APPLICATION NOTE

Atmel AVR2067: Crystal Characterization for AVR RF

Atmel MCU Wireless

Features

- Selection of appropriate crystals for Atmel® MCU Wireless applications
- Recommended list of 16MHz and 32kHz crystals for AVR® RF chips
    - Atmel ATmega256RFR2
    - Atmel ATmega128RFA1
    - Atmel AT86RF230
    - Atmel AT86RF231
    - Atmel AT86RF232
    - Atmel AT86RF233
    - Atmel AT86RF212
- IEEE® requirement for tight frequency tolerance
- Frequency tuning using TRIM_XTAL register
- PCB design guidelines
- Reference PCB layout, schematics and respective matching reports from crystal vendors included

Description

This application note provides an overview of how to choose and tune the crystals used in Atmel wireless solutions.

RF modules are highly dependent on the accuracy of crystal frequency because internal transceiver section generates the carrier frequency based on this 16MHz crystal frequency. Hence a small deviation in crystal frequency significantly affects the radio frequency signal.

Table of Contents

1. Introduction

In RF designs, crystal matching plays an important role in the robust operation of transceivers. If this crystal matching is not proper it may lead to poor RF performance and the design might violate regulatory requirements or even break the RF communication between the RF modules.

The scope of this application note is to guide the PCB designers to choose an appropriate crystal, which can satisfy the various application needs based on crystal size, ESR, load capacitance, negative resistance, frequency stability, power consumption, cost etc.

In this application note we provide the vast list of recommended 16MHz and 32.768kHz crystals which can be used with our transceivers and SoC chipsets.

2. Important Crystal Parameters

2.1 Total tolerance of the crystal

Total tolerance of the crystal mainly depends on the following parameters like:

- Frequency tolerance at 25ºC
- Frequency stability over the operating temperature
- Aging of the crystal

You can find these parameters mentioned as ppm (parts per million) in the respective crystal datasheets. Ideally the total tolerance of the crystal will be sum of these parameters in ppm. So it is important for the designer to have a prior knowledge of the operating temperature conditions of their end application/product.

As per the IEEE 802.15.4 standard the maximum carrier frequency deviation is limited to 40ppm [4]. This 40ppm deviation is inclusive of total tolerance of crystal, PCB design tolerance, tolerance of the components (eg. load capacitance), production tolerance etc.

Our recommended crystal tolerance selection plan shall include,

$$IEEE\ standard\ Requirement\ (40ppm) >= Frequency\ tolerance + Frequency\ Stability + Aging + other\ tolerances$$

Where,

Frequency tolerance + Frequency Stability + Aging, should be less than 30ppm.

Other tolerances like capacitor tolerances and production tolerances are assumed to be 10ppm or less.

2.1.1 Frequency tolerance

Frequency tolerance is the maximum frequency deviation from the specified oscillating frequency at 25°C and is specified in ppm. This parameter gives an indication of variations between individual crystals.

2.1.2 Frequency stability

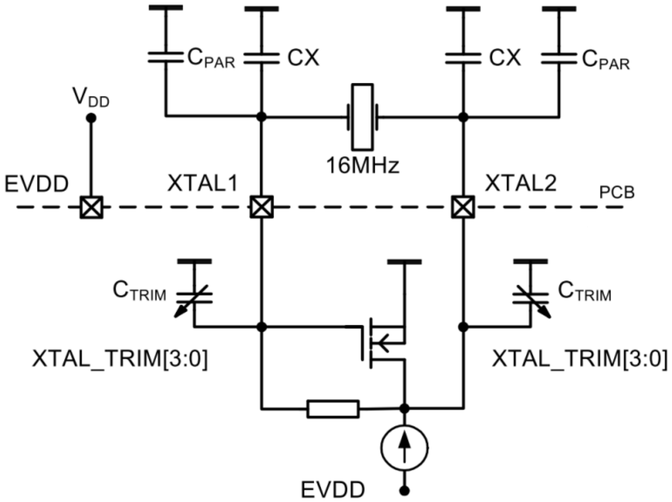
Frequency stability is the maximum allowable deviation from the nominal frequency over a specified temperature range, and is specified in ppm or percentage of nominal frequency. Deviation is usually referenced to the measured frequency at 25ºC.

2.1.3 Aging

Long-term stability or aging of a quartz crystal is a measure of the frequency stability during an extended time period and is usually expressed in terms of ppm per day or year. It applies to the cumulative process, which contributes to the deterioration of the crystal unit and which results in a permanent change in operating frequency of the crystal unit. Aging normally follows an exponential progression over time, so that most aging takes place in the first few months after manufacture.

2.2 Load capacitance

Figure 2-1. 16MHz crystal circuit.



As seen in Figure 2-1, the two capacitors (CX) are the loads of the crystal. The effective load capacitance, C_L, as seen from the XTAL1 and XTAL2 pins is given by,

$$C_L = 0.5 * (CX + C_{TRIM} + C_{PAR})$$

Where

C_L – Total load capacitance

CX – External load capacitance

C_{TRIM} – Internal load capacitance

C_{PAR} – Parasitic capacitance includes XTAL1/XTAL2 pins along with PCB stray capacitance

C_{PAR} can be approximated to or assumed to be in the range 2 to 5pF. Right choice of C_L is important for proper operating frequency and the influences of small and larger load capacitances are captured in the Section 5.3. It is recommended to use a crystal with C_L as specified in the Transceiver/SoC datasheets.

