Application Note

IMPINJ®

MONZA® X

ANTENNA APPLICATION NOTE

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FIGURES

1 OVERVIEW

The Impinj Monza® X-2K Dura and Monza® X-8K Dura ICs are UHF Gen2 RFID tag chips featuring an I2C data interface in addition to the UHF RF link. This application note provides details of the Monza X RF interface. Concepts presented here include the following:

- Antenna and air link principles unique to UHF RFID
- Monza X RF port characteristics and equivalent models
- Antenna options and antenna types suitable for use with Monza X
- Impedance matching techniques

Impinj publishes a separate application note detailing the data interface, available on the Impinj website:
https://support.impinj.com/hc/en-us/articles/202756838-Monza-X-Software-API-and-Application-Note

This application note references and builds upon information documented in the Monza X Dura data sheets, which may be found here:
https://support.impinj.com/hc/en-us/articles/202756848-Monza-X-2K-Dura-Datasheet
https://support.impinj.com/hc/en-us/articles/202756868-Monza-X-8K-Dura-Datasheet

A set of example antennas is provided with this document in the form of a zip archive of DXF layout artwork. That zip, Monza_X_Antenna_Design_Examples.zip, contains the following files, referred to in this document:

- MonzaX-slot1.DXF
- MonzaX-slot2.DXF
- MonzaX-loop1.DXF
- MonzaX-loop2.DXF
- MonzaX-monopole1.DXF
- MonzaX-monopole2.DXF

The layout files are intended to streamline the integration of Monza X into customer applications which call for an antenna on a circuit board. Monza customers are free to use these layouts, modify them as necessary, and integrate them into their pcb designs. All of the layouts have a layer called “ground” which shows keepouts or critical features in the immediate vicinity of the antenna. The outer boundaries of the ground polygon, away from the antenna, are non-critical and may be modified as desired.

Each antenna presented in this app note has been physically constructed and measured. Performance data come from actual over-the-air measurements in the Impinj antenna chamber.

2 ANTENNA AND AIR LINK PRINCIPLES

All UHF RFID communication links have some common considerations which are relevant regardless of the application. In all cases, the reader produces electromagnetic signals at some field intensity, which falls off with distance. The tag IC with its antenna is responsive to fields above some minimum threshold. Given these fundamental constraints we can calculate the maximum distance at which the reader can reliably communicate with a tag.

The following analysis assumes a propagating model, i.e., far field conditions. See Figure 1 for a representation of the link and important quantities. A similar analysis can be applied to near field links but doing so requires detailed knowledge of the characteristics of the particular reader antenna and tag antenna used.

Any reader producing radiated emissions can be measured in terms of its radiated power intensity. The maximum allowed reader radiated power is dictated by regulations which vary by region. In USA, the limit is +36 dBm (4 Watts) effective isotropic radiated power, or EIRP. Some readers may have other limitations which cap their radiated power at lower levels due to lower antenna gain, lower power amplifiers, battery limitations or thermal constraints, etc.

The tag IC and tag antenna combination are characterized by the receive isotropic power (RIP) required for operation. This measure is the reciprocal of that at the reader: EIRP for transmit, RIP for receive. Quantifying tag sensitivity in terms of field intensity accounts for several factors which are difficult to measure and can have widely varying values, such as the gain of small antennas on finite ground planes and impedance mismatch losses at the highly reactive, high parallel resistance tag IC RF port. Thus, the typical antenna metrics of gain, pattern, and VSWR are complicated to apply to tag antennas. Instead, all of these effects are lumped, along with the tag IC inherent sensitivity, into the tag RIP.

