Applications Note
Receiver Design Notes

This application note covers the TH71101, TH71102, TH71111, TH71112 fully integrated single frequency receivers. These receivers have some different features and cover different bands but they all have common architectures which make them very easy to use for different applications.

The receivers are divided into 2 main groups. One group covers from 310 to 480 MHz, and the other covers from 800 to 930 MHz. In the low frequency group, the VCO is 16 times the crystal frequency in and in the high frequency group, it is 32 times the crystal frequency. Within these groups, there are single and double conversion receivers. The double conversion feature is unique to Melexis. It allows the designer to have some image rejection without using a SAW filter on the input and the possibility of putting the image in a band which is less likely to cause interference. The only additional cost of the double conversion architecture is two surface mount coils and one capacitor to tune the output of MIX1 instead of two resistors for the collector loads in the single conversion design. The double conversion design also allows the receiver to be configured for the low frequency band from 26 to 67MHz. [1]

All receivers have both ASK and FSK detectors. This allows the designer make the same basic receiver with different parts for both the U.S. where ASK is preferred or Europe where FSK is preferred.

Crystal Selection:

The frequency tolerance of the receivers is the same as the tolerance of the reference crystal. Therefore, if the crystal is $\pm$50ppm, the receive frequency tolerance δF is given by:

$$\delta F = 50 \times 10^{-6} \times F_{in}$$

where F_{in} is the frequency the receiver is designed to receive. At 418MHz, this would result in a tolerance of $\pm 21KHz$. This is well within the bandwidth of commonly available 10.7MHz ceramic IF filters and allows the receiver to be set for frequencies other than the most commonly used ones. This helps to avoid interference from other transmitters plus it allows the image to be put at a wide range of frequencies.

The first consideration in selecting the operating frequency is determined by what kind of operation is allowed in the band and avoiding interference. For instance, the FCC allows only periodic operation in the low band from 315 to 434MHz. Since the Melexis receivers are crystal controlled, the receive frequency can be placed anywhere within the allowed band not necessarily at the center. For instance, 433.92MHz is very popular, but, in Europe, any frequency between 433.05 and 434.79MHz is allowable. The commonly used 10.7MHz ceramic filters are designed to have a minimum of 20dB selectivity at +/- 320 to 470KHz from Fo, so any frequency from 433.45 to 434.39MHz could be used.

The second considerations in selecting the operating frequency based on where the image frequency will fall. Single conversion receivers have the same sensitivity to the image as to the desired frequency unless they have a SAW bandpass filter on the input. The Melexis double conversion receivers have some image rejection and an image frequency which is much farther away in frequency, so the image can often be placed at a favorable frequency. The main frequencies to avoid for images are the UHF TV band because of the high power of the

[1] Melexis Application Note AN71102-LOW-RF

transmitters, and the cell phone bands. Also harmonics of TV signals can also be a problem because of the high transmitted powers.

The second consideration is to keep the VCO in the receiver IC inside its allowable range. The recommended VCO ranges are:

Low band receivers: 300 to 430 MHz
High band receivers: 800 to 915MHz

The third consideration is to make the first IF frequency in double conversion receivers as high as possible.

The crystal frequency selection in single conversion receivers is relatively simple. The difference between the input frequency and the VCO must be the IF frequency. The VCO can be above or below the input. If it is above, the image is below and conversely. For the low band receivers, the crystal is then the VCO frequency ÷16 and for the high band receivers, the crystal is the VCO frequency ÷32. The TH71101 and TH71111 data sheets give the design equations for the crystal frequency.

Crystal selection in the double conversion TH71102 and TH71112 receivers is more complicated because there are 4 possibilities for each receive frequency. The tables and design equations in the data sheets list the possibilities for the most commonly used frequencies.
A spreadsheet is also available for calculating the frequencies for the crystal as well as the 1st IF VCO and image frequencies.

The load capacitance presented to the crystal is the same for the Melexis receivers as for the transmitters. The internal capacitance is 15pF, so the crystal can be specified for a 15pF load or any load between 10pF and 15pF. If the specified load capacitance is less than 15pF, the series capacitor between the crystal and the reference oscillator pin (**RO**) of the receiver should be calculated so that 15pF in series with the external capacitor gives the specified crystal load.
As an example, if the crystal is specified for a load of 12pF, the series capacitor would be 60pF.
The crystal could also be specified for a load of 15pFand connected directly to the RO pin.
A good way to determine if the frequency of the crystal oscillator (RO) is correct is to apply a 1mV unmodulated signal to the receiver input and measure the IF frequency at the OUT_IFA pin using a sensitive counter. It should be within the calculated tolerance of 10.700 MHz. If it is not, the capacitor in series with the crystal probably needs to be changed.