2.3 Pullability

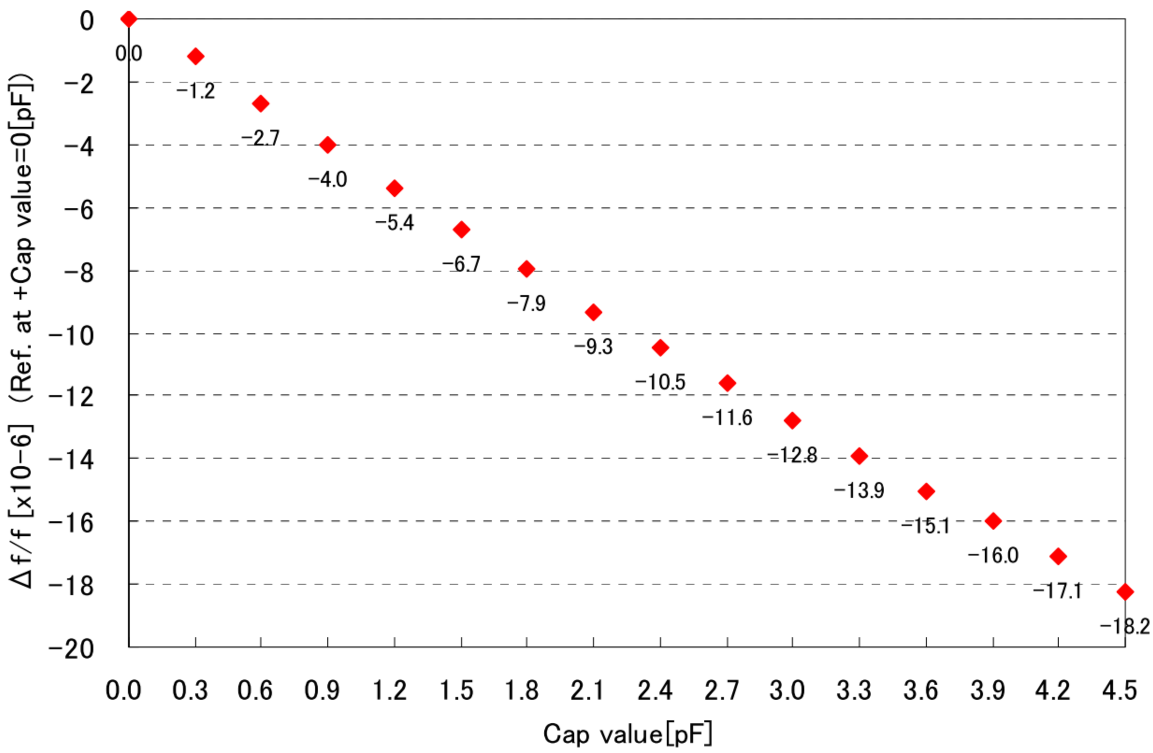
It is possible to slightly alter the oscillation frequency of a crystal by tuning the load capacitance value (CX). The pullability of the oscillating system refers to which extent it is possible to tune the resonance frequency of the crystal by changing the internal capacitance values.

This gives the freedom for the software developers to tune internal trimming capacitance to compensate the environmental effects. Software developers have to come up with their own method for determining the amount of compensating required for such scenarios.

Figure 2-2 shows the pull-ability of the crystal by varying the internal trim capacitance of the transceiver. In this example the crystal was matched with internal trim capacitance value of XTAL_TRIM =0 (i.e. 0pF).

If the application software uses tuning of internal trim capacitance it is recommended to match the crystal with XTAL_TRIM = 8 (i.e. 2.4pF) so we have the window to move both in positive and negative directions of the frequency.

Figure 2-2. XTAL_TRIM pullability plot for CX = 15pF EPSON® TSX-3225 16MHz on TB2_XMEGA®_231.



2.4 Equivalent Series Resistance (ESR)

ESR is the resistive element measured in Ohms of a quartz crystal resonator. Influences of ESR are discussed in the Section 5.2. We always recommend the designers to refer the ESR limits in the Crystal Parameter Requirements section of the device's datasheet [5].

3. Layout Guidelines

A quick checklist for the oscillator circuit layout is given below:

- The influence of spurious coupling and noise sensitivity due to parasitic antenna can be reduced by placing crystal, load capacitors and XTAL pins close to the device
- If it is not feasible to place these components closer, care should be taken while routing the signal lines
- Always avoid routing traces underneath the IC package and also under the crystal area
- Ensure that the ground plane underneath the oscillator is of good quality
- Ground connections from the load capacitors should be as short as possible and also make sure that they are of equal length from each capacitor
- Do not use a separate ground plane under the oscillator with a narrow connection to the reference ground as this can act as an antenna
- To avoid coupling from surrounding signal traces, it is good practice to place a grounded guard ring around the oscillator and its components

- PCB cleaning is recommended to reduce flux residues from soldering
- Use high-quality PCB and soldering materials
- Dust and humidity will increase parasitic capacitance and reduce signal isolation, so protective coating is recommended

For more details, refer to the following application notes, which provide solutions to potential design issues, which might be faced during the PCB design phase:

a. Atmel AVR042: AVR Hardware Design Considerations [2].
b. Atmel AVR186: Best Practices for the PCB layout of Oscillators [3].

