Electronic Immobilizers for the Automotive Industry

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Introduction

In recent years increasing numbers of car thefts have highlighted the urgent need for effective and safe protection in the automobile industry. TEMIC introduced the industry's first single-chip reader IC for an automotive immobilizer anti-theft system in November 1994. Since 1995, insurance companies have insisted on new cars being protected against theft by an immobilizer. An electronic immobilizer with an integrated transponder security system for cars is a form of passive theft protection because the transponder does not need a battery as power is supplied by the reader.

The U2270B combines flexible coil driver circuitry, a highly integrated NF read channel and on-chip power supply. Along with TEMIC's e5530 transponder, the U2270B can be used to create a complete, compact and effective anti-theft system with minimum components.

This application note is a guide for designing an immobilizer which incorporates the U2270B. First of all, the magnetic coupling is explained and the parameters that are relevant for appropriate reading distance are identified. Next, solutions to overcome constellations with no modulation at the reader side are described. Then, the designer is guided through the application procedure. The dimensioning of the peripherals and the selection of the appropriate antenna adjustment strategy to guarantee the requested reading distance are discussed. In the following chapter, typical application examples are presented and a selection of the peripherals as well as the method of the antenna adjustment are described. A description of the adequate signal-detection software is given for applications where antenna adjustment is performed through a microcontroller.

System Design Considerations

Magnetic Coupling

Energy Transfer to the Transponder

The U2270B serves as an interface between the transponder and the microcontroller which compares the received data. This interface operates in two directions. In one direction, energy is transferred from the reader to the transponder. The reader creates a magnetic field via a reader air coil called the reader antenna (see figure 1). The reader coil is part of a resonant circuit tuned to the operating frequency. The antenna is energized by using series resonance. The resulting low impedance enables the driver circuit to transfer the energy with relatively low voltage which is limited in most automotive applications.

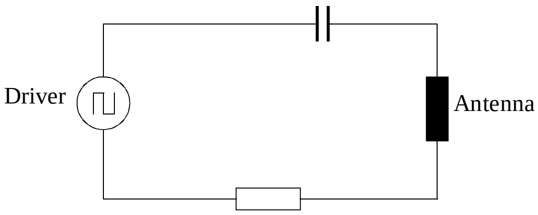

Figure 1. Reader antenna circuit

Modulation

The magnetic field generated by the reader induces a voltage in the transponder's resonant circuit which supplies the transponder IC. The current in the transponder coil generates a magnetic field which is superimposed to the reader's field. If the transponder's supply voltage is high enough, it begins to transmit by damping the resonant circuit in accordance with the data signal. The resulting signal strength mainly depends on the transponder coil's (ferrite antenna) characteristics and the amplitude shift caused by damping. This is shown in figure 2.

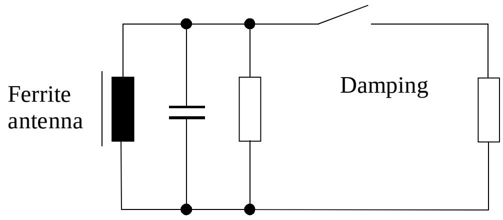

Figure 2. Equivalent circuit of the transponder (simplified)

Demodulation

Data is transferred in the other direction from the transponder to the microcontroller. The signal from the transponder is very small compared to the reader voltage. This leads to slight voltage modulation at the reader coil. The reader antenna operates in parallel resonance for the incoming signals, ensuring high sensitivity and pre-selection (bandpass) of the useful frequency band. Due to the high voltage across the reader coil, demodulation has to be external (see figure 3). The signal is fed into the INPUT pin of the reader IC via a rectifier and decoupling capacitor. The LF read channel amplifies and conditions the signal to convert it into the appropriate digital output data.

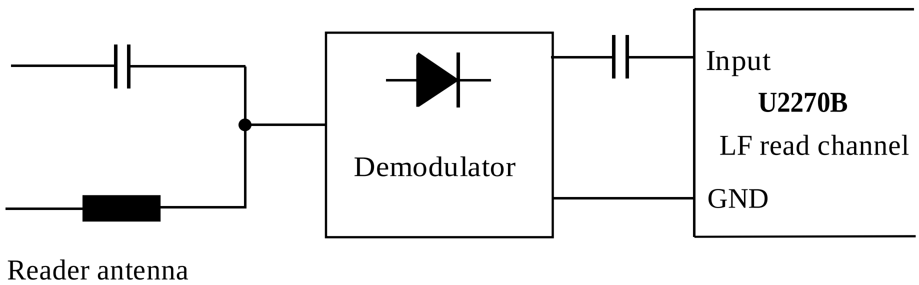

Figure 3. Demodulation path

Reading Distance

Energy Transfer Vs. Signal Detection

For correct operation, the transponder needs a minimum magnetic field intensity to generate internal supply voltage. If the existing frequency is different to the transponder's resonant frequency, the field intensity must be higher, depending on the transponder’s resonance curve. The magnetic field intensity on the axis of a free-air (short cylindrical) coil can be calculated by the formula below. Furthermore, the formula for calculation of the coil’s inductance is also given.

$$H = \frac{I \times N}{2 \times r \left(1 + \frac{d^2}{r^2}\right)^{1.5}}$$

$$L = N^{2\cdot} \times r \times \pi \times \mu_0$$
$$\left(\mu_0 = 1.257 \times 10^{-6}\right)$$

- H: Magnetic field intensity
- I: Current through the coil
- N: Number of turns
- r: Radius of the coil
- d: Distance between center of the coil and the transponder
- L: Inductance of the coil

