Voltage Level Conversion

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Keywords

- *5 V MCU*
- *Voltage levels*
- *Digital thresholds*
- *Parallel interface*
- *Voltage translator*
- *3-5V conversion*

Introduction

Chipcon RF-ICs operate with supply voltages lower than the old industry-standard 5V. Running at a lower voltage enables the ICs to be less expensive and have lower power consumption than they would have had if they used a 5 V supply. Also, lower operating voltages are good for battery-operated systems.

However, this can cause problems if a designer wants to use an older 5 V circuit in the same design. Typically, the other circuit is an older microcontroller. This application note will therefore use the interface of a CC1000 RF transceiver to a 5 V microcontroller as an example, although the information is general and applies to all situations where two digital ICs with different voltage levels need to communicate.

Voltage level conversion is also sometimes needed to communicate via external interfaces. For instance, RS-232 uses voltage levels of –5 and 5 V, while the PC parallel port uses 0 and 5 V voltage levels.

Logic levels

Four parameters define the logic levels for a digital logic family: V_{IL}, V_{IH}, V_{OL} and V_{OH}.

- V_{IL} defines the maximum voltage level that will be interpreted as a '0' by a digital input.
- V_{IH} defines the minimum voltage level that will be interpreted as a '1' by a digital input.
- V_{OL} defines the guaranteed maximum voltage level that will appear on a digital output set to '0'.
- V_{OH} defines the guaranteed minimum voltage level that will appear on a digital output set to '1'.

The output parameters are usually given for a given output current, as the output levels are dependant on the load impedance applied to the logic output. A CMOS output stage will usually swing to the supply rails if it is not loaded.

A voltage level between V_{IL} and V_{IH} will result in an undefined logic state, i.e. it could be either '0' or '1'. Also, most CMOS inputs will draw excessive current if an undefined voltage level is applied.

For proper operation when a digital output is connected to a digital input, the V_{IL} of the input should be higher than the V_{OL} of the output. Correspondingly, the V_{IH} of the input should be lower than the V_{OH} of the output.

A thorough description of logic levels and conversion between them can be found in [1], pp. 475, 565-590.

Interfacing the CC1000 to a 5 V MCU will be used as an example in this application note. Figure 1 shows the voltage levels in this case.

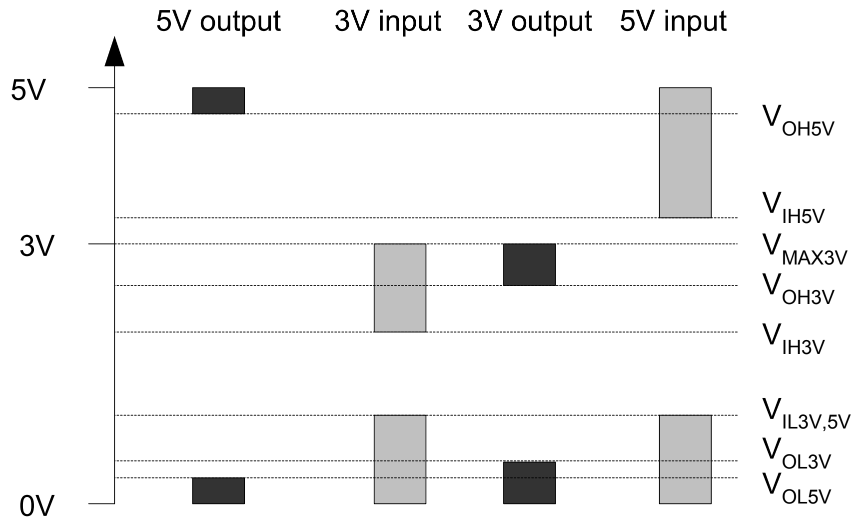

Figure 1. Typical voltage levels for CC1000 (3V) and HCMOS (5V)

In practice

Today, most digital ICs have CMOS output levels. These will deliver rail-to-rail swing, as long as they are not heavily loaded. Since CMOS inputs have very high input impedance, a CMOS output will have rail-to-rail operation when used to drive a CMOS input.

Input levels depend on the logic family; some families have CMOS-type input levels with the switching level at 0.5·VDD, some other families have TTL-type levels with the switching level at a lower level. Make sure you read the data sheet of the circuit to find out what the input and output levels are.

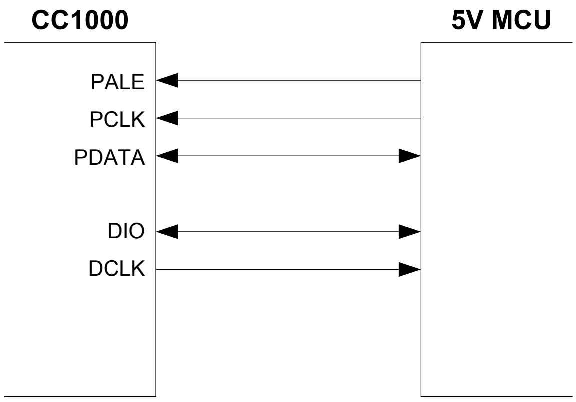

Figure 2: Example circuit

Let's use the circuit in Figure 2 as an example. Here, a 5 V microcontroller requires two-way communication with a CC1000 RF transceiver running on 3.0 V.

If we handle the MCU->CC1000 signals first, the problem here is that a 5 V signal from the MCU will violate the absolute maximum rating for pin voltage on the CC1000, which is VDD+0.3V. This means that you risk destroying the CC1000 by applying a 5V signal to it. Applying a higher supply voltage to the CC1000 will not work, since although the absolute maximum rating for the CC1000 supply voltage is 5.0V, the operating range is 2.1V to 3.6V. The CC1000 will not operate correctly if you try to run it on a voltage above 3.6V.