4. Hardware and Software Descriptions

The firmware and PCB design files are attached in zip form and can be downloaded by clicking on the CD icon. A list of contents available in the attached is provided in Section 7.

We have made different board layouts based on the crystal sizes as shown in Figure 4-1.

Figure 4-1. Board layouts and crystal sizes.

S.no	Board name	16MHz crystal size [mm x mm x mm]	32kHz crystal size [mm x mm x mm]
1	TB1_MEGARF	2.5 x 2 x 0.6	2.1 x 1.3 x 0.6
2	TB2_MEGARF	3.2 x 2.5 x 1.1	3.2 x 1.5 x 0.9
3	TB3_MEGARF	5.2 x 3.2 x 1.2	5.0 x 1.9 x 0.9
4	TB4_MEGARF	13.9 x 5 x 4.3	7.0 x 1.5 x 1.4
5	TB5_MEGARF	5.2 x 3.4 x 1.0	2.1 x 1.3 x 0.6
6	TB6_MEGARF	13.9 x 5 x 4.3	3.2 x 1.5 x 0.9
7	TB7_MEGARF	2.5 x 2 x 0.6	3.2 x 1.5 x 0.9
8	TB1_XMEGA_212	2.5 x 2 x 0.6	-
9	TB2_XMEGA_212	3.2 x 2.5 x 1.1	-
10	TB3_XMEGA_212	5.2 x 3.2 x 1.2	-
11	TB4_XMEGA_212	13.9 x 5 x 4.3	-
12	TB1_XMEGA_231	2.5 x 2 x 0.6	-
13	TB2_XMEGA_231	3.2 x 2.5 x 1.1	-
14	TB3_XMEGA_231	5.2 x 3.2 x 1.2	-
15	TB4_XMEGA_231	13.9 x 5 x 4.3	-

Figure 4-2 and Figure 4-3 shows the screenshot of schematics and layouts of the board, which are used for the crystal characterization. Schematics and Gerber of all these boards are available in the attachment.

Figure 4-2. 16MHz crystal schematic and layout of TB1_XMEGA_212/231 board.

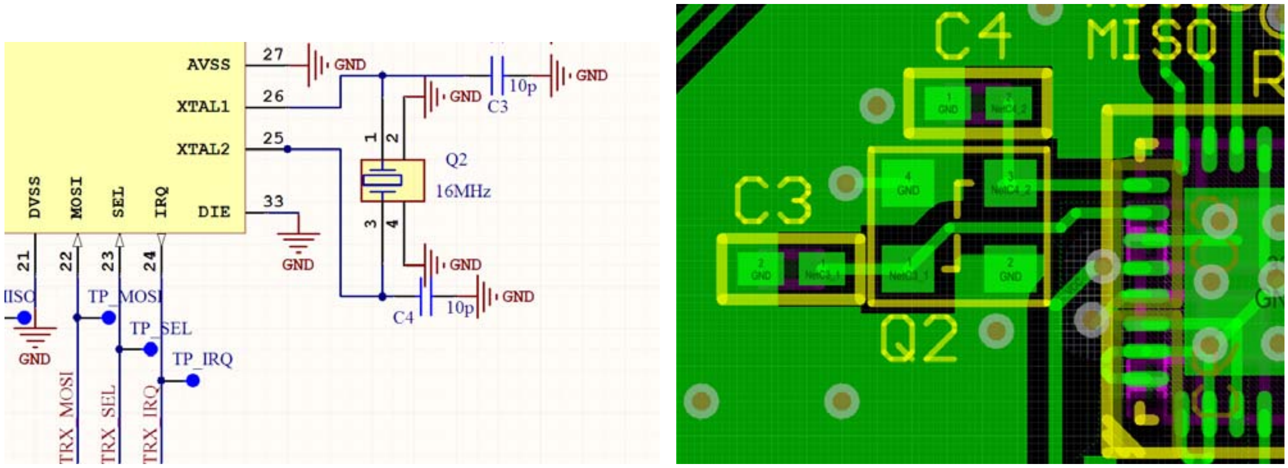
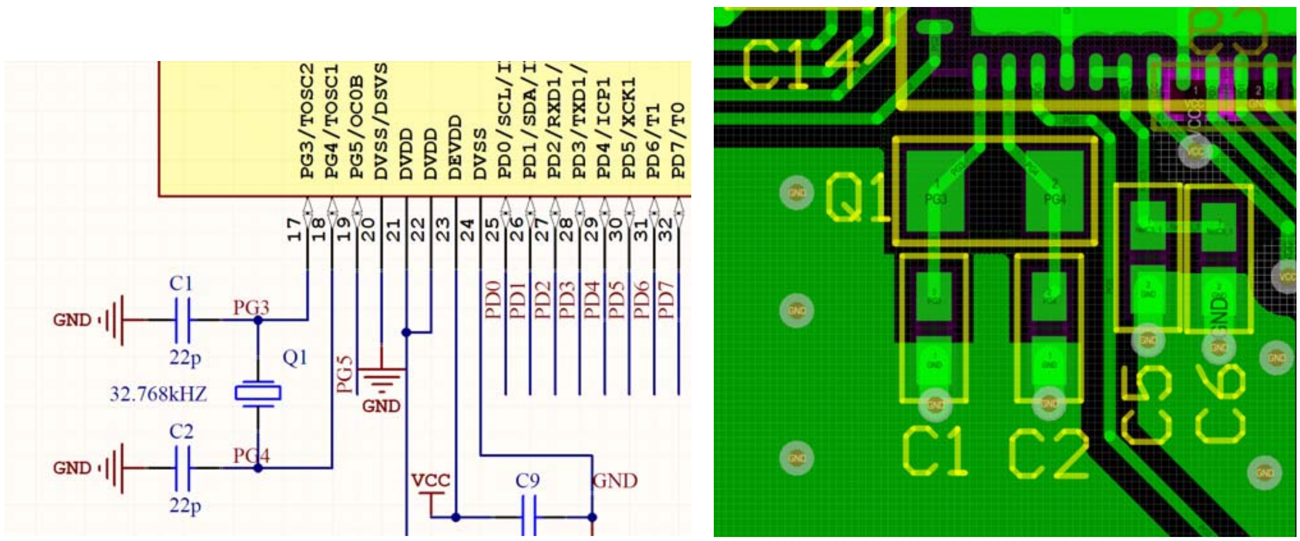