LNA (RF amplifier) considerations:

The LNA input equivalent is 26 Ohms in parallel with approximately 2pF. This makes it a pretty good match for a quarter wave monopole antenna. If the antenna is shorter than this, it will be capacitive and have a lower resistance.[2] This can be compensated for by adding a matching network between the antenna, but if the Q of the coils used in the matching network is not high, any advantage to be gained with the matching network will by lost because of losses in the network. Multi-layer types coils have a very low Q and should be avoided. Therefore, it is usually sufficient to connect the antenna directly through a 100pF capacitor directly to the LNA input. A

[2] Melexis Application Note "Transmitter and Receiver Antenna Basics"

1k to 10k resistor from the antenna to ground is usually added to discharge any static charges on the antenna. A coil can also be used to tune out the 2pF input capacitance of the LNA and it will double as static protection. The 26Ohms in parallel with 2pF can be used to design a matching network for a SAW filter if one is used.

Since the output of the LNA is heavily loaded by the mixer input, the LNA stability is usually not a problem. The **MIX1** input equivalent is 31 Ohms in parallel with 1.6pF. For practical purposes, the 1.5pF can be neglected and 33 Ohms can be used for calculations. Therefore, the capacitor in series with the input to MIX1 can be transformed to the load across the LNA coil using the following equations:

The series reactance of the mixer input capacitor, $X_s = \frac{1}{\omega C_s}$

Let R_p be the load across the LNA output coil

$$R_p = 33 + \frac{X_s^2}{33}$$

This load also mostly determines the loaded Q of the LNA output tuned circuit which then determines the image rejection of the receiver (unless a SAW filter is used on the input).

The approximate overall noise figure is 8dB for the low band receivers and10dB for the high band receivers. The 3rd order intercept point for the receiver is approximately –32dBm. If a 1.5K resistor is added from the OUT_MIX2 pin to ground, the IP3 increases to –17dBm, and the current consumption increases about 1mA. The IP3 for these receivers is usually not very high because of their low current consumption, and it is usually not a problem because the RF power levels are usually very low. The term IP3 is a calculated number based on the required level to two interfering signals to produce a signal on the desired channel. It may be more useful to specify the maximum level of two unwanted signals which will produce a signal at the minimum sensitivity level. For these ICs, it is around 316 microvolts or -57dBm. In actual practice, it is unlikely that two signals evenly spaced above or below the desired signal will be present as might occur for communications receivers.

The single tuned circuit between the LNA and mixer will provide some image rejection, and more can be obtained by using a double tuned circuit. The disadvantage of the double tuned circuit is that the coupling must be controlled and the tuning is more critical because the Q of the tuned circuit on the LNA output is higher since it is not loaded by the mixer. An image rejection of over 30dB in the low band and 15db in the high band can be reached with the double tuned filter.

LNA gain control:

The gain of the LNA can be reduced approximately 25dB by driving the GAIN_LNA pin higher than 1.4V. When the pin is less than 0.8V or grounded, the LNA is in at normal gain. The hysteresis of the GAIN_LNA control voltage is around 0.6V. The corresponding change in the RSSI voltage for 25dB LNA gain change is about 0.7V. This means that if the GAIN_LNA pin is directly connected to the RSSI pin, the LNA gain control may oscillate as it passes through the switching point. Therefore, a voltage divider should be used so that the LNA gain change occurs

when the RSSI voltage is higher than 1.4V. The resistors in the voltage divider can be large values so as not to load the RSSI output because the GAIN_LNA input is a CMOS input.
On the other hand, for most ASK and FSK applications, it is not necessary to change the LNA gain. FSK signals are limited in the IF amplifier and large signals simply drive the receiver further into limiting. ASK reception when the receiver is overloaded is also good as long as the dynamic range of the transmitted signal is great enough. This is discussed in the ASK detection section.
Another use for the LNA gain control is to operate it at the low gain setting in very short range applications. This greatly reduces the possibility of the receiver picking up unwanted signals, and the transmitters can be operated at a power level which gives the desired range.