To ensure detection, the modulated signal must exceed the sensitivity level of the read channel. The presence of interfering signals (electromagnetic interference, EMI) should be considered. The ratio between the reader and transponder voltage for both directions can be described using the parameters coupling factor, inductance and Q factor of each reader and transponder. They are given by the following formulas:

$$U_T = U_R \times k \times \sqrt{\frac{L_T}{L_R}} \times Q_T$$

$$\Delta U_R = \Delta U_T \times k \times \sqrt{\frac{L_R}{L_T}} \times Q_R$$

- U_T: Transponder voltage
- U_R: Reader voltage
- k: Coupling factor (common for both directions)
- L_R: Reader inductance
- L_T: Transponder inductance
- Q_T: Transponder Q factor
- Q_R: Reader Q factor
- ΔU_R: Modulated (differential) voltage at the reader coil
- ΔU_T: Modulation voltage at the transponder

The coupling and Q factors improve transmission in both directions. Q factors are limited by physical and design conditions and are mentioned in the following chapters. A compromise must be found as far as the inductances are concerned because they have opposite effects in both directions

Avoidance of Zero Modulation

The formulas above are valid if the resonant circuits of reader and transponder are aligned to the oscillator frequency. If the resonant circuits are off resonance, the modulated signal fed back from the transponder will not be in phase to the reader (self-induced) voltage. This can lead to the following effects:

- Amplitude modulation on the reader voltage will be lost if the phase shift is 90° (zero modulation).
- The signal will be inverted if the phase shift is more than 90°.

Table 1 shows the various solutions possible to avoid the effects mentioned above.

Power Supply Environment

The reader IC also incorporates an internal power supply. This enables the user to operate the system not only from an unregulated supply voltage in the range of 7 V up to 16 V, but also from an existing 5-V supply rail. If internal stabilization is used, the U2270B can be set to a power-down mode, via the pin STANDBY, where the supply current is very low.

Table 1. Comparison of the various solutions available to avoid zero modulation

Possible Solutions to Avoid Zero Modulations	Remarks
• Alignment of the resonant circuits and the oscillator frequency	• Not possible if more than one transponder is used • Not suitable for mass production
• Reduction of the Q factor of the reader and/or the transponder resonant circuits	• Less phase shift at equal frequency deviating • Reading distance is reduced (see "Antenna Design"*)
• Alternating the oscillator frequency in steps within the tolerance range	• Troublesome if the resonant frequencies of reader and transponder are quite different*
• Controlling the oscillator frequency to be equal to the resonance of the reader antenna	• Additional control circuit required • Tolerance considerations are only 2 dimensional instead of 3 dimensional • Antenna design is easier (see "Oscillator Control Loop")
• As above, plus alternating the reader resonance frequency by a switched capacitor	• Less tolerance restriction (see "Reader Application with Tuning")

* Note: If the reader-resonant circuit is driven off resonance, the (FM) noise of the oscillator is converted into an AM noise which is detected by the demodulator. The increasing noise level leads to lower reading distances.

Application Procedure

Dimensioning of the Peripherals

Oscillator Control Loop

Controlling the oscillator frequency to be equal to the resonance of the reader antenna has several advantages. (refer to table 1) This approach is therefore proposed for the applications described in this chapter. The frequency control is achieved by applying an oscillator control loop incorporating a phase detector.

Figure 4 shows the equivalent circuit of the oscillator control loop, figure 5 shows the waveforms of the driver outputs coil 1, coil 2 and the corresponding antenna voltage, measured between R_1 and R_2.

T_1: low cycle of coil 1 output

T_2: low cycle of coil 2 output

T_{2a}: time interval of T_2 where the antenna voltage is negative

T_{2b}: time interval of T2 where the antenna voltage is positive

A_a: integral of the antenna voltage during T_{2a}

A_b: integral of the antenna voltage during T_{2b}

The oscillator control loop is a phase control loop that controls the phase shift between driver voltage and antenna voltage. The feedback current through D_1 and D_2 controls the oscillator frequency in such a way that a 90° phase shift between the above mentioned voltages is achieved. In this condition, the reader antenna is driven at its resonant frequency.

During T_1, no feedback information is transferred through D_1 and D_2 into C_1. In the meanwhile, D_3 and D_4 are conducting. Therefore, D_1 and D_2 are reverse biased.

During T_2, feedback information can be transferred through D_1 or D_2. During T_2, a current flows through R_2 and D_1 out of C_1. If the antenna voltage is positive (during T_{2b}) current flow occurs through R_1 and D_2.

The resulting current into C_1 is the sum of the currents during T_2. If the resonant frequency of the antenna is higher than the oscillator frequency, the phase shift and therefore T_{1a} and T_{2b} change. T_{2a} is reduced and T_{2b} is increased accordingly. As a result, the control current (sum of A_a and A_b) differs from zero and becomes positive. This results in an additional current into pin RF and in a higher oscillator frequency until $f_{res} \approx f_{osc}$. The control loop operates proportional, the loop gain is ≈ 15 for the proposed application in the data sheet. A higher Q factor of the reader antenna results in a higher loop gain. The damping effect of R_1 and R_2 should be considered as it lowers the Q factor of the reader antenna.

Signal Detection

The useful signal appears as a very small amplitude modulation of the reader antenna voltage. The demodulator consists of a diode, a charge capacitor and two resistors for charging and discharging. The high-pass function of the capacitive coupling (C_2) has to be matched to the transponder code used (see figure 6).