Figure 4-3. 32kHz crystal Schematic and layout of TB1_MEGA_RF board.



We have two firmwares; one runs on the Atmel ATmega128RFA1 (Section 4.2) and other runs on the Atmel ATxmega256A3 with transceiver (Section 4.3). The crystal characterization procedure for changing XTAL_TRIM values were given as comments in firmware files. Firmware for the ATmega128RFA1 and ATxmega256A3+Transceiver platform is available in the CD. See Section 7.

4.2 Features of ATmega128RFA1 firmware

- XTAL_TRIM register settings are configured automatically based on jumper settings for 16MHz crystal
- Logic level indications are provided for each XTAL_TRIM value
- For 32kHz crystal an asynchronous timer overflow is used to toggle an I/O pin, clock frequency divided by 2 (that is 16384Hz) will be observed on pin PB4

4.3 Features of ATxmega256A3 + transceiver firmware

- XTAL_TRIM register settings are configured automatically based on jumper settings for 16MHz crystal
- Logic level indications are provided for each XTAL_TRIM values

5. Application Specific Crystal Selection

The comparative study below here will help you to choose an appropriate crystal for the targeted application. Crystals may not satisfy each and every unique application requirements. In such scenarios designers have to prioritize their application requirements and choose a crystal accordingly.

Because all application requirements cannot be fulfilled we may have to compromise on certain low priority requirements.

For example a crystal with faster startup time and smallest crystal dimension might not be available at lower cost so the designer can choose either faster startup crystal (which will be larger) or smallest crystal (with larger ESR hence slower startup time) or a crystal with optimal startup time and size.

5.1 Large vs. small crystals

c. Smaller the enclosure of crystal, the higher is the cost.

d. Larger crystals have lower ESR value.

e. Larger crystals have faster startup time. Figure 5-1 shows the comparison of NDK crystals with respect to startup time.

Figure 5-1. Crystal size vs. startup time.

S.no	Vendor	Part number	Frequency	Crystal size [mm]	ESR [Ω]	Startup time [ms]
1	NDK	NX2520SA	16MHz	2.5×2.0×0.5	80	2.5
2	NDK	NX3225SA	16MHz	3.2×2.5×0.55	80	2
3	NDK	NX5032GA	16MHz	5.0×3.2×1.3	50	1.5

5.2 Large vs. small ESR

a. The lower the ESR of a crystal, the more active it is and less drive is required to activate it.

b. Crystal with higher ESR value will start slower and if the ESR is higher than the specified limit as given in device's datasheet then it might not even start.

c. High ESR crystals might not be suitable for an application requiring stability over a wide temperature range.

5.3 Large vs. small load capacitance

a. Crystal with larger load capacitance tends to start slower.

b. If the load capacitance of the crystal is larger the pullability factor will be smaller, so frequency can be tuned very finely.

Figure 5-2, Figure 5-3, and Figure 5-4 illustrates the pullability curve of the crystal. Referring to plots it is observed that at smaller load capacitance the slope is significantly large when compared to the larger load capacitance value.

Figure 5-2. Load capacitance vs. pull-ability for C_L = 7pF microcrystal (CM7V-T1A 32.768kHz - 7pF) on TB2_MEGARF board.