IF1:

This applies only to the TH71101 and TH71112 double conversion receivers.
MIX1 is internally coupled to MIX2 and the balanced collectors of MIX1 are brought out to the IF1N and IF1P pins so they must be supplied with Vcc. This is normally done using 2 coils. The IC has an internal capacitance of 20pF from the IF1N and IF1P pins to ground so this must be included in the tuning capacitance for the coils. For example, if the IF1 frequency is 57MHz and the inductance of each coil is 100nH, the required tuning capacitance between the IF1N and IF1P pins would be 39pF. However, 10pF must be subtracted from this because of the internal 20pF on each pin, so the capacitor would be 27pF (the closest E-series value to 29pF). The equation for calculating the tuning capacitor is:

$$C_{IF1P-IF1N} = \frac{1}{(2\pi f)^2 (2L)} - 10pF$$

Where L is the inductance of each coil and $C_{IF1P\text{-}IF1N}$ is the capacitor between the two IF1 pins.

IF amplifier and filtering:

For FSK or FM applications, the 3dB below limiting sensitivity of the IF amplifier is about 16 microvolts.
The IF input RSSI range is approximately 40uV to 160mV or -75dBm to –3dBm. The slope of the RSSI out is approximately 26mV/dB of RF signal.

10.7MHz ceramic filters are used in these applications because they are by far the cheapest way to perform the required filtering. However, this does not prevent the designer from using any other IF frequency up to 21.4MHz or down to 455KHz. The output resistance at OUT_MIX2 is approximately 330 Ohms so if a different filter is used, it may be necessary to add a matching network to match the 330 Ohms to the filter. However, the internal resistance at IN_IFA is around 2.2K. The IF filter can be terminated by adding a resistor from the IN_IFA pin to the FBC2 pin which is the bias for the IF input transistor.

Selection of an IF filter depends on the application. If ASK modulation is used, the bandwidth occupied by the RF signal is **2 times the signal bandwidth**. Thus, if the data rate is 2400 bps, the pulse width is 417 microseconds, and the minimum IF bandwidth is 4800Hz. However, a bandwidth this narrow will result in some pulse distortion, and either an expensive crystal IF filter or a 455KHz IF would be required. However, a low cost 150KHz 10.7MHz filter can be used and post detection filtering can be done at the RSSI output by simply making the capacitor on the RSSI pin larger or adding an active filter to the output using the internal op-amp in the IC.

An ASK data rate of 100kbps would require a wider IF filter of around 200KHz. Since the 180KHz wide IF filters do not have a very sharp attenuation, they will usually work well at these data rates.

If FSK is used, the rule-of-thumb is that the occupied bandwidth is 2 times the peak deviation plus 2 times the signal bandwidth. Thus a data rate of 50Kbps with a peak deviation of 50KHz would require a filter with a 200KHz bandwidth. Furthermore, FSK signals are more sensitive to group delay variations in the filter, so a filter with a low group delay variation should be used. Alternatively, a filter with a wider than required bandwidth can be used because the group delay variation near the center will be pretty constant.

If the FSK signal requires a relatively wide bandwidth which is limited by the IF filter, it is not possible to improve the sensitivity very much with post-detection filtering without seriously affecting the rise time of the pulses. On the other hand, if the FSK data rate is slow, the sensitivity can be improved significantly by post-detection filtering at the FM detector output. This may be as simple as adding some capacitance to ground.

Many designers assume that FSK will give a sensitivity improvement over ASK because FM receivers have lower noise than AM receivers and the communications theory says so.

However, FM is better than AM only when the modulation index is greater than $\frac{\pi}{2}$. [3]

The FM modulation index is usually referred to as β.

$$\beta = \frac{\Delta f}{f_m}$$

Where Δf is the peak frequency deviation and f_m is the modulating frequency.

The main reason AM broadcast receivers are susceptible to noise is because they operate at frequencies where the harmonics of noise produced by power line devices and other switching devices are very strong. The second reason is that the IF bandwidth of these receivers is very narrow, and short impulses are stretched into long ones by the IF filter. This results in a much longer lasting and louder sounding pulse at the detector output.

When a system designer has to make a decision between ASK and FSK, it is more important to consider possible sources of interference. For example, in Europe the short-range-devices (SRD) band at 868 to 870MHz is close to the GSM phone transmit frequency range (starting at 880MHz in E-GSM). An 868MHz ASK receiver (e.g. for car keyless entry) would respond on the mobile phone's AM-like frame bursts and hence will detect the AM signal. An FSK receiver would not face this problem – therefore FSK should be used in Europe's 868MHz band.

