Application Note: JN-AN-1186

JN516x and JN517x Temperature-Dependent Operating Guidelines

When using the NXP JN516x or JN517x wireless microcontroller in environments with significant temperature variation, periodic recalibration of the radio is recommended. In addition to this, the 32MHz crystal oscillator temperature characteristic needs to be compensated for operation above 90 ºC. This Application Note describes the software functions that perform these operations.

1 Introduction

The JN516x and JN517x devices feature an integrated radio, which is calibrated at start-up for optimum performance. In operating environments with a significant variation in temperature (e.g. greater than 20ºC) due to diurnal or ambient temperature variation, it is recommended to recalibrate the radio to maintain performance. Recalibration is only required on Routers and End Devices that never sleep. End Devices that sleep when idle are automatically recalibrated when they wake.

In order to maintain the tolerance of the radio reference frequency to within the 40ppm limit specified by the IEEE 802.15.4 standard, it may be necessary to compensate the 32MHz crystal oscillator at operating temperatures above 90 ºC. All AT cut quartz crystals exhibit a steep rise in resonant frequency above 90-100 ºC. Therefore, provision has been made in the 32MHz crystal oscillator of the JN516x and JN517x devices to increase the crystal load capacitance and thereby reduce the oscillating frequency – this process is known as 'frequency pulling'.

This Application Note describes a set of software functions which measure temperature using the on-chip temperature sensor and trigger a recalibration if there has been a significant temperature change since the previous calibration. Frequency pulling of the main crystal oscillator by adjusting the crystal load capacitance can be performed using a standard Integrated Peripherals API function.

2 Requirement for Periodic Recalibration

The JN516x and JN517x radio has been designed so that on start-up it selects a calibration curve for the voltage controlled oscillator (VCO) to produce the specified performance from the devices. If the operating/ambient temperature of the device changes significantly from when calibration occurred, the device performance may be reduced. Recalibration is then required to maintain performance.

The recalibration process may be triggered under software control. Due to the time taken (less than 200 µs) to recalibrate the radio, there is the potential for packets to be missed on heavily loaded nodes (e.g. Routers).

Bench testing has shown a small increase in PER when operating at the limits of the calibration curve. However, process variation during device manufacture may lead to a more significant effect on some devices, so periodic recalibration is recommended.

2.1 Theoretical Behaviour

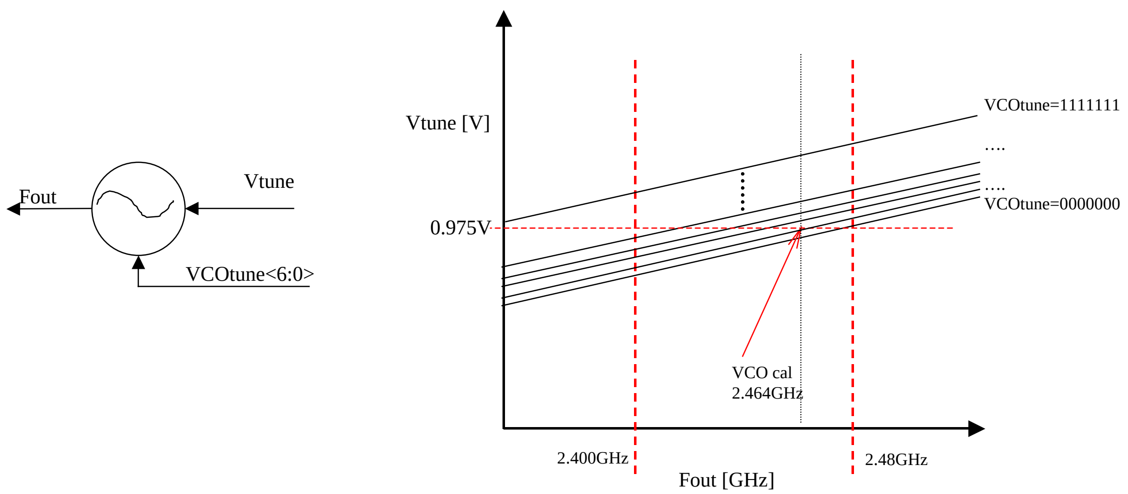

Figure 1: Simplified Diagram of VCO and Characteristics

Figure 1 shows an idealised VCO behaviour on the JN516x device. It has an input voltage, *Vtune*, a 7-bit tuning word, *VCOtune<6:0>*, and an output sinusoid port.