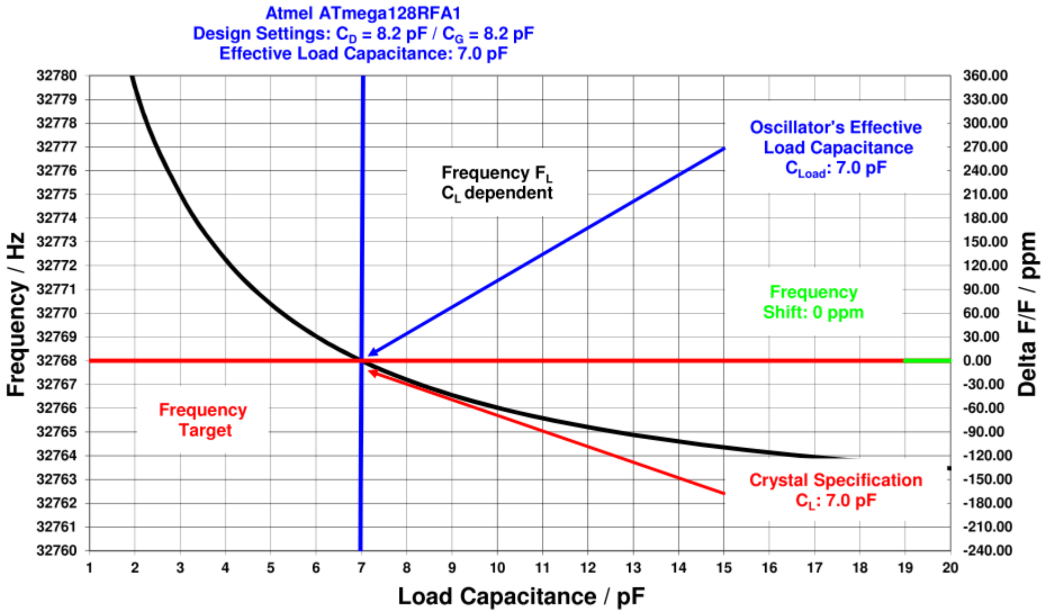


Figure 5-3. Load capacitance vs. pull-ability for C_L = 9pF microcrystal (CM7V-T1A 32.768kHz - 9pF) on TB2_MEGARF board.

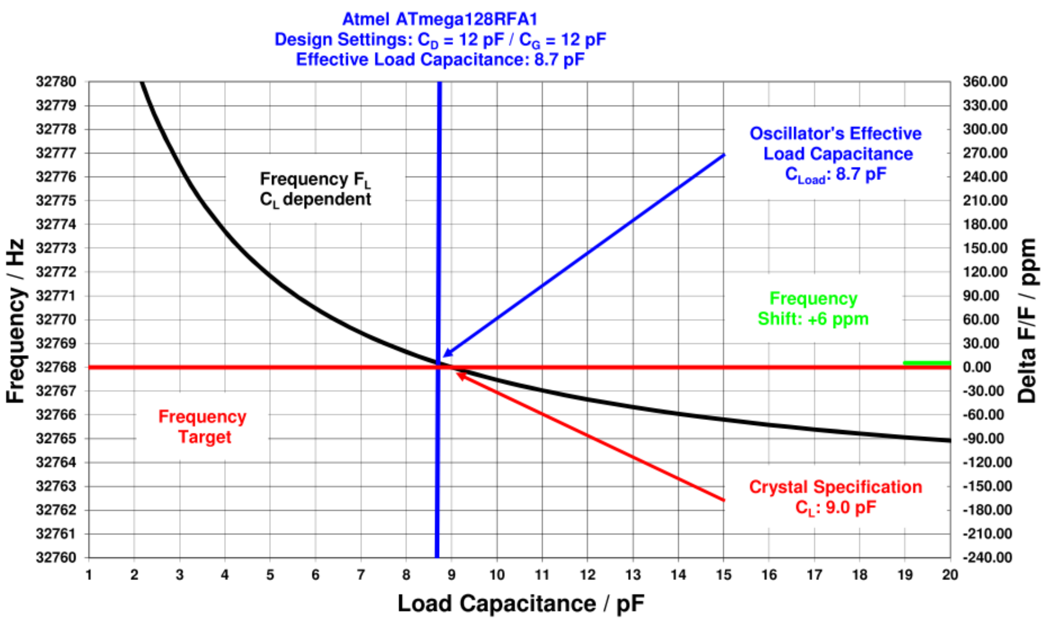
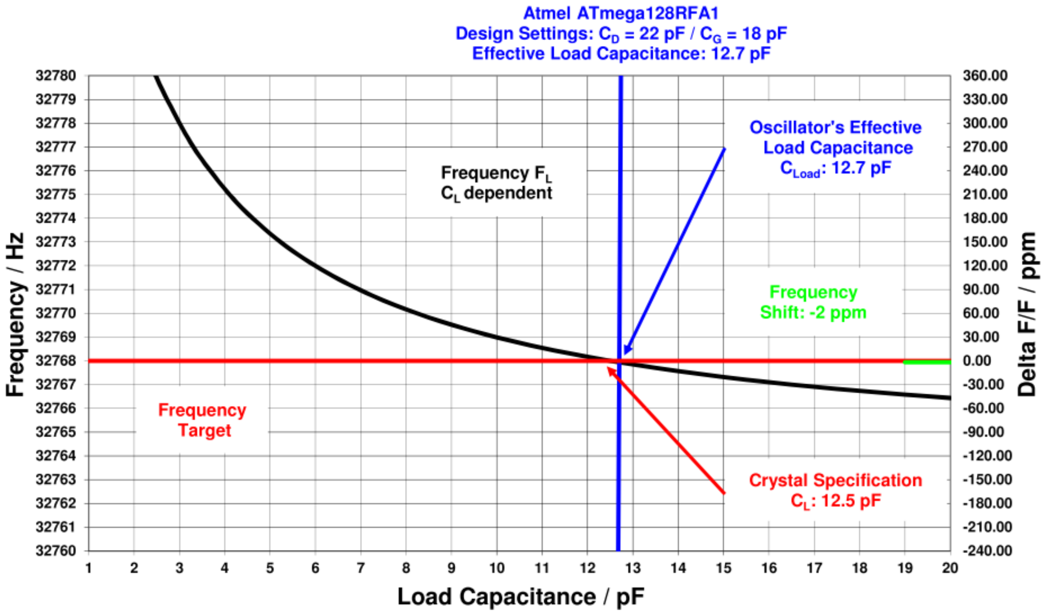


Figure 5-4. Load capacitance vs. pull-ability for C_L = 12.5pF microcrystal (CM7V-T1A 32.768kHz – 12.5pF) on TB2_MEGARF board.