The maximum selectivity which can be obtained with these receivers is about 30dB because this is the limit for the ceramic filter and because of leakage between the mixer output and IF input

[3] Black "Information Transmission Modulation and Noise", McGraw-Hill, 1970

pins. If more selectivity than this is needed outside the bandwidth of the IF filter, a pi matching network can be added from the mixer out to the IF filter. The filter should be designed with the lowest inductance and highest capacitance which is practical. The effect of this filter is to have a low impedance across the mixer output off resonance so the unwanted frequencies are shorted to ground.

ASK Detection:

The RSSI output pin is used to detect ASK signals. This output is proportional to the log of the RF input level IN_IFA . and is smooth without any discontinuities from about .4 to 1.9V. Using a logarithmic detector for ASK has the advantage that an AGC (automatic gain control) system is not needed. Most AM receivers have AGC systems to keep the output level constant with changing RF input levels because the detector is linear for low distortion. Some newer types of receivers use logarithmic detectors with an anti-log circuit to produce a reasonably linear output. However, in pulse modulated systems, amplitude distortion is not important. The RSSI range is about 60dB, so if the on/off ratio of the RF pulse is 60dB or more, the transmitter can work from being next to the receiver to its maximum range. This is true for Melexis transmitters, but not for SAW based transmitters. Most SAW based transmitters either turn an RF amplifier on and off or turn the oscillator on and off. In either case, the RF signal never goes to zero and is usually about 30dB down from the on level when it is on. The result is that when the transmitter is brought close to the receiver, the RF level during the off time is above the maximum receiver RSSI level and the receiver will not detect the pulses.

The RSSI output has an internal 36K resistor to ground fed by a current source, so the post-detection filtering can be done by simply connecting a capacitor in parallel with this resistor. The evaluation boards come with 330pF which gives a time constant of 12us or a 3dB frequency of 13KHz. If the data rate is 2400bps, this capacitor can be increased to give a significant sensitivity improvement. The maximum value of the capacitor will be determined by how much pulse distortion the microprocessor which decodes the information can tolerate. This is a case where the software designer may be able to work with the RF to achieve significant performance improvements.

FSK Detection:

The FSK detector is the well known phase-coincidence (or quadrature) detector. The detector input impedance on the IN_DEM is 47K. The quadrature detector is a phase detector, so it can also be used as a phase detector for a PLL (phase locked loop) FM detector.

For most applications, the simple quadrature detector is suitable. The IF signal is coupled into the detector circuit with a capacitor between the OUT_IFA pin and the IN_DEM pin. 1.5pF is shown on the evaluation schematics, but it is not critical and values close to this can be used to reduce the number of different values on the board. When a ceramic discriminator is used, this capacitor and the capacitor across the resonator determine the correct tuning of the detector.

The peak output of the detector on pins OUTP and OUTN depends on the peak deviation of the FSK or FM signal and the Q of the circuit on the detector. Most applications use a ceramic discriminator as the tuned element. This simply acts as a parallel tuned circuit at 10.7MHz. Sometimes, a parallel capacitor is needed to tune the resonator. The Q of the resonator is quite high and so the detector output will be high with small deviations. Furthermore, errors in the center frequency due to crystal tolerances in the transmitter and receiver may cause the received signal to fall at the frequency limits of the detector. This can be corrected by adding an AFC (automatic frequency control) to the resonator as is shown in some of the evaluation board schematics. The problem with an AFC circuit is that is must have a time constant which is longer than the data pulses or the average of the data pulses if they are not encoded in some kind of format which does not have and DC average. Since the AFC time constant is long, it will take some time for it to center the signal which is being received, so the first few pulses of the data signal may be lost. Thus, if AFC is used for an FSK system, some allowance must be made for this.

The Q of the detector circuit can be reduced by adding a resistor across the detector or increasing the value of the capacitor from the OUT_IFA (pin 15) to the IN_DEM (pin 16) so the IF amplifier output loads the detector. The tuning capacitor across the resonator must them be decreased so the resonator is tuned to its center frequency. This will increase the detector bandwidth so it can detect wider deviation signals or signals which are not exactly at the center frequency. The detector output will be smaller, but if a comparator is used to convert the FSK signal to a logic level output, the detected signal will still be much larger than any offset tolerances of the comparator. If it is being used to detect and audio signal, the audio level will be lower, but this can usually be made up for by increasing the audio amplifier gain.

Coil tuned quadrature detectors produce the nicest output but they must be tuned. At 10.7 MHz a 3.3uH coil with a 56pF tuning capacitor works well. A load resistor of 4.7K will reduce the Q so that deviations of up to 75KHz can be demodulated. Ceramic resonators are available for commonly used IF frequencies, and they do not to be tuned.

