I refer respectively to the voltage and current.

$$\eta = \frac{P_{OUT}}{P_{IN}} = \frac{V_{OUT} I_{OUT}}{V_{IN} I_{IN}}. \tag{2.2}$$

In the remaining of this section we describe the main features of the different types of voltage regulators as well as a control strategy used in switching regulators for low power loads.

2.2.1 Linear Regulators

Linear regulators are based on an active device, such as a bipolar junction transistor or field effect transistor, operating in its *linear region* (Fig. 2.9), or a passive device (*e.g.* a Zener diode), operating in its *breakdown region*. The regulating device is employed as a variable resistor: it continuously adjusts a voltage divider network to maintain a constant output voltage. Linear regulators provide a regulated output that is lower than their input ($V_{OUT} < V_{IN}$). A dropout between input and output is

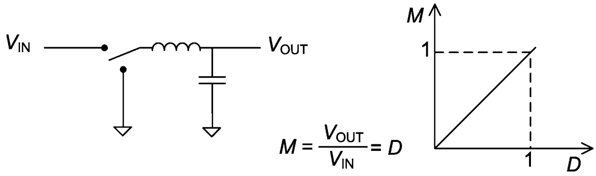


Fig. 2.10 A buck converter and its conversion ratio

required, although its value can be very small (this is the case for *low-dropout linear regulators*) [24].

I_{IN} equals I_{OUT} plus the current consumed by the control circuitry (I_q). Equation (2.3) assumes $I_q \ll I_{OUT}$. Efficiency increases as the voltage difference between input and output (ΔV) is decreased. Maximal efficiency is achieved when the difference between input and output is equal to the dropout voltage (V_{DO} in (2.3)).

$$\eta = \frac{V_{OUT}}{V_{IN}} = \frac{1}{1 + \frac{\Delta V}{V_{OUT}}},$$
$$\eta_{MAX} = \frac{1}{1 + \frac{V_{DO}}{V_{OUT}}}. \tag{2.3}$$

Commercial IC linear regulators are easy to use. For example, regulators with fixed output voltage require only two external capacitors to function. Furthermore, they do not suffer from any significant noise, since they do not require any switching elements, and therefore, their circuit board layout is not critical. The power that is not delivered to the load is dissipated as heat in the regulator. Thus, when used in high-power applications these regulators demand board space for thermal dissipation [25].

2.2.2 Switching Regulators

Switching regulators can *step up* (increase), *step down* (decrease), or *step up or down* (increase or decrease) their input voltage. Their name derives from the fact that they use a switch in combination with a filter to change the voltage level. The conversion ratio ($M = V_{OUT}/V_{IN}$) is the ratio of output voltage to input voltage. It depends on the switch's duty cycle (D). The most common topologies for switching regulators are *buck converter* (which step down; see Fig. 2.10), *boost converters* (which step up; see Fig. 2.11) and *buck-boost converter* (which step up or down, depending on D, and invert V_{IN}; see Fig. 2.12) [26]. Switches are usually implemented with transistors and diodes. Synchronous converters use two transistors that are alternatively activated, which increases the efficiency. The duty cycle is usually controlled in order to maintain a fixed output voltage. Section 2.2.4 describes a control strategy suited for low-power loads.

Contrariwise to linear regulators, ideal efficiency is 100%, as no dissipative elements are present. In practice, though, internal power losses (P_{LOSS}), which are classified as either *dynamic* or *static*, limit the maximum efficiency. Dynamic losses