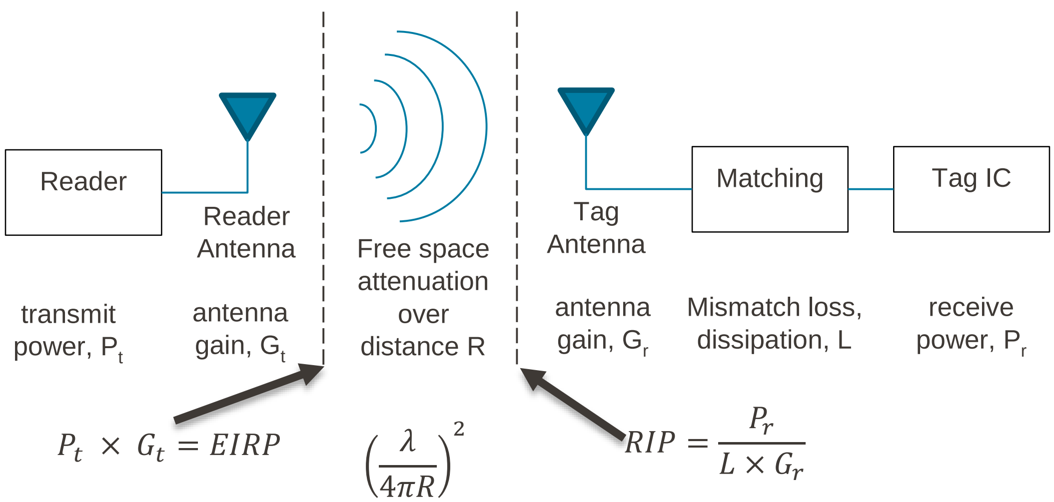


Figure 1 : RFID communication link terms

A passive RFID link is usually limited by the ability to transfer operating power to the tag. The forward power channel limitation is removed when the IC has a local source of power, such as Monza X with the DCI bit enabled and a DC power source present on the DCI pin. In this battery assist mode, the range limit will be imposed by either the forward data link or the reverse data link, depending on the sensitivity of the reader's receiver.

The power available to the receiver in a typical radio link is given by the familiar Friis equation, stated here in linear quantities:

$$P_r = P_t G_r G_t \left(\frac{\lambda}{4\pi R}\right)^2$$

It is possible to combine terms, fill in constants including wavelength at 900 MHz, solve for the distance R (in meters), and restate the equation with quantities in dB:

$$R = 10^{\frac{EIRP - RIP - 31.5}{20}}$$

The graph of this equation for a few typical values of EIRP is given in Figure 2, below.