The FM detector outputs OUTP and OUTN are very high impedance with only 20uA of current available. The capacitance on these pins is what really limits the maximum FSK data rate. Most systems using this type of IC have low data rates, so this is usually not a problem. The pulse distortion at higher data rates can be improved by simply adding resistors to the output pin or pins. The nominal output voltage from these pins is 1.23V, so for example, a 100K resistor from the OUTP pin to ground and 150K to VCC (when Vcc is 3V) will decrease the rise time so that good pulse fidelity at 100 KBPS can be achieved. The output level will be reduced, but it will still be much larger than the comparator tolerance.

For FSK and ASK applications, the internal op-amp, OAP, OAN and OUT_OA is usually used as a comparator. If the receiver is used as an FM receiver, the op-amp can be used as a buffer amplifier by connecting OAN to OUT_OA and connecting OAP to OUTP. Usually de-emphasis is needed in FM applications, and it is better to connect the RC de-emphasis network to the output of the op-amp. Simply adding a capacitor from OUTP to ground will not produce repeatable de-emphasis because the output impedance at OUTP can be from 100 to 300K.

Mute:

The ASK and FSK circuits used in the evaluation boards produce a random data output from the receiver noise when no input signal is present. Sometimes, this will fill up buffers in a microprocessor decoder so that it takes some time for the microprocessor to recognize a good data signal. The random data may also cause a signal decoder to occasionally produce an output. For ASK systems, the comparator can have one input offset so the data signals must be larger than the noise to produce an output. For FSK systems, the RSSI can be applied to a second comparator with an adjustable threshold so the FSK output is inhibited unless the RSSI is above a pre-set level. This is easily accomplished by connecting the collectors of a dual comparator together. An alternative approach would be to use some kind of gating circuit which requires a minimum pulse width to produce an output because the noise pulses are narrower than the data pulses.

PLL Synthesizer:

The slope of the internal VCO is approximately 250MHz/V at 433MHz for the low band devices and 300MHz/V at 868MHz for the high band devices. The slope decreases at the ends of the band. The VCO is divided by 16 in the low band receivers and by 32 in the high band ones, so

For the low band receivers, $K_o = \frac{250\text{MHz} \times 2\pi}{16} = 98.17 \times 10^6$ radians/sec/V

For the high band receivers, $K_o = \frac{300\text{MHz} \times 2\pi}{32} = 58.9 \times 10^6$ radians/sec/V

The phase detector current is 60uA so the detector constant is $\frac{60\,\mu A}{2\pi} = 9.55\,\mu A\ /\ \text{radian}$.

Therefore, for the low band receivers, $K_d K_o = 937.5$

For the high band receivers, $K_d K_o = 562.5$

The VCO is the same as the one used in the transmitters and is inherently noisy, so the PLL loop bandwidth is made wide to suppress the noise. This still allows suppression of the reference oscillator spurs because the reference frequency is that of the crystal and is from 16 to 28MHz.

Stand-by and Start-up:

The start-up time from ENRX (pin 28) = 1 to normal operation is 900uS maximum. This is very short for a receiver and is important for pulsed conditions when the goal is to preserve battery life.

For example, if the receive data rate is 9600bps and the data stream were 16 bits, the data would last only 1.67mS. The receiver would be on for 2.57mS. The receiver current consumption is around 9mA at the high LNA gain, so if the receiver were turned on every 2 seconds for 2.6mS, the average current consumption would be only 11.7uA.

It should be noted that all the receivers require a custom crystal frequency but they can be operated at any desired frequency within the allowed range of the VCO by simply substituting a signal generator for RO. The level on the RO pin should be around 0dBm or 224mVrms and must be coupled to pin 26 through a capacitor.

Data Modulation types:

Sometimes the question comes up concerning the type of modulation format which can be used with the Melexis receivers. The receiver simply puts out the same data that went into the transmitter. Under ideal conditions, it will act as a wire between the transmitter and receiver. However in practice, the receiver output is not a perfect replica of the transmitted signal because it will always be narrower and it may include some noise pulses. It does not recover any clock information. This is up to the person designing the software for the decoder which is, in most cases, a microprocessor. If ASK modulation is used, NRZ, Manchester, Bi-Phase and any unipolar code can be used. Bipolar modulation like RZ and any codes using 3 levels usually require FSK so the different levels can be represented by $f_0, (f_0 + \Delta f), (f_0 - \Delta f)$. The 3 level codes would require at least 2 comparators on the output.

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