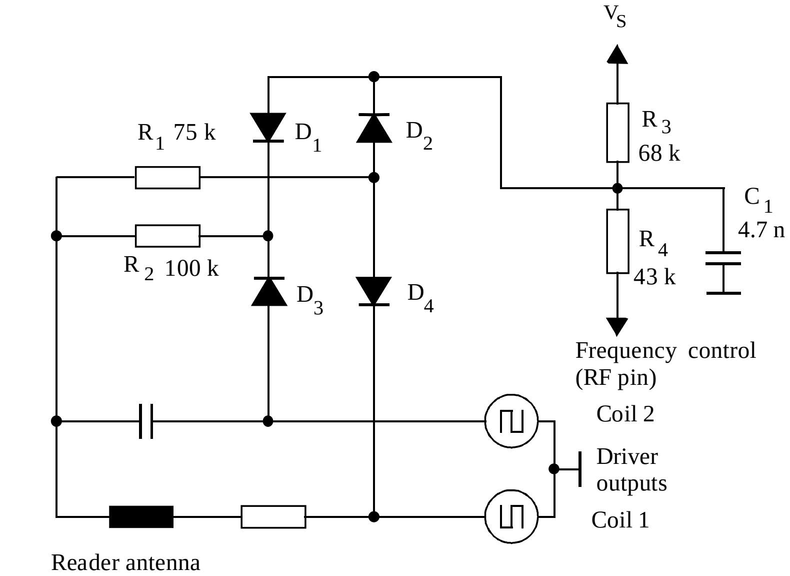

Figure 4. Function principle of the oscillator control loop

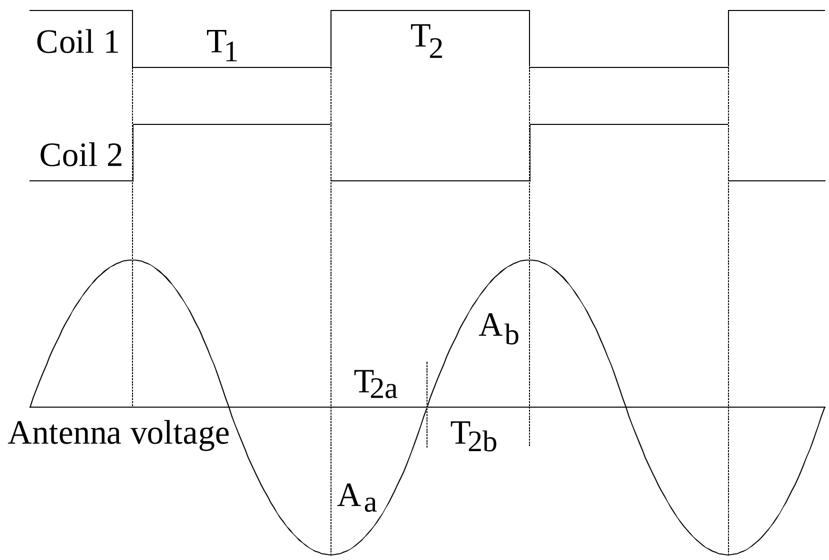

Figure 5. Relevant signals of the oscillator control loop

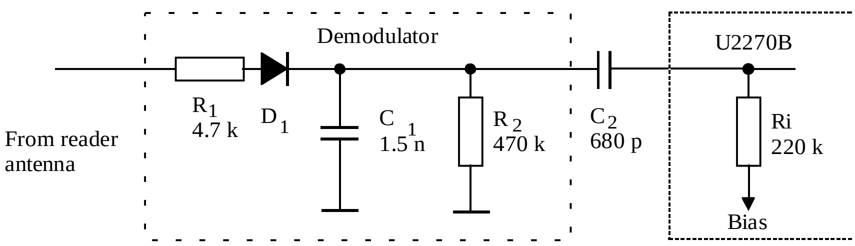

Figure 6. Demodulator with high-pass coupling

The component values are given for a bit rate of approximately 4 kbit/s using bi-phase or Manchester encoding (see figure 6). If a lower data rate is used the value of C2 should be increased accordingly. After demodulation, the signal is filtered and amplified by the read channel inside U2270B. The gain and lower cut-off frequency of the integrated amplifier can be set via the pin GAIN. If maximum gain is required, the pin GAIN is connected via a capacitor (C_{Gain}) to ground. For a lower gain, a resistor (R_{Gain}) is connected in series to the capacitor. The gain (G) and the cut-off frequency (f_{Out}) can be calculated by the formulas below. The value of R_i can be assumed as being 2.5 kΩ.

$$G = 30 \times \frac{R_i}{R_i + R_{Gain}}$$

$$f_{cut} = \frac{1}{2 \times \pi \times C_{Gain} \times (R_i + R_{Gain})}$$

Power Supply and Load Dump Protection

The system can be operated from either a 5-V stabilized supply or an unregulated voltage in the 7-V up to 16-V range, for example, from a vehicle's battery. A protective resistor should be used (see "Typical Application") to withstand overvoltage conditions. The minimum resistance can be determined by the following equations:

Assumptions:

- R_{THJA}: 120 K/ W
  Thermal resistance junction to ambient
- T_{JMAX}: 150°C (maximum junction temperature)
- U_Z: 18 V internal clamping voltage
- R_Z: 90 Ω internal resistance of the clamping diode
- U_{IN}: Maximum continuous input voltage
- U_{IN_LD}: Maximum input voltage ‘load dump’
- T_{amb}: ambient temperature
- F: Factor depending on the duration of a load dump pulse; F = 2 if t < 500 ms, F = 3 if t < 200 ms

$$P_{tot} = \frac{T_{JMAX} - T_{amb}}{R_{THJA}}$$ Power dissipation continuous

$$P_{tot\_LD} = F \times P_{tot}$$ Power dissipation load dump

$$R_{Prot} \geq \frac{U_{IN} - U_Z}{\sqrt{\frac{P_{tot}}{R_Z} + \left(\frac{U_Z}{2R_Z}\right)^2} - \left(\frac{U_Z}{2R_Z}\right)} - R_Z$$

Protective resistor continuous

$$R_{Prot} \geq \frac{U_{IN\_LD} - U_Z}{\sqrt{\frac{P_{tot\_LD}}{R_Z} + \left(\frac{U_Z}{2R_Z}\right)^2} - \left(\frac{U_Z}{2R_Z}\right)} - R_Z$$

Protective resistor load dump

This calculation considers a worst-case situation, since it is performed using R_{THJA}. Thermal resistance is lower in normal applications as the IC is mounted on a PC board.