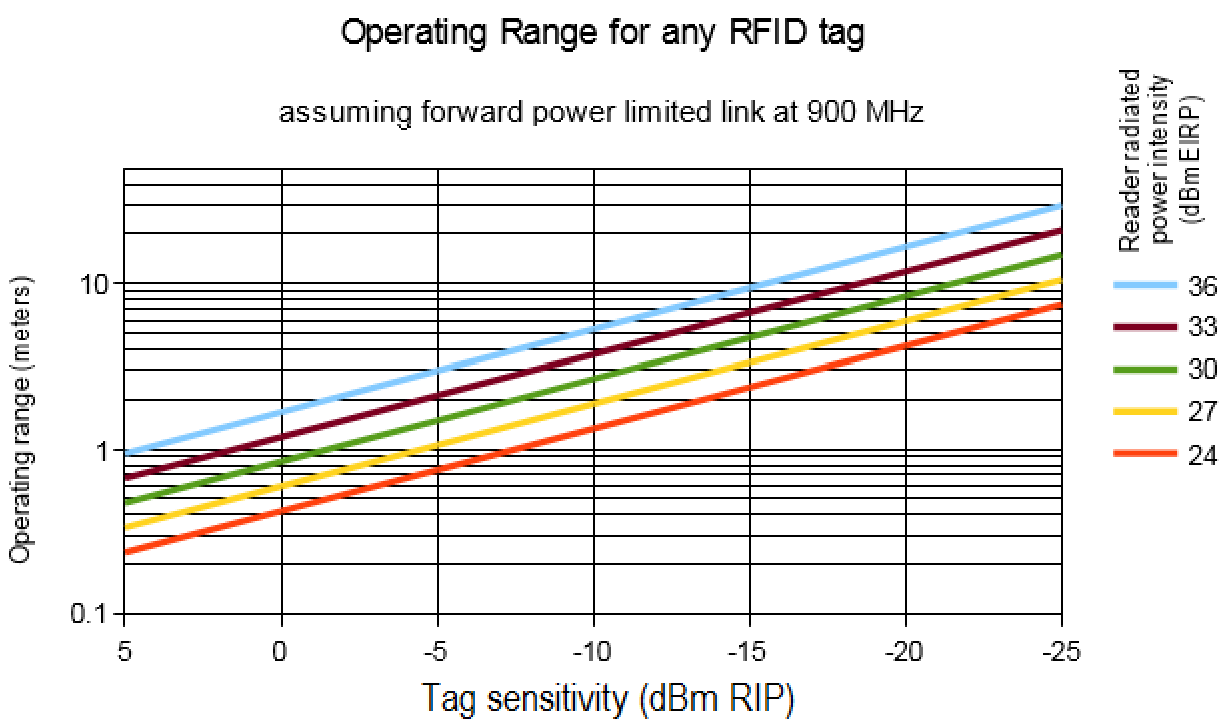


Figure 2: Curves relating range to RIP for various values of EIRP

Here are two examples using the above curves to find operating range of a reader-tag link:

<u>Example 1</u>:

Reader power = 1 W = +30 dBm

Reader antenna gain = +6 dBi → Reader EIRP = +36 dBm

Tag sensitivity = -15 dBm RIP

→ Range is ~10 m

<u>Example 2</u>:

Reader power = 200 mW = +23 dBm

Reader antenna gain = +4 dBi → Reader EIRP = +27 dBm

Tag sensitivity = -5 dBm RIP

→ Range is ~1

3 RF PORT MODEL

Monza X has two independent RF ports which may be used singly or together in any combination of signal amplitude and phase. The ports are AC coupled and may be shorted at low frequencies (i.e., DC) with no impact on performance. Internal to the chip, the power and data signals from the ports are power-summed, so that in the case of simultaneous excitation the phase relation between the signals at the two ports does not influence performance.

Each port is defined as a balanced input across two terminals: Port 1 on pins 1 and 2, and Port 2 on pins 6 and 7. The ports have an RFP and an RFN terminal, however the designation of RFP vs. RFN is arbitrary; the terminals forming a port have approximately the same loading impedance.

For maximum efficiency, the signals incident on each port should be purely odd-mode (differential) to the greatest extent possible. Even-mode signal components are not damaging to the chip, but do reduce the efficiency of the power conversion circuits internal to the IC. Balanced, pure odd-mode signals can be ensured by using symmetric antennas or by using appropriate impedance matching structures to produce balanced signals from unbalanced antennas.

For purposes of simulation and calculation, the loading impedance of a port can be modeled using lumped-element approximations as shown in Figure 3. The large signal model is most relevant to the antenna designer; it is the conjugate of the optimum source impedance, which is *not* equal to the chip input impedance. This indirect, source-pull method of deriving the port model is necessary due to the non-linear, time-varying nature of the tag RF circuits. The small signal model is a broadband model which accounts for out-of-band and even-mode effects over the entire frequency range from 500 MHz to 6 GHz. This circuit is useful for modeling the load that Monza X presents to duplex filters or multi-band antennas that also support wi-fi, GPS, Bluetooth, or other services.