We therefore need to do voltage conversion in order to connect the microcontroller output to a CC1000 input.

For the signals going from the CC1000 to the MCU, there is no danger in exceeding the absolute maximum ratings for the MCU, since the VDD of the CC1000 is lower than the VDD of the microcontroller. However, the V_{OH} of the CC1000 is 2.5V (VDD=3.0V, current = 2.5 mA). Since the microcontroller has a CMOS input, it will not draw any appreciable current, so in practice the output voltage of the CC1000 will be 3.0V. However, the V_{IH} for 5V CMOS is usually above 3.0V (typically around 3.3V), so we need voltage conversion in this direction as well.

Voltage level conversion methods

There are several ways of doing voltage level conversion; we will go through the most important methods next.

Voltage level conversion ICs

Several semiconductor manufacturers provide voltage level conversion ICs, especially designed for doing level conversion. Some examples are Philips' 74LVC4245 and Maxim's MAX3370. These chips typically accept two different VDDs, and take care of converting the levels from one level to the other. Usually, they are bi-directional and also offer a high-impedance for the outputs. Some circuits even free you from specifying a direction; they work both ways without switching.

For RS-232 level switching, a huge range of ICs is available. Many ICs also include step-up circuitry, so that the interface can generate 5 and –5 V even when running on a 3 V supply.

This is the easiest and most elegant option, and is especially nice for bi-directional signals, such as the DIO and PDATA signals in the MCU-CC1000 example.

Pros:
- Elegant, simple
- Operation guaranteed by manufacturer

Cons:
- Price
- Some devices are single-source

Open-drain ICs

The industry-standard 74HC series of logic ICs include several devices with an open-drain output. An open-drain output stage consists of one transistor that can pull the output down to ground, but no pull-up transistor. The user of the circuit needs to use an external pull-up resistor, but this can pull up to a different voltage, and therefore do level conversion. However, many open-drain output ICs include ESD protection diodes on the output. These circuits cannot be used to convert from 3V to 5V, as the protection diodes would become reverse biased. Open-drain circuits without ESD protection diodes may be used to convert from a low voltage to a higher one.

Pros:
- Simple
- 74HC ICs are widely sourced.

Cons:
- Passive pull-up can result in a slowly-ramping signal if load capacitance is high
- Draws static current when output is low
- Suitable only for one-directional operation
- Circuits that include ESD protection diodes on the outputs cannot be used to convert from a low voltage to a high voltage

Discrete

You can do voltage level conversion using discrete bipolar transistors.

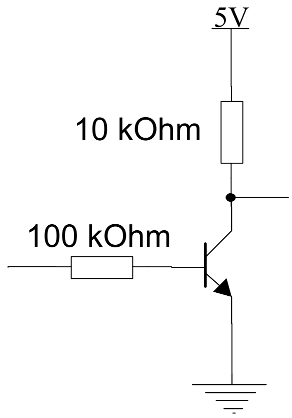

Figure 3. Voltage level conversion using an NPN bipolar transistor

The circuit shown above converts from a voltage swing of 0-3V to a voltage swing of 0-5V. The resistor values may have to be modified depending on the switching speed required. At the same time, the resistor connected to the collector should be as large as possible in low-power applications, since static current will be drawn when the output from the circuit is low. Also note that this circuit inverts, i.e. it will drive the output low when the input is high and vice versa.
You can use the same circuit with an n-channel enhancement FET transistor, but in this case you do not need a resistor in series with the base. Make sure that you select a transistor with an appropriate threshold voltage.

Pros:
- Inexpensive
- Transistors are widely sourced

Cons:
- Passive pull-up can result in a slowly-ramping signal if load capacitance is high
- Draws static current when output is low
- Suitable only for one-directional operation

Programmable logic

Several programmable logic circuits include some form of voltage level conversion functionality. For instance, Altera MAX7000-series PLDs can accept a wide range of voltage levels. Others, like the Xilinx Spartan series of FPGAs have several I/O banks, where each bank can have its own supply voltage and use its own logic levels.

If you are considering using programmable logic in your design, you may get voltage conversion functionality “for free” if you choose an appropriate device.

Pros:
- “Free” if design requires programmable logic anyway
- Bi-directional operation no problem

Cons:
- Most designs do not require programmable logic. Programmable logic chips are too expensive to be used merely for voltage conversion.

Passive voltage divider

If you are only concerned with avoiding violation of the absolute maximum ratings of the 3V circuit, you can use a resistor voltage divider to divide down the 5V signal to 3V. With an appropriate choice of resistors, this will work fine, but it will draw static current all the time. Typical resistor values for the figure below can be R1=22kΩ, R2=33kΩ. If the 5V device has a low enough threshold voltage that it will function with a 3V input voltage, this can be a good approach for bi-directional signals, as the voltage divider only divides down the voltage in one direction.

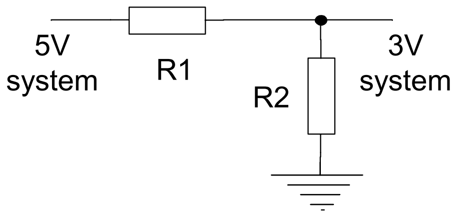

Figure 4. Passive voltage divider

Pros:
- Very low cost
- Can work on bi-directional signals if 5V system has low enough threshold voltage (V_{IL5V}<V_{OL3V})

Cons:
- Draws static current all the time
- Can result in a slowly-ramping signal if load capacitance is high
- If 5V V_{IH} is higher than 3V supply voltage, this circuit is only suitable for one-way 5V->3V conversion

References

Cited references

[1] P. Horowitz, W. Hill: *The Art of Electronics, 2nd edition*. Cambridge University Press

General references

[2] Philips Semiconductors: *AN240: Interfacing 3V and 5V applications*

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