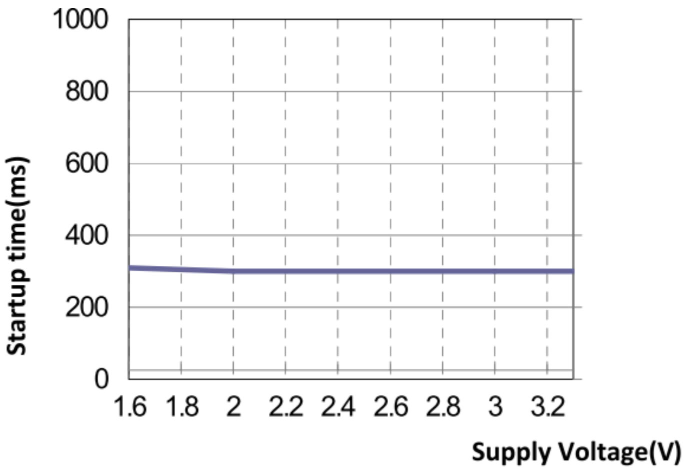


5.4 Dependency on supply voltage

The transceiver's oscillators are powered by an internal regulator and there will not be any change in the characteristics of the crystal, if the supply voltage is varied between 1.8V to 3.3V.

The startup time of 32.768kHz is shown in Figure 5-5 and it is observed that startup time is independent of the supply voltage.

Figure 5-5. Startup time vs. supply voltage plot of Citizen crystal (CM315D 32.768kHz) on TB2_MEGARF board.



5.5 Safety factor

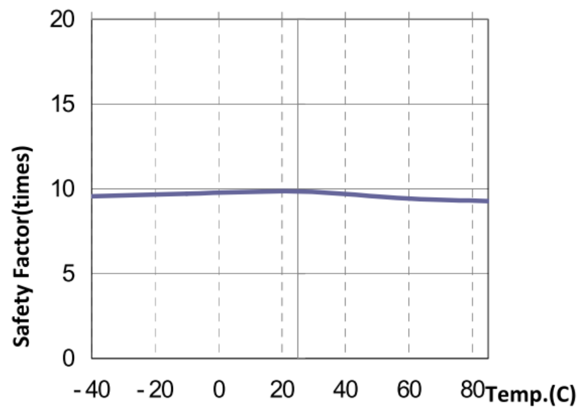
a. The negative resistance should be a minimum of five times the specified maximum resistance value (ESR) of the crystal unit, to have an excellent safety factor.

b. Please check for ESR and Negative resistance parameters in the characterization reports of crystal vendors available in Section 7.

c. For more details regarding the test procedures, refer the application note Atmel AVR4100: Selecting and testing 32kHz crystal oscillators for Atmel AVR microcontrollers [1].

Figure 5-6 shows the safety factor of 32.768kHz crystals with respect to temperature.

Figure 5-6. Safety factor vs. temperature plot of Citizen crystal (CM315D 32.768kHz) on TB2_MEGARF board.



5.6 Extreme temperature stability

a. For applications which requires stability over an extreme temperatures should choose a crystal which has a least ppm variation over temperature difference.
b. A crystal with low ESR is preferred for use in applications requiring extreme temperature stability.
c. Large crystals with small load capacitance and low ESR are the best choices for reducing the power consumption.
d. Test reports from some crystal vendors have the Frequency vs. temperature plot.

Frequency variation of both 16MHz and 32.768kHz crystals with respect to temperature is shown in Figure 5-7 and Figure 5-8 respectively.

Figure 5-7. Frequency vs. temperature of EPSON crystal (FA-20H 16MHz) on TB2_MEGARF board.