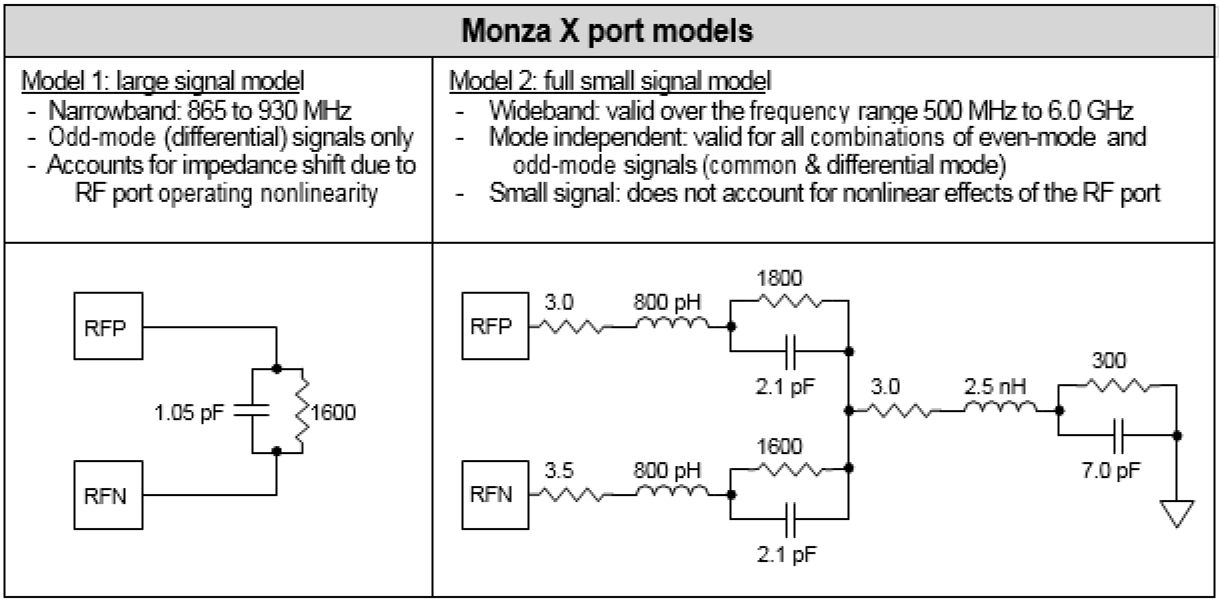


Figure 3 : Port models: lumped element equivalents

4 ANTENNA OPTIONS

Most antennas for Monza X fall into one of four categories, summarized in Figure 4. The categories are distinguished by how much of the RFID system resides on the host circuit board (represented in the diagrams by the light gray rectangle).

When using both RF ports, it is possible to implement two distinct antenna types in the same application. For example, a circuit board may have an on-board antenna connected to Monza X Port 1 which is used during manufacture while also supporting a remote antenna on Port 2 to provide long range operation when the board is inside a shielded enclosure.

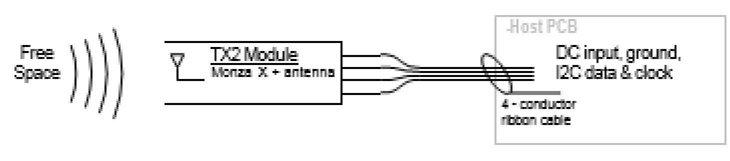
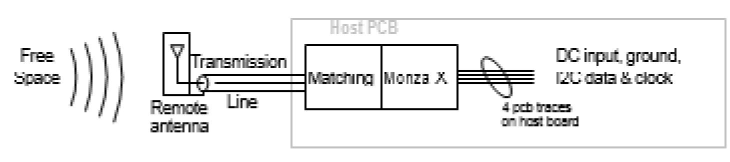
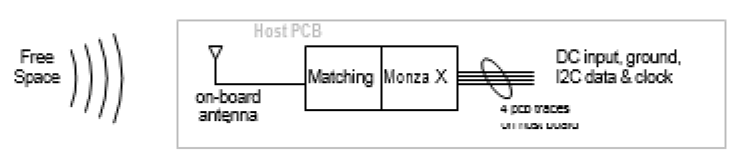
Antenna Type	Block Diagram
<u>TX2 Module</u> A compact circuit board with antenna, impedance matching, and Monza X all on clock, and data. **Simplicity: Free space to I2C**	
<u>Remote</u> Antenna located in a favorable RF environment and connected to host pcb by coaxial cable. Connector and impedance matching on board. 50 Ohm interface. **Ultimate performance and testability**	
<u>Off-board</u> Metal structure near the pcb used as an antenna. Connection from pcb to antenna made by spring contact, fastener, or soldered joint. Impedance matching on board. **Good performance at a favorable cost**	
<u>On-board</u> Antenna formed in the traces of the pcb. Impedance matching implemented within the antenna structure. Board is RFID-enabled from the moment it is populated. **Lowest cost and greatest manufacturability**	

Figure 4 : Antenna categories and characteristics

The following pages cover each of the four antenna categories in greater detail. In every example given, all measured sensitivity numbers apply to the fully passive mode – operation with no DC input present. When an external source of DC power is available to Monza X and the DCI bit is set, the measured sensitivity typically improves by approximately 10 dB (operating RIP reduces by 10 dB). In order to fully realize the range benefit of this improved sensitivity, it is necessary for the reader to have sufficient link margin in its receiver. The observed 10 dB improvement was obtained with an Impinj Speedway reader. Other readers may see less improvement, depending on their receive capability.