The *VCOtune* parameter is chosen to ensure that the VCO can meet the tuning range across all channels from 2.403GHz (RX lowest channel) to 2.48GHz (TX highest channel). In addition, the VCO must operate with a tuning voltage between 0.7V and 1.25V to meet the PLL design specifications. Figure 1 shows that out of the 127 possible tuning codes, no one code covers the whole frequency band. Process variation may lead to a faster or slower VCO, which may effectively raise or lower the *VCOtune* lines in the above graph. In this case, one of the other *VCOtune* values will then be selected. Temperature variation will also change the device operation, which may lead to the F_{out} falling outside of the specified operating region, in which case an alternative *VCOtune* line would be selected by recalibrating.

2.2 Expected Behaviour

The effects and side effects of operating the radio outside of its calibrated range may theoretically include the transmitter operating ‘off-channel’ and a reduction in receive sensitivity.

If the radio is outside of its calibrated range, the transmitted power will be maintained but may be off-channel and even out-of-band (greater than 2.48GHz or less than 2.405GHz.). The receiver sensitivity may be degraded to the point where no packets are received, i.e. PER is 100%.

During our tests on the JN5168 chip, ‘worst case’ silicon (due to process variation) has not been identified that shows this behaviour. However, when the VCO was intentionally set to ‘uncalibrated’, it resulted in 100% PER and no on-channel transmitted signal, until recalibration was performed. When the radio was re-calibrated, normal operation was restored.

3 Requirement for 32MHz Crystal Oscillator Correction

All AT cut quartz crystals exhibit a steep rise in resonant frequency above 90-100 ºC. Therefore, to keep the VCO frequency within the 40ppm limit set by the IEEE 802.15.4 standard, it is necessary to provide a means to compensate for this rise in frequency. This is achieved by decreasing (pulling) the frequency of the crystal by increasing the load capacitance seen by the crystal. Extra internal capacitors of about 1pF can be switched-in on each of the two oscillator pins (XTAL_OUT and XTAL_IN).

The oscillator in the latest versions of the chip (JN5169 and JN517x) has been modified in order that the 32 MHz frequency is less sensitive to temperature variations.

The states of the switching capacitors are:

- For JN5161, JN5164 and JN5168
    - Code 0 = no additional capacitance, which is the default state
    - Code 1 or 2 = 1pF extra load capacitance
    - Code 3 = 2pF extra load capacitance

The figure below shows how adding the capacitance avoids exceeding the frequency error limit at high temperatures.