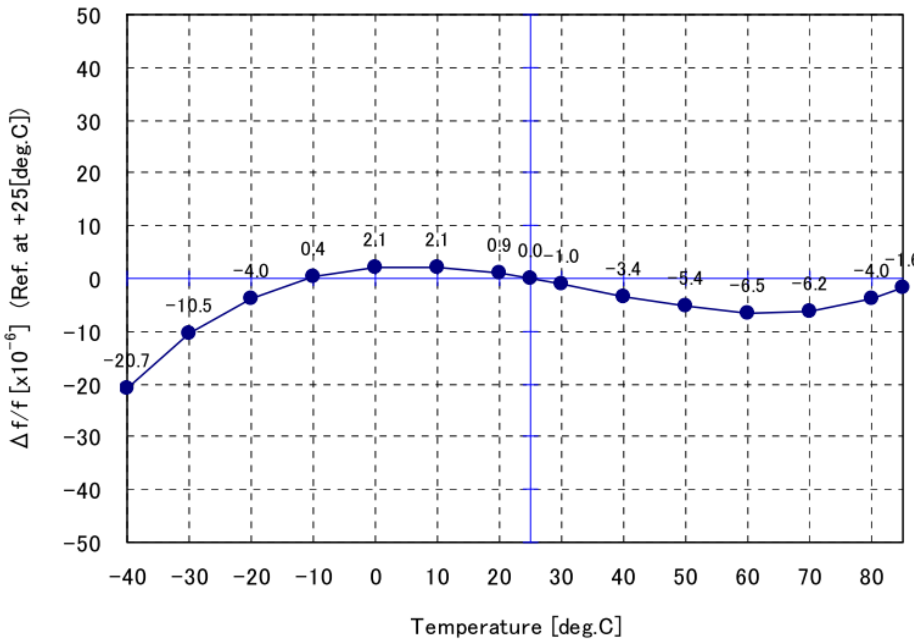
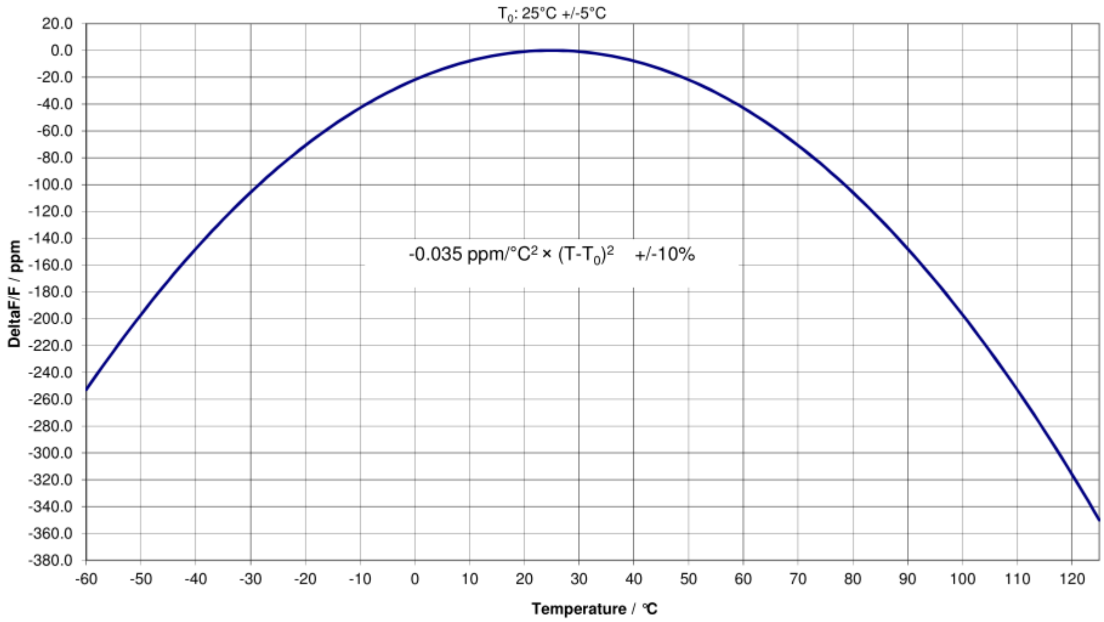


Figure 5-8. Frequency vs. temperature of microcrystal (CM7V-T1A 32.768kHz) on TB2_MEGARF board.



5.7 Reducing power consumption

a. For applications which periodically sleep and wake up, a quick startup time and low power consumption for startup are key parameters.

b. To generate the same voltage swing, crystals with larger ESR and larger load capacitance consumes more power than crystals with small ESR and load capacitance values.

c. Hence, larger crystals with small load capacitance and lower ESR are a better choice.

6. Recommended Crystals

From the recommended list of crystals given in Section 6.1 and 6.2 one should be able to find a suitable crystal for their application based on crystal size, ESR, load capacitance, negative resistance, frequency stability, power consumption, cost etc.

The following list contains only Atmel ATmega128RFA1, AT86RF212, and AT86RF231 chipsets but these recommended crystals can be used in Atmel ATmega256RFR2, AT86RF230, AT86RF232, and AT86RF233 designs as well. The oscillator section in these series of chipsets does not vary.