4.1 TX2 Module

An example of the Monza X TX2 module is shown in Figure 5. This product combines an antenna, impedance matching, and the Monza X IC all on a thin substrate. All RF and antenna features are implemented on the substrate, leaving only DC and data bus connections for the developer to accommodate. This approach provides significant benefits in terms of development time and effort.

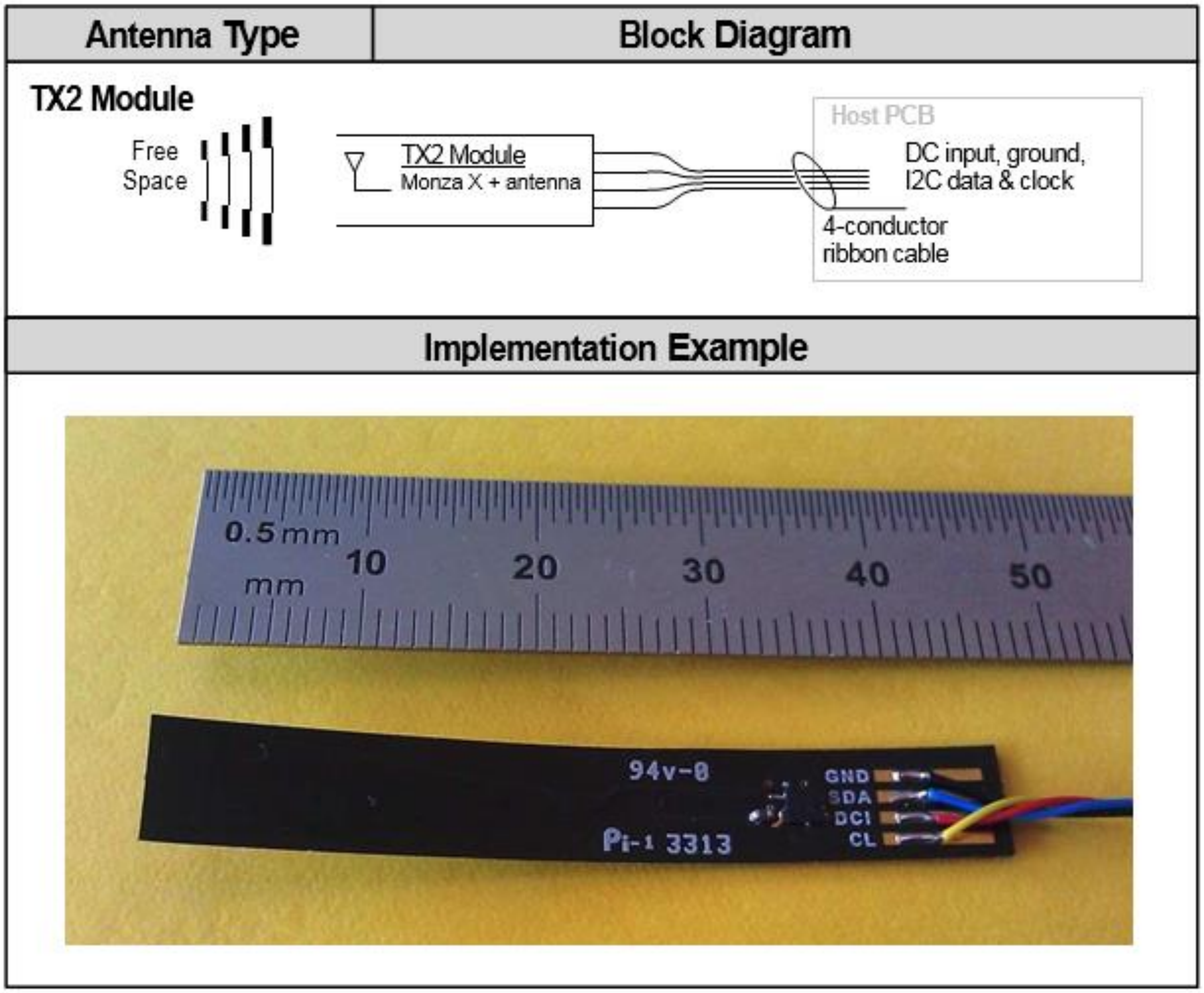


Figure 5 : Monza X with matching and antenna in TX2 module

Read range and sensitivity are highly dependent on objects in the immediate vicinity of the module. Under ideal conditions, the measured sensitivity is approximately -8 dBm RIP, yielding a read range of about 4.5 meters from a full-power fixed reader. Metal or lossy dielectric materials that are a few centimeters from the antenna or closer will diminish the read range.