Antenna Design

Since the resonant frequency of the reader antenna is defined by the system, the parameters to be determined are:

- Inductance of the coil
- Q factor of the resonant circuit

The inductance depends on the coil dimensions and the number of turns (see "Energy Transfer vs Signal Detection"). The inductance value of the reader antenna must be set so as to balance the energy transfer and the signal detection. If the parameters of the transponder are known, the coupling factor can be calculated. Resonant frequencies of reader antenna and transponder are equal. Therefore, the formula given in the chapter "Energy Transfer vs. Signal Detection" is re-arranged:

$$k = \frac{U_T}{U_R \times Q_T} \times \sqrt{\frac{L_R}{L_T}}$$ Coupling factor

$$\Delta U_R = \Delta U_T \times k \times \sqrt{\frac{L_R}{L_T}} \times Q_R$$ Modulation voltage of the reader antenna

The Q factor of the reader antenna depends on the loss resistance of the coil and iron losses if the coil is mounted on a lock cylinder. To be independent of the peripheral parameters (i.e. mounting accuracy, lock cylinder material) a serial resistor should be added. A high Q factor improves signal transmission, but if it is too high the transient response could have a negative effect on the data signal. Values of the Q factor up to 15 do not affect the data signal.

Frequency Tolerance Considerations

The resonant frequencies of reader antenna and transponder(s) are not equal in most applications and result in the following effects (see "Avoidance of Zero Modulation"):

- The internal supply voltage of the transponder is reduced due to its resonant curve.

- The amplitude modulation of the reader voltage is lost if the phase shift is 90°, (zero modulation) or the signal is inverted if the phase shift is more than 90°.

In order to maintain proper operation for the immobilizer system, the following conditions must be fulfilled:

- The transponder needs enough power to operate.
- The phase shift between reader voltage and modulation voltage must be below 90°.

The transponder voltage can be calculated if the maximum (requested) tolerance between the resonant frequencies is known.

$$\varphi = \arctan\left(QT \times (1 + \frac{Tol}{100}) - \frac{1}{\frac{1}{QT} \times (1 + \frac{Tol}{100})} \right)$$

$$U_T = U_R \times k \times \sqrt{\frac{L_T}{L_R}} \times Q_T \times \cos(\varphi)$$

U_T: Transponder voltage

U_R: Reader voltage

k: Coupling factor (common for both directions)

L_R: Reader inductance

L_T: Transponder inductance

Q_T: Transponder Q factor

Tol: Tolerance between resonant frequencies (in %)

φ: Phase shift between reader and transponder voltages

The phase shift between reader and transponder voltages is also very important for achieving potential zero modulation. If the transponder modulates slightly, zero modulation can occur at a phase shift of $\varphi > 45°$. This also means that if the system is operated in such a way that guarantees φ to be less or equal to 45°, zero modulation cannot occur. The maximum tolerance where this requirement can be fulfilled is given with:

$$MaxTol = \left(\frac{1}{2} \times \frac{\left(1 + \sqrt{1 + 4 \times QT^2}\right)}{QT} - 1 \right) \times 100$$

MaxTol: Maximum tolerance for a given Q factor to avoid zero modulation

Q_T: Transponder Q factor

If MaxTol > To1 (the desired maximum tolerance), zero modulation cannot occur. The transponder can be operated at its lowest possible supply voltage respectively magnetic field strength. This is shown in the data sheet.

If MaxTol < Tol, there are three possible solutions to avoid the likelihood of zero modulation:

- 1: Usage of more accurate frequency-determining components for the reader antenna and/ or the transponder. The maximum value for the tolerance between the resonant frequencies is MaxTol, as calculated with the above formula.
- 2: Alternating the reader resonance frequency by means of a switched capacitor. Two different resonance frequencies can be selected, (see "Application with Tuning") resulting in double the value for the maximum tolerance compared to 1 ($2 \times$ MaxTol).
- 3: Lowering the Q factor of the transponder: This is achieved by applying enough magnetic field so that the transponder’s internal clamping diode conducts. This internal diode limits the maximum internal supply voltage to protect the IDIC. The reduction of the Q factor depends on the current flow through that diode. The required Q factor to avoid zero modulation can be calculated with the following formula:

$$Q_T = 100 \times \frac{100 + Tol}{(Tol \times (200 + Tol))}$$

Q_T: required transponder Q factor

Tol: Maximum (desired) tolerance between resonant frequencies (in %)

The voltage of the transponder is determined by the transponder’s internal clamping diode. This means that the magnetic field must be significantly higher with this solution compared to solutions 1 and 2. The required coupling factor can be determined with the following formula:

$$k = \frac{U_T}{U_R \times Q_T \times \cos(\varphi)} \times \sqrt{\frac{L_R}{L_T}}$$

k: Coupling factor (common for both directions)

U_T: Transponder voltage (clamping voltage in this case)

φ: Phase shift between reader and transponder voltages [cos (φ) = cos (45°) in this case]

U_R: Reader voltage

L_R: Reader inductance

L_T: Transponder inductance

Q_T: Reduced transponder Q factor corresponding to the formula above

Application Examples

Overview

A wireless immobilizer or identification system consists of two sub-systems – the transponder and the reader system. The U2270B enables the design of reader systems with less components. It enables a microcontroller or digital logic to read and to process the identifier or the key code from a transponder.

This chapter describes typical applications for the U2270B and describes how to decode the transponder signal. All considerations are made for the TEMIC transponder e5530 at a frequency of 125 kHz.

Typical Reader Application

This circuit is suitable for systems with a small range or small tolerances of reader and transponder resonant circuits. The application shown in figure 7 is a proposal for a 12-V supply voltage. The microcontroller is supplied by the internal power supply of the U2270B.