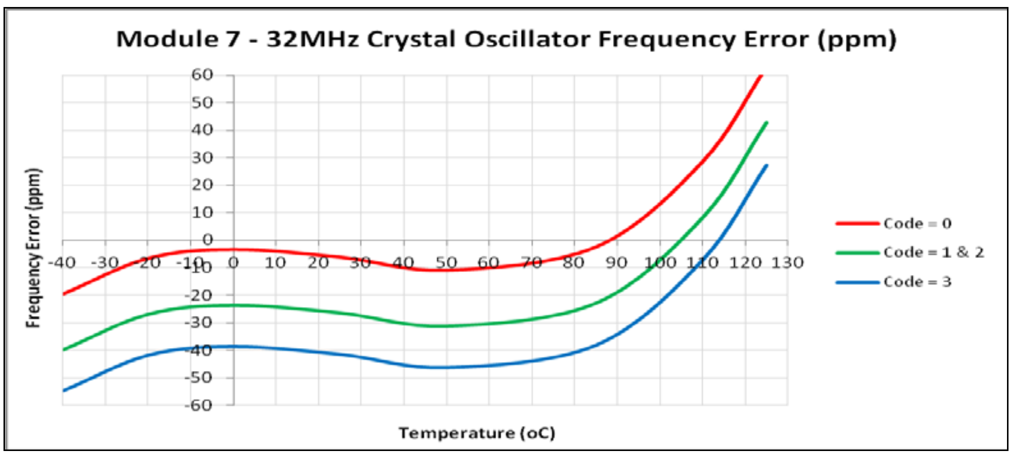

Figure 2: The effect on the frequency error of adding load capacitance on JN5161, JN5164 and JN5168

- For JN5169 and JN517x
    - Code 0 = no additional capacitance, which is the default state
    - Code 1 = 1 pF extra load capacitance
    - Code 2 = 2 pF extra load capacitance
    - Code 3 = 3 pF extra load capacitance

  The figure below shows how adding the capacitance avoids exceeding the frequency error limit at high temperatures.

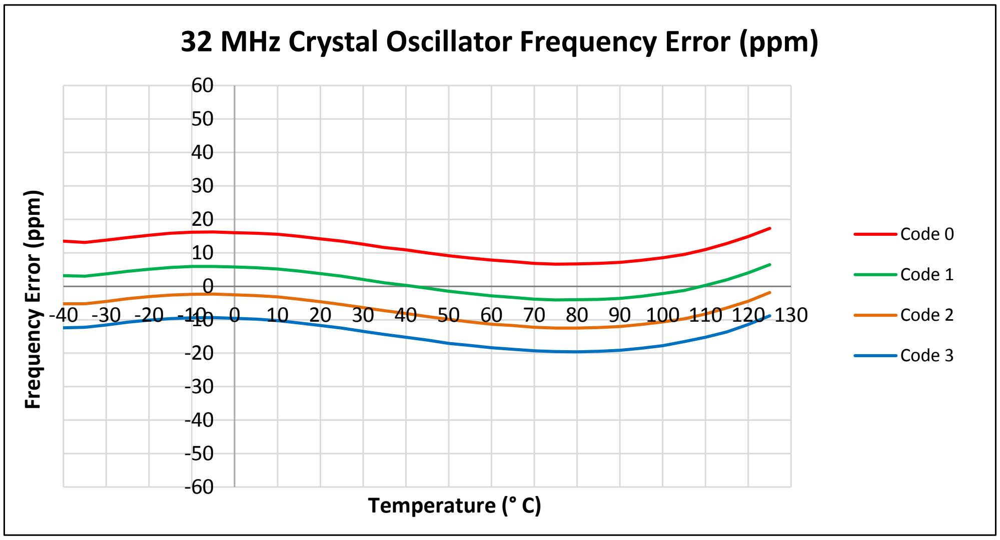

Figure 3: The effect on the frequency error of adding load capacitance on JN5169 and JN517x

In a typical application for high temperature operation, two thresholds would be set - for example, 95 ºC and 110 ºC. So at 95 ºC the frequency error would move from the red trace to the green and then, at the higher threshold, to the blue trace.

When selecting a crystal suitable for operation up to 125 ºC, it is important to check the value of the pulling coefficient. The crystal pulling coefficient specifies the sensitivity of the crystal frequency with respect to the crystal load capacitance. Crystals suitable for use with the JN516x and JN517x devices will typically have a crystal pulling coefficient value in the range 15 to 25 ppm/pF. Although the crystal pulling coefficient has a positive value, it should be noted that the crystal frequency will decrease with increasing crystal load capacitance.