Impinj does not produce the TX2 module. However, developers interested in the module may contact their Impinj sales representative for further discussion.

4.2 Remote antennas

Products which employ Monza X in shielded enclosures or other difficult RF environments can achieve RFID visibility through the use of remote antennas. A typical remote antenna implementation consists of the antenna, a coaxial cable, a connector, impedance matching components, and the Monza X IC. One example of a commercial off-the-shelf 915 MHz ISM band antenna is shown in Figure 6. The assembly is provided with an attached coaxial cable terminated in an IPEX connector.

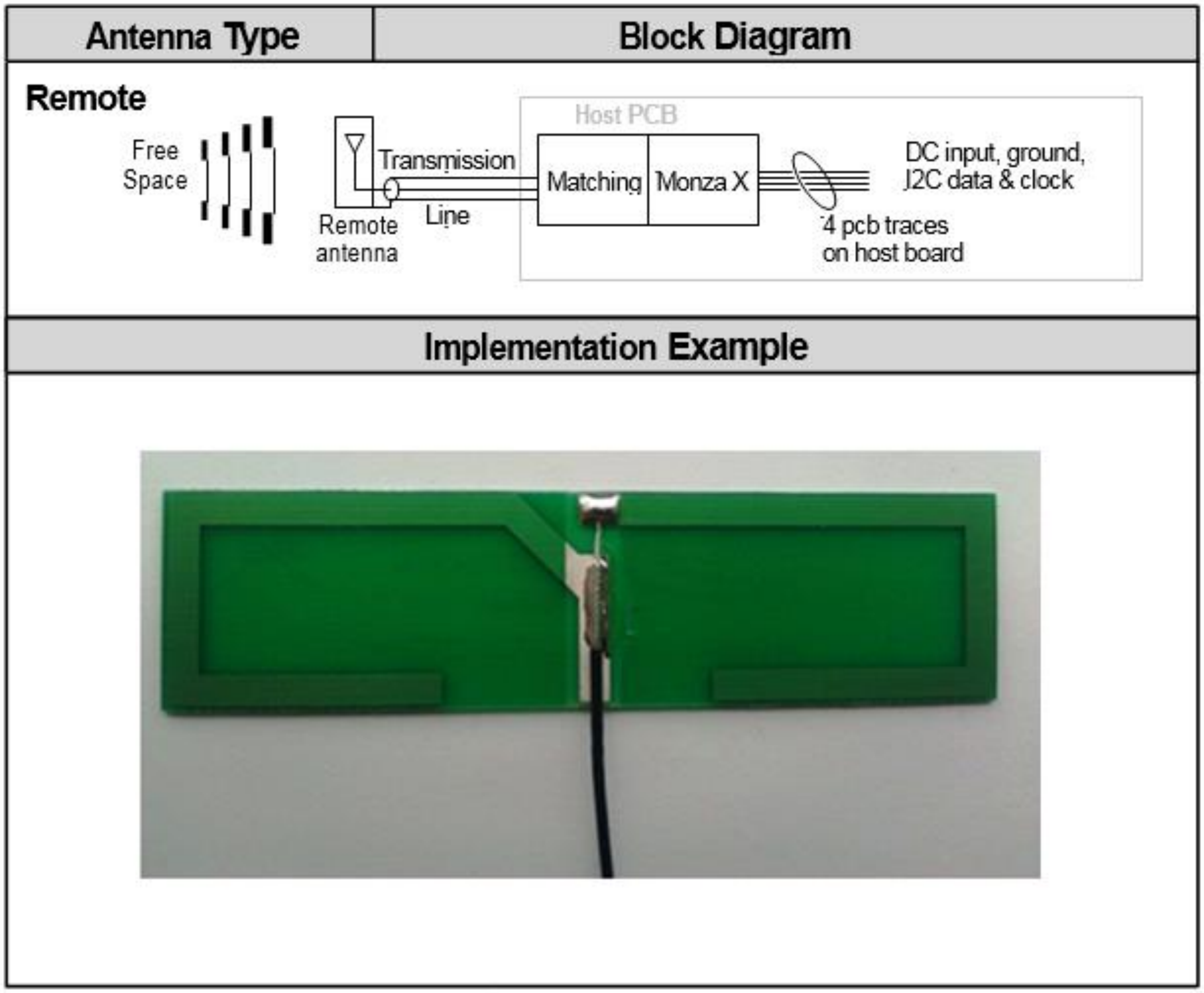


Figure 6 : Remote antenna

The coaxial cable that guides the antenna energy to the host pcb is a relatively low impedance, unbalanced structure. For best sensitivity, the signal must be transformed into balanced signal and impedance value has to be matched to achieving maximum power transfer into the Monza X port. The following page outlines two methods of doing the transformation.

4.2.1 Impedance matching