Reader Application with Tuning

This application (see figure 8) allows the tuning of the reader antenna circuit. Thus, reader and transponder antennas with larger tolerances can be used. The microcontroller is able to minimize the difference between reader and transponder resonant frequencies. This improves the communication range and avoids zero modulation.

Data Decoding

The identifier or key code of the normal transponders is encoded as a Manchester or bi-phase code and the clock for the baud rate is generated by the transponder from the oscillation at the reader antenna. A typical transponder code can be seen in figure 9.

Figure 9 shows the timing of the Manchester and bi-phase code in an ideal situation. However, the timing of the code at the decoder input is affected by various effects of modulation, demodulation and noise in most applications. There is a jitter at the rising and falling edge of the data signal. Additionally, the clocks of the transponder signal and the decoder system are asynchronous. The decoder should evaluate the reader output signal with the method shown in figure 10 to achieve a maximum range and minimum errors.

The reader output signal is shown in figure 10. The valid time intervals (worst-case considerations) are related to one edge of the data signal. Table 2 provides the pulse lengths for the reader output signal. If the decoder operates with this timing, guaranteed decoding of the Manchester- (see figure 11) or the bi-phase code (see figure 12) is possible.

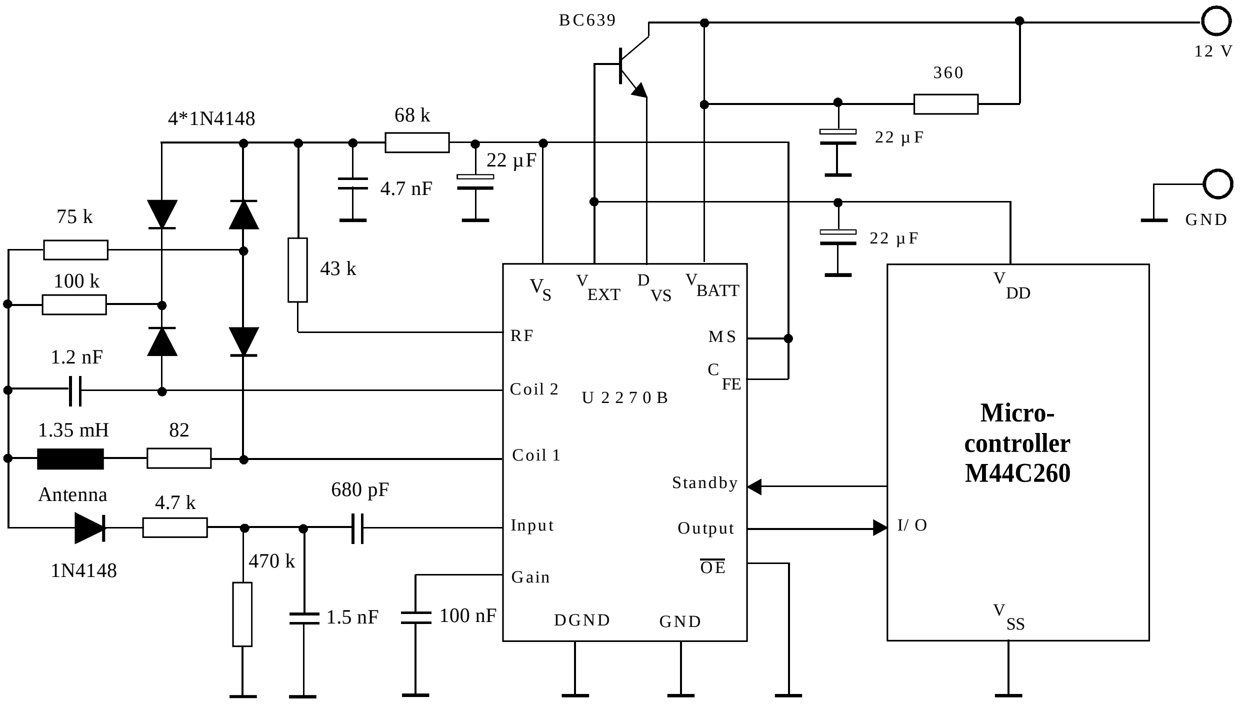

Figure 7. 12-V application for small reading range requirements

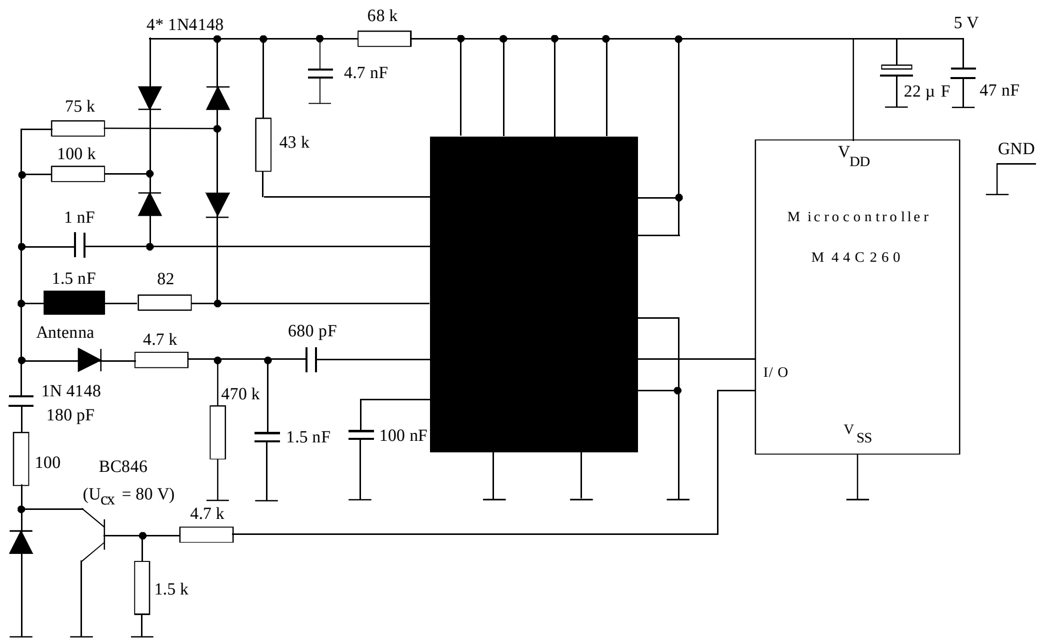

Figure 8. 5-V application for enhanced reading-range requirements

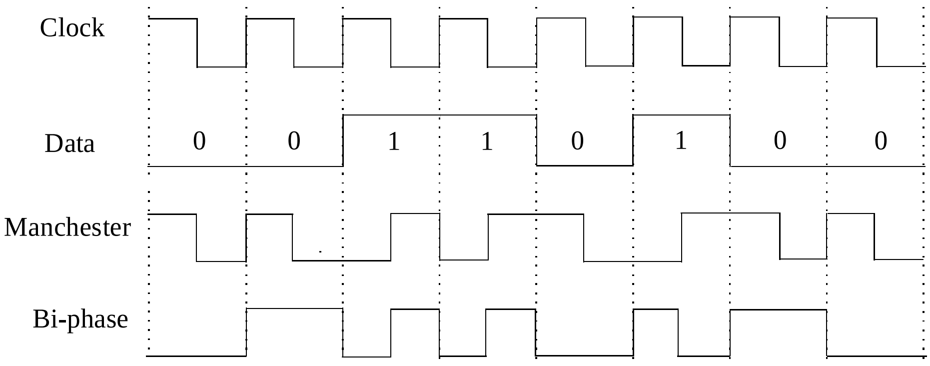

Figure 9. Manchester and bi-phase code

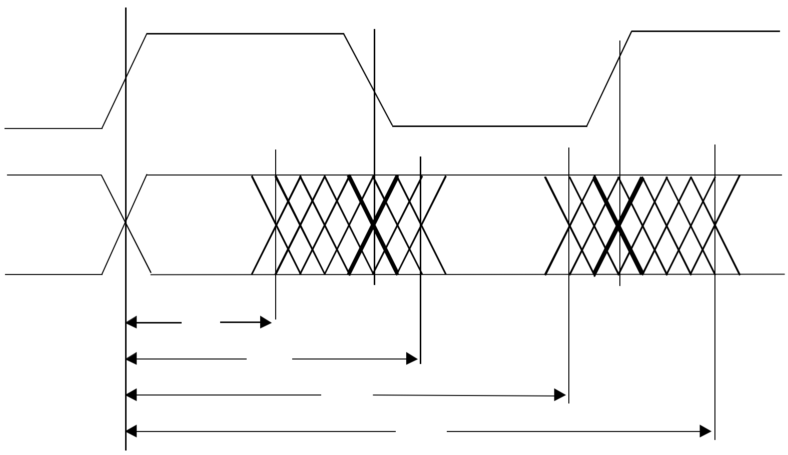

Figure 10. Valid time frame for the reader-output signal

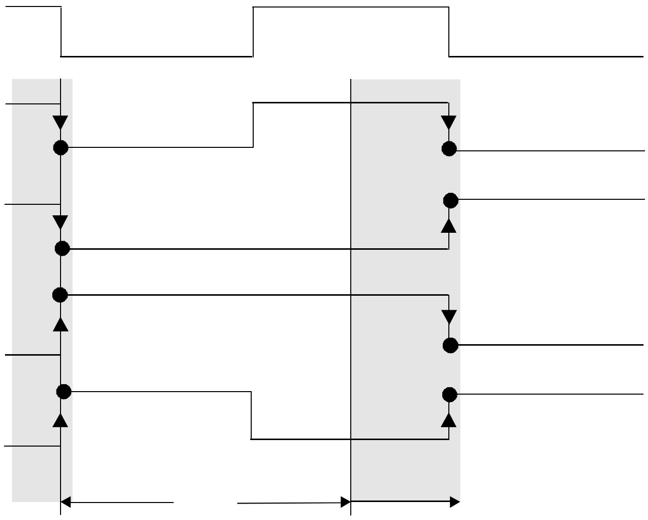

Figure 11. Decoding of Manchester code

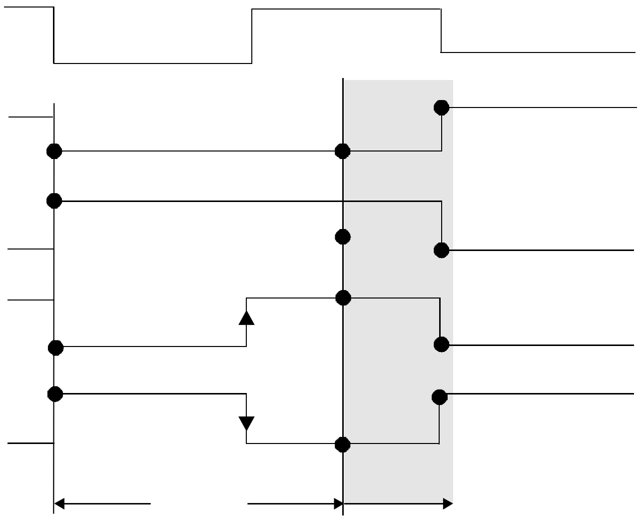

Figure 12. Decoding of bi-phase code

Table 2. Pulse lengths for the reader output signal

Description	Symbol	Value	Units	Condition
Short pulse length minimum	t_{S1}	90	µs	f_{Osc} = 125 kHz ± 3%
Short pulse length maximum	t_{S2}	180	µs	″
Long pulse length minimum	t_{L1}	210	µs	″
Long pulse length maximum	t_{L2}	300	µs	″

To decode the Manchester or bi-phase code, the clock of the transponder and the decoder must first be synchronized. The codes are encoded as a signal with two frequencies f_{clock} and $2 \times f_{clock}$. A positive or negative pulse with the length of one clock period must be detected for the synchronization. After that, the bit-stream can be decoded. The flowcharts in figures 13 and 14 show how to decode the transponder signal for Manchester and bi-phase encoding and also indicate error detection.