The formula for calculating the crystal pulling coefficient (Δf) is given by:

$$\Delta f = \frac{C_m \times 10^{-6}}{2 \times (C_L + C_S)^2}\, ppm / pF$$

where,

C_m is the crystal motional capacitance (e.g. 4.4fF)
C_L is the crystal load capacitance (e.g. 9pF)
C_S is the crystal shunt or package capacitance (e.g. 1pF)

See Annex A for the definition of C_m, C_L and C_s.

The example crystal capacitance values quoted above yield a crystal pulling coefficient of 22ppm/pF. Therefore, an increase of the crystal load capacitance (C_L) by 1pF will reduce the crystal oscillating frequency by 4ppm.

In Section B4 of the JN516x IEEE802.15.4 Wireless Microcontroller Datasheet, the following crystals are listed, which have been tested and shown to perform well with regard to frequency pulling, but the user is not limited to these. AEL X32M000000S039 and Epson Toyocom X1E00002101670 (CL = 9pF, Max ESR 40R).

See Section 5.2 for details of adjusting the crystal load capacitance.

4 Application Scenarios

Due to the wide variation in applications for the JN516x and JN517x devices, it is desirable for the developer to identify how rapidly the temperature may vary in the application operating environment. The causes of temperature variation may range from slow diurnal (Day/Night) changes (e.g. equipment located outdoors) to rapid changes when co-located equipment is switched on (e.g. lighting fixture). The rate of application data transmission and loading on the network may also be taken into account when determining the checking period for the calibration.

Once the temperature range and rate of change of temperature have been identified, the time-period for checking the calibration may be estimated. This time-period should be chosen to be less than the time taken for the ambient temperature of the chip to change by the recalibration range. For example, for an environment with diurnal temperature variation of 80ºC, the time taken for the temperature to change by this amount will be ~12 hours – that is, changing by 20ºC in 3 hours, and so the recalibration check-time period would be set to 3 hours. In practice, a more frequent call may be made.

In lighting applications, the lamp fixtures can reach temperatures well above 100ºC, and therefore 'pulling' of the main crystal oscillator will be required. The application program will know when the lamp is turned on or off, or if the lamp has a dimmer function, when the light level is changed. In these circumstances, the temperature sensor should be checked more frequently than when the lamp is in a steady state. The aim should be to guarantee, that a change of 2ºC can be detected. The sampling time selected will depend on the thermal inertia of the fixture and the power consumed by the lamp.

5 Software Functions

5.1 Recalibration Functions

To maintain device performance and to enable an application to control when recalibration takes place, the following user callable functions are available:

bAHI_PeriodicRecalInit()

bAHI_PeriodicRecal()

bAHI_PeriodicRecalRange()

eAHI_AttemptCalibration()

Recalibration can be performed semi-automatically by setting up and using the periodic recalibration module. Alternatively, the application can take complete control of when recalibration is performed.

To enable the periodic recalibration module, a call is made to the **bAHI_PeriodicRecalInit()** function at the start of the application. The calibration period and temperature range can be set, if desired, otherwise the default values of one hour and 20ºC will be used. The application then periodically calls the **bAHI_PeriodicRecal()** function to check whether a recalibration is required and, if necessary, recalibrates.

Note that for applications that use the ADC, there is a risk of contention with these functions, as the internal temperature measurement performed also uses the ADC. There is also a risk of the timer expiring, causing this function to be invoked when the application is sending or has just sent data. To minimise this, the application controls when **bAHI_PeriodicRecal()** is called. The application selects a suitable time (e.g. the ADC is not being used and the application is not in the middle of a data transfer) for the recalibration to be performed. This function will only return TRUE if the module deemed recalibration necessary. A return of FALSE does not indicate an error but indicates that recalibration was not performed at this time.

Applications that make extensive use of the ADC and cannot tolerate sharing this resource must perform the temperature measurements in the application and decide when a recalibration is necessary. The function **eAHI_AttemptCalibration()** is provided which will force an immediate recalibration without using the ADC.