6.1 16MHz crystals

Part number	Crystal size [mm]	Chipset	ESR [Ω]	C3 [pF]	C4 [pF]	Frequency tolerance [ppm]	Frequency stability [ppm]	Aging [ppm/yr]	Matched value [ppm]
NDK-NX2520SA-16.000M-STD-CSW-5	2.5×2.0×0.50	ATmega128RFA1	80	15	15	±15	±15	±5	-4
NDK-NX2520SA-16.000M-STD-CSW-5	2.5×2.0×0.50	AT86RF212	80	15	15	±15	±15	±5	-4
NDK-NX2520SA-16.000M-STD-CSW-5	2.5×2.0×0.50	AT86RF231	80	15	15	±15	±15	±5	-4
NDK-NX3225SA-16.000M-STD-CSR-6	3.2×2.5×0.55	ATmega128RFA1	80	15	15	±15	±25	±5	-2
NDK-NX3225SA-16.000M-STD-CSR-6	3.2×2.5×0.55	AT86RF212	80	15	15	±15	±25	±5	-4
NDK-NX3225SA-16.000M-STD-CSR-6	3.2×2.5×0.55	AT86RF231	80	15	15	±15	±25	±5	-1
NDK-NX5032GA-16.000M-STD-CSK-8	5.0×3.2×1.3	ATmega128RFA1	50	15	15	±20	±30	±10	+5
NDK-NX5032GA-16.000M-STD-CSK-8	5.0×3.2×1.3	AT86RF212	50	15	15	±20	±30	±10	+2
NDK-NX5032GA-16.000M-STD-CSK-8	5.0×3.2×1.3	AT86RF231	50	15	15	±20	±30	±10	+2
EPSON-FA-20H, 16MHZ,10PPM, 9PF	2.5×2.0×0.55	ATmega128RFA1	80	12	12	±10	±30	±3	+0.6
EPSON-FA-20H, 16MHZ,20PPM, 9PF	2.5×2.0×0.55	AT86RF212	80	12	12	±10	±30	±3	-0.2
EPSON-FA-20H, 16MHZ,20PPM, 9PF	2.5×2.0×0.55	AT86RF231	80	12	12	±10	±30	±3	+0.1
TAITIEN-XXBBPLNANF 16.000000 MHZ	3.2×2.5×0.7	ATmega128RFA1	80	12	12	±10	±15	NA	-1.8
TAITIEN-XXBBPLNANF 16.000000 MHZ	3.2×2.5×0.7	AT86RF212	80	12	12	±10	±15	NA	-2.75
TAITIEN-XXBBPLNANF 16.000000 MHZ	3.2×2.5×0.7	AT86RF231	80	12	12	±10	±15	NA	-3.06

6.2 32.768kHz crystals

Part number	Crystal size [mm]	Chipset	ESR [Ω]	C1 [pF]	C2 [pF]	Frequency tolerance [ppm]	Operating temperature range [°C]
Seiko-SSP-T7-F-12.5pF	7.0x1.5x1.4	ATmega128RFA1	65k	18	18	±20	−40 to +85
Citizen-CM51932768DZYT	4.9x1.8x1.0	ATmega128RFA1	70k	12	12	±20	−40 to +85
Citizen-CM315D32768DZYT	3.2x1.5x0.9	ATmega128RFA1	70k	12	10	±20	−40 to +85
Microcrystal-CM7V–T1A 32.768kHz-7pF ±20ppm-TA-QC	3.2x1.5x0.65	ATmega128RFA1	50/70k	8.2	8.2	±20	−40 to +85
Microcrystal-CM7V–T1A 32.768kHz-9pF ±20ppm-TA-QC	3.2x1.5x0.65	ATmega128RFA1	50/70k	12	12	±20	−40 to +85
Microcrystal-CM7V–T1A 32.768kHz-12.5pF ±20ppm-TA-QC	3.2x1.5x0.65	ATmega128RFA1	50/70k	18	22	±20	−40 to +85
NDK-NX3215SA-32.768K-STD-MUA-9	3.2x1.5x0.8	ATmega128RFA1	70k	12	12	±20	−40 to +85
NDK-NX2012SA-32.768K-STD-MUB-1	2.0×1.2×0.55	ATmega128RFA1	80k	12	12	±20	−40 to +85

7. CD Content

The following contents are available in the attachment.

- CD
  - Crystal reports
  - Firmware
    - Code
  - Schematics and Gerbers
    - ATmega128RFA1-Boards
      - GBR_TB1_ ATmega128RFA1
      - GBR_TB2_ ATmega128RFA1
      - GBR_TB3_ATmega128RFA1
      - GBR_TB4_ ATmega128RFA1
      - GBR_TB5_ ATmega128RFA1
      - GBR_TB6_ ATmega128RFA1
      - GBR_TB7_ATmega128RFA1
      - Schematics
    - ATxmega256A3+AT86RF212-Boards
      - GBR_ TB1_ATxmega256A3+AT86RF212
      - GBR_TB2_ ATxmega256A3+AT86RF212
      - GBR_TB3_ ATxmega256A3+AT86RF212
      - GBR_TB4_ ATxmega256A3+AT86RF212
      - Schematics
    - ATxmega256A3+AT86RF231-Boards
      - GBR_ TB1_ATxmega256A3+AT86RF231
      - GBR_ TB3_ATxmega256A3+AT86RF231
      - GBR_TB2_ ATxmega256A3+AT86RF231
      - GBR_TB4_ ATxmega256A3+AT86RF231
      - Schematics

8. Conclusion

This application note provides an overview of the relation between the various parameters of the crystal along with their tradeoffs. We have focused on the application perspective only. For in-depth knowledge of the crystal operation and theory, please contact the crystal vendors.

9. References

1. Atmel AVR4100: Selecting and testing 32kHz crystal oscillators for Atmel AVR microcontrollers (www.atmel.com/images/doc8333.pdf).
2. Atmel AVR042: AVR Hardware Design Considerations (www.atmel.com/images/doc2521.pdf).
3. Atmel AVR186: Best Practices for the PCB layout of Oscillators (www.atmel.in/Images/doc8128.pdf).
4. IEEE Std 802.15.4™-2006: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs).
5. MCU Wireless datasheets (www.atmel.com/products/microcontrollers/wireless/default.aspx).

10. Revision History

Doc. Rev.	Date	Comments
42068A	01/2013	Initial document release

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