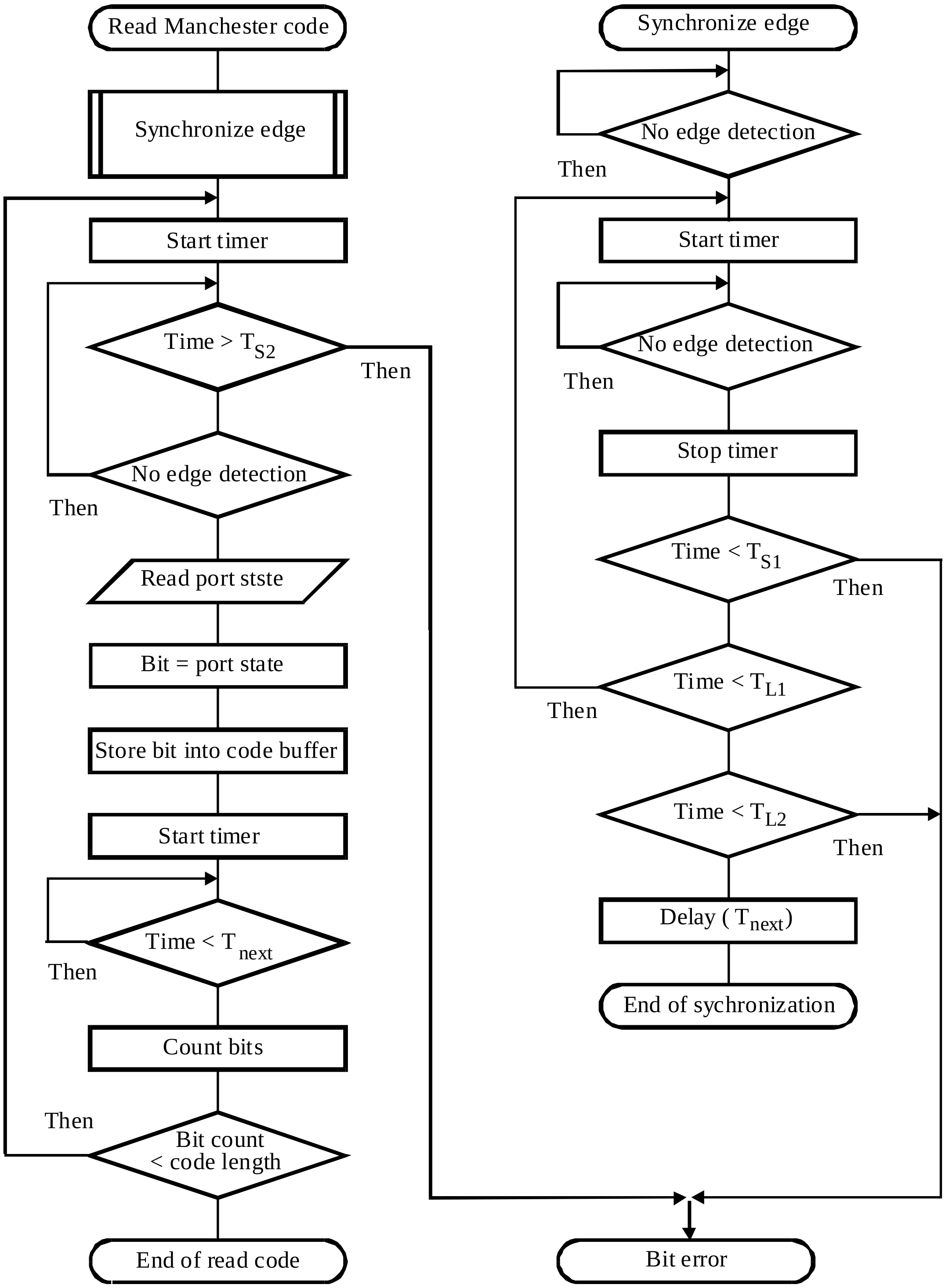

Figure 13. Decode flowchart for Manchester code

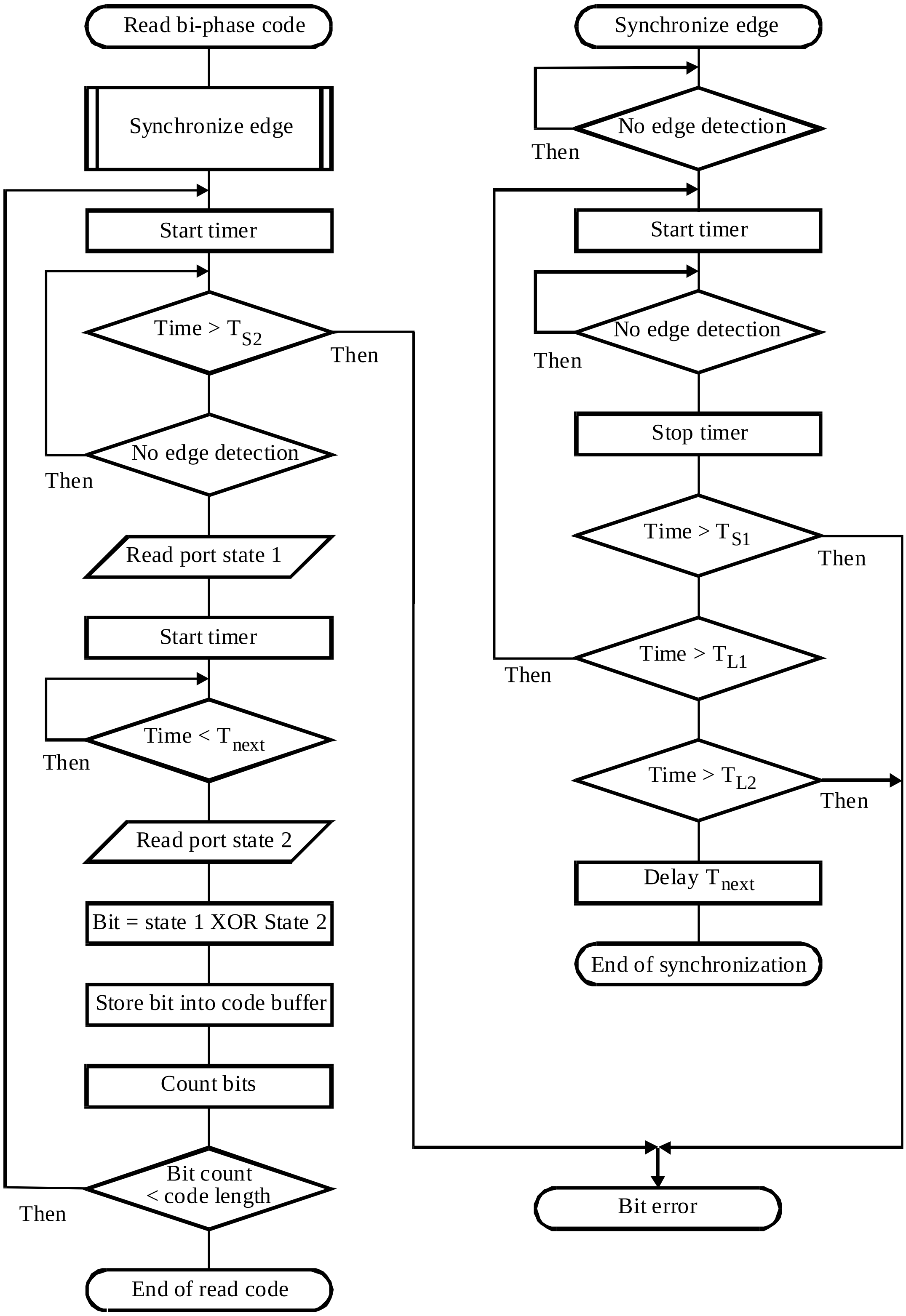

Figure 14. Decode flowchart for bi-phase code

In figures 13 and 14, the following time constants are used to evaluate the reader signal:

Table 3. Time constants for evaluating the reader signal

Used Time Constants (f_{Osc} = 125 kHz ± 3%)		
Symbol	**Value**	**Unit**
TS1 = t_{S1}	90	µs
TS2 = t_{S2}	180	µs
TL1 = t_{L1}	210	µs
TL2 = t_{L2}	300	µs
T_{next} = t_{S2}	180	µs

The complete process of reading a transponder is shown in figure 15. If the standby option is used the microcontroller must wake up the reader via the standby pin. Then it must synchronize and read the bits. The reading is not synchronized with the