Note: It is not necessary to call any of the periodic functions if this direct approach is to be used.

The function prototypes are detailed below.

bAHI_PeriodicRecalInit()

The function initialises the recalibration module:

bool_t bAHI_PeriodicRecalInit(uint32 *u32RecalCheckPeriod*, **uint8** *u8TempDelta***);**

where:

- *u32RecalCheckPeriod* is the time (in seconds) between recalibration checks (0–68719). A value of zero will force the use of the default time of 1 hour. The maximum value gives a period of approximately 19 hours.
- *u8TempDelta* is the temperature change (in degrees Celsius) required before a recalibration is performed (0–40). A value of zero will force the use of the default 20ºC.

Returns: TRUE indicates recalibration enabled, FALSE indicates invalid parameter.

This function must be called to enable the periodic timer within the module.

> **Note:** This function must also be called following a MAC reset.

bAHI_PeriodicRecalRange()

This function allows the recalibration parameters to be changed on-the-fly:

bool_t bAHI_PeriodicRecalRange(uint32 *u32RecalCheckPeriod*, **uint8** *u8TempDelta***);**

where:

- *u32RecalCheckPeriod* is the time (in seconds) between recalibration checks
- *u8TempDelta* is the difference in temperature (in degrees Celsius) before a recalibration is triggered

Returns: TRUE indicates parameters successfully updated. FALSE indicates invalid parameters.

bAHI_PeriodicRecal()

This function requests a periodic recalibration (which is only performed if a recalibration is due):

bool_t bAHI_PeriodicRecal(void);

Returns: TRUE indicates the recalibration module performed a calibration. FALSE indicates that a recalibration was not necessary.

> **Note:** This function must be called in a timely manner to allow the recalibration to be performed.

eAHI_AttemptCalibration()

This function forces the recalibration module to perform an immediate calibration (note that the ADC and internal temperature sensor will not be accessed):

eAHI_AttemptCalibration(void);

Returns: E_CAL_SUCCESS (0x00)

E_CAL_SCAN_IN_PROGRESS (0x01)

5.2 Crystal Frequency Pulling Function

The JN516x/7x Integrated Peripherals API contains a function for pulling the 32MHz crystal frequency by the application of additional crystal load capacitance.

vAHI_ClockXtalPull()

The function applies additional crystal load capacitance to the 32MHz crystal oscillator.

void vAHI_ClockXtalPull(uint8 *u8PullValue***);**

For further details, please refer to the *JN516x Integrated Peripherals API User Guide (JN-UG-3087)* or *JN517x Integrated Peripherals API User Guide (JN-UG-3118)*, as appropriate.

Note: It is the responsibility of the application to perform a temperature measurement and call **vAHI_ClockXtalPull()** with the appropriate parameter value.

As previously described in Section 3 and with reference to Figure 2, a typical application for high temperature operation will have two temperature thresholds - for example, 95ºC and 110ºC. At 95ºC, **vAHI_ClockXtalPull()** should be called with a parameter value of 1 and at 110ºC it should be called with a parameter value of 3. A hysteresis of 2ºC below these temperature thresholds should be adequate to avoid unnecessary changing of the crystal load capacitance due to small temperature fluctuations.

6 Including the Software Functions

6.1 Function Header Files

For the JN516x, the recalibration functions are included in the library **libRecal_JN516x.a** which is supplied as part of the JN516x SDK libraries, as is the header file **recal.h**.

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To access these library functions, you are required to include the header file in the application source code:

1. Add **#include "recal.h"** to the application source code.

The crystal frequency pulling function is included in the Integrated Peripherals API header file **AppHardwareApi.h**, which is contained in the JN516x or the JN517x SDK environment. To include this function:

2. Add **#include "AppHardwareApi.h"** to the application source code.

6.2 Modify the Makefile

Add the following lines to the makefile of the application to specify the locations of the above include files:

```
INCCFLAGS += -I$(COMPONENTS_BASE_DIR)/HardwareApi/Include/
INCCFLAGS += -I$(COMPONENTS_BASE_DIR)/Recal/Include/
LDLIBS += libRecal_${JENNIC_CHIP}.a
```

Note: The exact modifications required depend on the application's makefile.