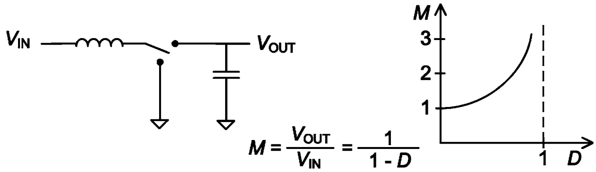


Fig. 2.11 A boost converter and its conversion ratio

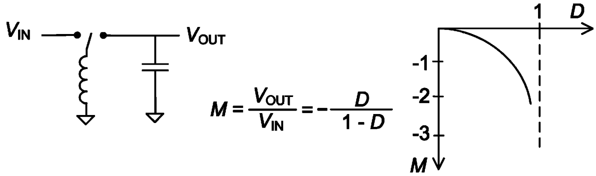


Fig. 2.12 A buck-boost converter and its conversion ratio

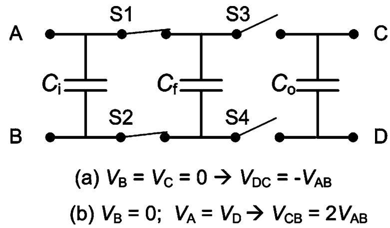


Fig. 2.13 (**a**) An inverter charge pump and (**b**) a doubler charge pump

are load dependent (*i.e.* they increase as the load current increases) and derive from parasitic elements, the conduction losses of the switch, and the switching losses (which also depend on switching frequency). In contrast, static losses are constant, regardless of the load current. They are associated to the control part of the converter (*i.e.* the quiescent current going into the control circuit). Dynamic losses predominate at higher I_{OUT}, whereas static losses predominate at lower I_{OUT}. Obviously, the lower the P_{LOSS}, the greater the efficiency. Efficiency for milliampere load currents is typically greater than 90%, but decreases for lower I_{OUT}. Nonetheless, several power saving techniques have been developed to improve efficiency at low output currents. Switching regulators generate electromagnetic interference (EMI) from the switched current of the inductor. Thus, in order to lessen the effects of EMI on the analog parts of the entire system, the board should be carefully laid out. Electromagnetic interference can also be minimized through the use of filters.

2.2.3 Charge Pumps

Charge pumps are switching converters that periodically switch capacitors to step down, step up, or step up or down voltages; they do not employ inductors for these functions. They are based on the charge-transfer process. Figure 2.13 shows the charge-transfer basic circuit. When S1 and S2 are closed the charge is transferred from the input capacitor (C_i) to the *flying capacitor* (C_f). In contrast, when S1

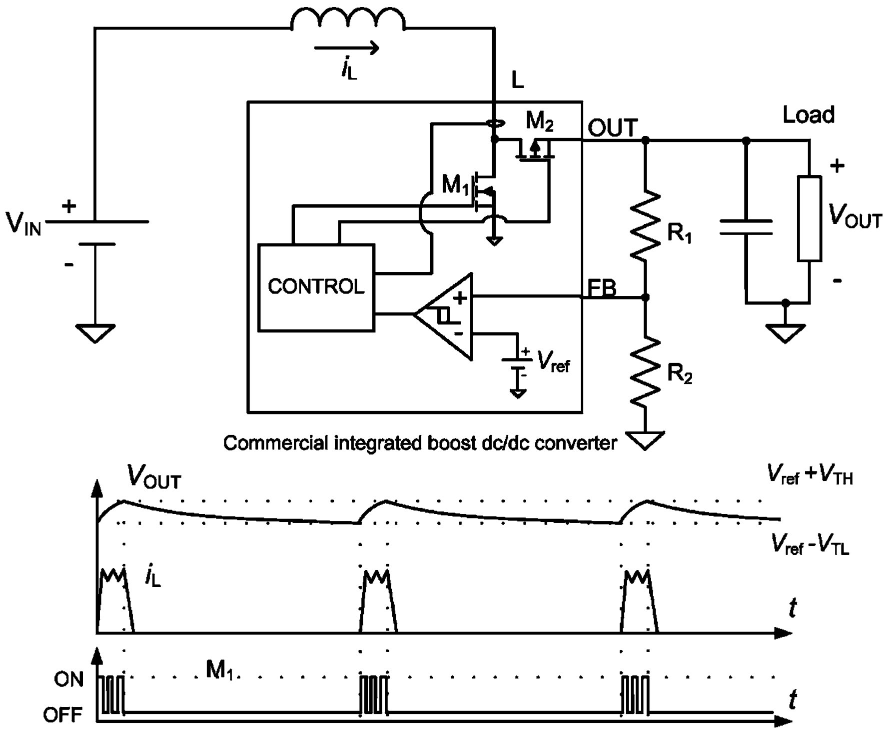


Fig. 2.14 Pulse frequency modulation used in a boost regulator at light loads [29]

and S2 are subsequently opened, and S3 and S4 are closed, there is charge transfer between C_f and the output capacitor (C_o). Assuming no losses, in steady state $V_A - V_B = V_C - V_D$. If B and C are connected and grounded, then an *inverting charge pump* is obtained (Fig. 2.13(a)). Alternatively, if A and D are connected, and B is grounded, then a *doubler charge pump* (*i.e.* one which doubles the input voltage) is obtained (Fig. 2.13(b)) [27].

Analogously to conventional switching regulators, different control strategies for the switches are used in order to maintain a fixed output voltage. Further, they also present dynamic and static power losses. Commercial devices feature several power-saving modes to improve efficiency at low load currents. Charge pumps generate some noise, but it is smaller than that of conventional switched regulators. These devices support loads in the range of hundreds of milliamperes.