beginning of the code. Therefore, the first bit of the identifier must be found by searching the 8-bit header code (TEMIC transponder) in the code buffer. This allows very fast access to the identifier because the microcontroller can start reading at any place within the bit stream. If all bits are free of errors and the identifier is also correct, the read access is finished. If there is a bit error or a bad identifier the microcontroller can repeat the reading. In applications with a tunable reader antenna, the controller should change the antenna adjustment before it starts to read again. After the read access, the reader can then be switched into standby mode.

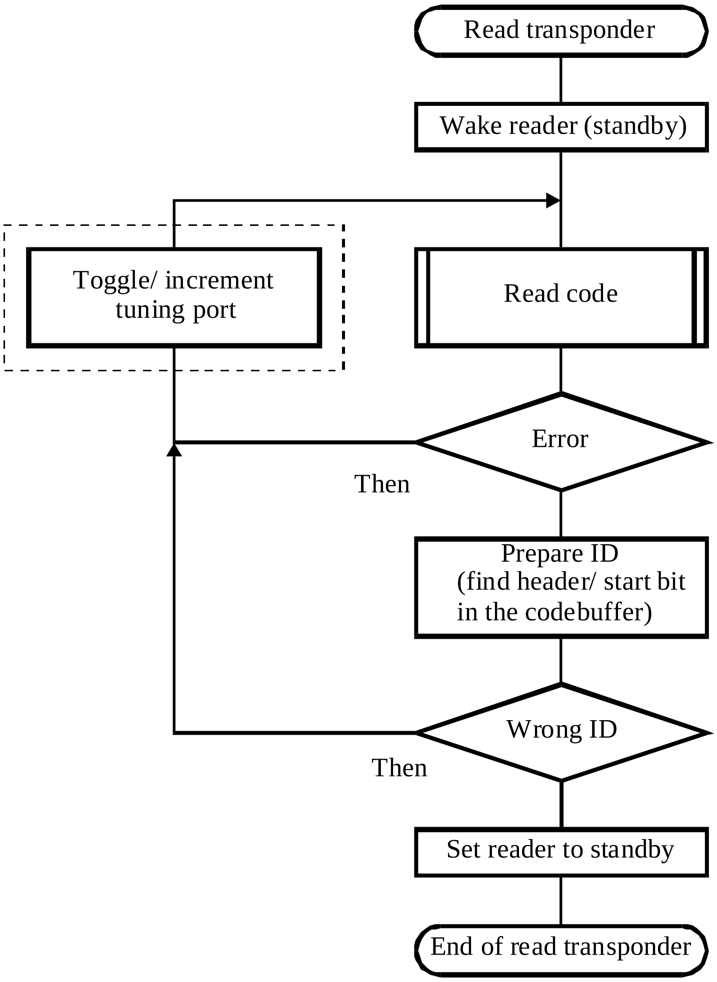

Figure 15. Decode flowchart for read code