6.3 Modify the Application

Make the following additions in your application code to implement periodic recalibration:

1. Insert a call to **bPeriodicRecalInit()**, specifying the required recalibration time-period and temperature delta.

2. Insert a call to **bPeriodicRecal()** in the main processing loop. Note that:

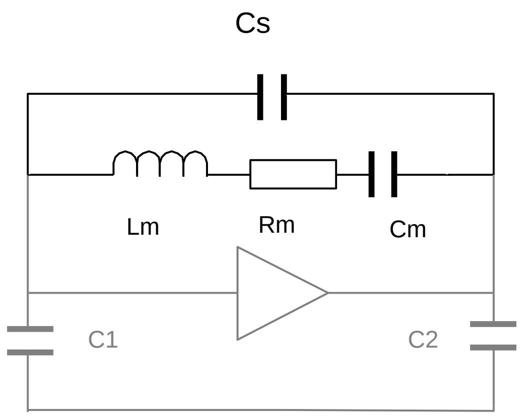
- The call to **bPeriodicRecal()** simply allows the application to indicate that it will permit a recalibration to take place – the call does not force a recalibration.
- The call will only return TRUE if a successful calibration took place.

ANNEX A Development Support

A.1 Crystal Oscillators

This section covers some of the general background to crystal oscillators, to help the user make informed decisions concerning the choice of crystal and the associated capacitors.

A.1.1 Crystal Equivalent Circuit



Where:

C_m is the motional capacitance

L_m is the motional inductance. This together with C_m defines the oscillation frequency (series)

R_m is the equivalent series resistance (ESR)

C_S is the shunt or package capacitance and this is a parasitic

A.1.2 Crystal Load Capacitance

The crystal load capacitance is the total capacitance seen at the crystal pins, from all sources. As the load capacitance (CL) affects the oscillation frequency by a process known as 'pulling', crystal manufacturers specify the frequency for a given load capacitance only. A typical pulling coefficient is 20 ppm/pF - to put this into context, the maximum frequency error in the IEEE802.15.4 specification is +/-40ppm for the transmitted signal. Therefore, it is important for resonance at 32MHz exactly, that the specified load capacitance is provided.

The load capacitance can be calculated using:

$$CL = \frac{C_{T1} \times C_{T2}}{C_{T1} + C_{T2}}$$

Total capacitance $C_{T1} = C_1 + C_{1P} + C_{1in}$

where:

C_1 is the capacitor component
C_{1P} is the PCB parasitic capacitance. With the recommended layout this is about 1.6pF
C_{1in} is the on-chip parasitic capacitance and is about 1.4pF typically

C_{T2} is similarly calculated.

Hence, for a 9pF load capacitance and a tight layout, the external capacitors should be 12pF.

A.1.3 Crystal ESR and Required Transconductance

The resistor in the crystal equivalent circuit represents the energy lost. To maintain oscillation, power must be supplied by the amplifier, but how much? Firstly, the Pi connected capacitors (C_1 and C_2 with C_S from the crystal) apply an impedance transformation to R_m when viewed from the amplifier. This new value is given by:

$$\hat{R} = R_m \left(\frac{C_s + C_L}{C_L} \right)^2$$

The amplifier is a trans-conductance amplifier, which takes a voltage and produces an output current. The amplifier together with the capacitors C_1 and C_2 form a circuit, which provides a negative resistance when viewed from the crystal.

The value of this resistance is given by:

$$R_{NEG} = \frac{g_m}{C_{T1} \times C_{T2} \times \omega^2}$$

where

g_m is the transconductance

ω is the frequency in rad/s

Derivations of these formulas can be easily found in textbooks.