2.2.4 Control Strategy

Switched regulators and charge pumps require a control strategy for turning their switches on and off. *Pulse width modulation* (*PWM*) is the most widely used control strategy for high load currents [26]. Alternatively, *pulse frequency modulation*

(*PFM*), which is based on hysteresis control of the output voltage, is a control strategy employed to achieve low power consumption by the converter and high efficiency with light loads [28]. We only dealt with PFM, as it is intended for low-power loads.

Figure 2.14 shows a schematic of an inductor-based synchronous PFM boost regulator together with the temporal evolution of the output voltage (V_{OUT}), the inductor current (i_L), and the control signal of the internal switch M_1. Switches M_1 and M_2 remain off until V_{OUT} falls below a low threshold value ($V_{ref} - V_{TL}$). Then, the switches alternately turn on in order to transfer electrical charge from the input to the output until V_{OUT} reaches a high threshold value ($V_{ref} + V_{TH}$), at which point the process restarts. For light loads, the inactive period increases, maintaining low overall power consumption and high efficiency. The same concept can be applied to buck or buck-boost switching regulators and to charge pumps. Several regulators employing this strategy are commercially available.

2.3 Conclusions

This chapter describes the power consumption performance of all the parts of autonomous sensors: sensors, signal conditioners, MCUs and transceivers.

Regarding the power supply, the sensors can be classified as either *modulating* or *self-generating*. Modulating sensors modulate a signal and can be resistive, inductive or capacitive. The power dissipated by resistive sensors can be sizeable for some low value sensors. Ideally, inductive and capacitive sensors do not consume power. However, both their parasitic elements and the required ac excitation circuitry waste power. Self-generating sensors generate an electrical signal (sometimes quite small) from the physical quantity to be measured. A signal conditioning stage is usually required to interface sensors to the MCU (ADCs or timers). Specially, those sensors providing small-level signals may need precision op amps that inherently present high-power consumption. As a result, special care must be put on the design of sensors and their signal conditioning in order to minimize the power consumption of this stage. Several techniques proposed in the literature can be used to reduce the power consumption of some sensors. Finally, designers must select devices that meet the system requirements with the lowest power consumption.

Microcontroller units acquire the signal from the sensors and perform other tasks. Their power consumption in active mode is two to three orders of magnitude less than that of the transceiver. However, if not properly handled, the active blocks inside the MCU and the input/output ports can considerably increase the final power consumption of the MCU. Additionally, the power consumption can vary several orders of magnitude between active and sleep states. So, MCUs must be carefully handled in order to keep their power consumption in a low level.

The transceiver communicates with the other nodes of the network via an RF signal. It is usually considered the most power hungry part, but some sensors can surpass its power consumption, especially if not correctly designed. The power consumption during data transmission is four orders of magnitude higher than the power consumption during sleep.

The MCU and the transceiver consume more current at increasing supply voltage. Thus, one power-saving strategy is to operate at the minimum supply voltage (provided that the required functionalities can run at this voltage level). However, this may not always be desirable: for example, an MCU cannot operate at maximum frequency at its minimum supply voltage. Hence, power-saving techniques such as DVS can also be considered.

Autonomous sensor operation is based on DPM, whereby all the parts that are not used are disabled, resulting in several power consumption modes. We accounted for these when developing a model for the autonomous sensor that considers the load as a pulsed current sink. Power consumption varies widely among these modes, and in very low duty cycle applications the relative power consumption during sleep can be crucial. The described load model is a tool for sizing the power supply.

The voltage supply from the power source has a voltage range that often falls outside of that accepted by the load. Thus, a power conditioning stage is required. Furthermore, as the power consumption of the autonomous sensor decreases with decreasing supply voltage, power conditioning can be considered in all cases for increasing lifetime. A thorough study of efficiency and circuit complexity (among other criteria) must be considered when designing the power conditioning stage.

We have briefly presented here several power conditioning circuits: *linear regulators*, *switching regulators* and *charge pumps*. Linear regulators can only decrease voltage. They are simple and generate no significant noise. Switching regulators and charge pumps can increase or decrease their input voltage and require a control strategy to turn their switches on and off. Both power-conditioning circuits suffer from *dynamic* and *static* power losses that ultimately determine their efficiency at a given load. Charge pumps do not use inductors, and consequently, enable simpler and more compact designs.

PFM is a control strategy used in commercial switching regulators and charge pumps intended for light loads. It is based on hysteresis control of the output for shortening the active time of the internal components of the regulator (and consequently, its power consumption).

Future work should propose smarter power conditioning circuits and control strategies for their application in very low power autonomous sensors.

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