In order to give quick and reliable oscillator start-up, a common rule-of-thumb is to set the amplifier negative resistance to be a minimum of 4 times the effective crystal resistance. This gives:

$$\frac{g_m}{C_{T1} \times C_{T2} \times \varpi^2} \geq 4R \left(\frac{C_S + C_L}{C_L} \right)^2$$

This can be used to give an equation for the required transconductance.

$$g_m \geq \frac{4R_m \times \omega^2 [C_S (C_{T1} + C_{T2}) + C_{T1} \times C_{T2}]^2}{C_{T1} \times C_{T2}}$$

Example: Using typical 32MHz crystal parameters of R_m =40ohms, C_S =1pF and C_{T1} = C_{T2} = 18pF (for a load capacitance of 9pF), the equation above gives the required trans-conductance (gm) as 2.59mA/V. The JN516x and JN517x devices have a typical value for trans-conductance of 4.4mA/V.

The example and equation illustrate the trade-off that exists between the load capacitance and crystal ESR. For example, a crystal with a higher load capacitance can be used, but the maximum ESR value that can be tolerated is reduced. Also note that the circuit sensitivity to external capacitance [C1 , C2] is a square law.

Meeting the criteria for start-up is only one aspect of the way these parameters affect performance. They also affect the time taken during start-up to reach a given (or full) amplitude. Unfortunately, there is no simple mathematical model for this, but the trend is the same. Therefore, both a larger load capacitance and larger crystal ESR will give a longer start-up time, which has the disadvantages of reduced battery life and increased latency

A.2 32MHz Oscillator

The JN516x and JN517x devices contain the necessary on-chip components to build a 32 MHz reference oscillator with the addition of an external crystal resonator and two tuning capacitors. The schematic of these components are shown in Figure 4 below. The two capacitors, C1 and C2, will typically be 12pF ±5% and use a COG dielectric. As with all crystal oscillators, the PCB layout is especially important, both to keep parasitic capacitors to a minimum and to reduce the possibility of PCB noise being coupled into the oscillator.

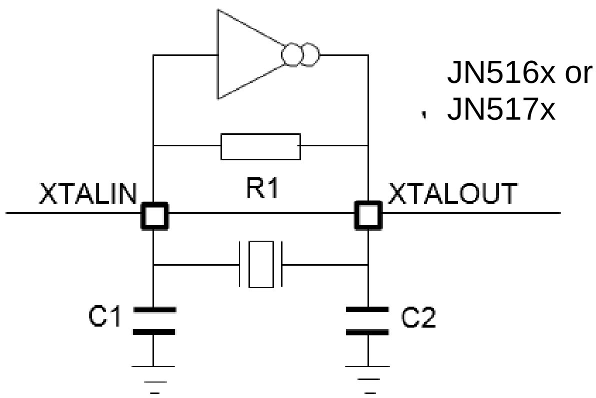


Figure 4: Crystal Oscillator Connections

The clock generated by this oscillator provides the reference for most of the JN516x/7x subsystems, including the transceiver, processor, memory, digital and analogue peripherals.

Parameter	Min	Typ	Max	Notes
Crystal Frequency		32MHz		
Crystal Tolerance			40ppm	Including temperature and ageing
Crystal ESR Range (Rm)	10Ω		60Ω	
Crystal Load Capacitance Range (CL)	6pF	9pF	12pF	
Not all combinations of Crystal Load Capacitance and ESR are valid				
Recommended Crystal	Load Capacitance 9pF and max ESR 40 Ω			
External Capacitors (C1 and C2) for recommended crystal		15pF		CL = 9pF, total external capacitance needs to be 2*CL, allowing for stray capacitance from chip, package and PCB

Table 1: 32MHz Crystal Requirements

Revision History

Version	Notes
1.0	First release
1.1	Updated with data from JN517x

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