A lumped element implementation of a balun with impedance transformation is shown in Figure 7, based on an evolution of the tapped resonator balun topology. This circuit has a compact pcb footprint and provides tuneability through the choice of component values but has the drawbacks of reduced efficiency and higher cost due to the use and placement of additional components. A pi-matching circuit is a well-known matching circuit that can transform a high impedance (Monza X) value to a lower impedance value (50 Ohm antenna). Different evolution of tapped resonator balun topologies are shown in Figure 7, below. Moreover, one variation of pi-matching circuit is shown in the right most schematic diagram.

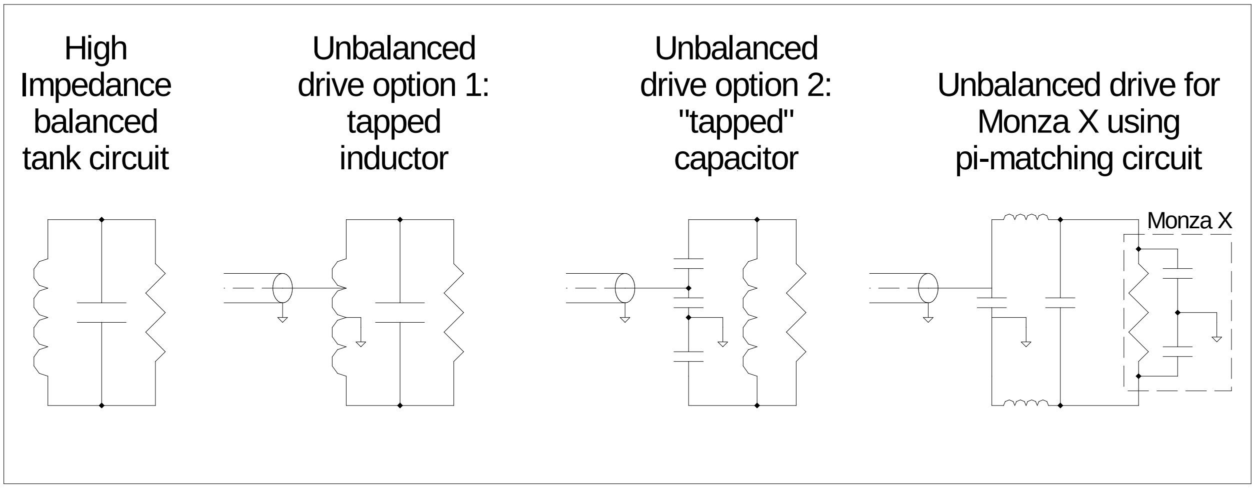


Figure 7 : Derivation of Monza X tapped resonator matching circuit

The values of the components will determine how good the matching is and the bandwidth of the matching circuit. They are not only dependent on the impedance values at either end but also on layout and PCB board parameters. The schematic diagram with values determined from experiment are shown in Figure 8, and an example of layout of the circuit is shown in Figure 9. Again, keep in mind the values depend on the layout so any change made to the layout will require validation and possibly retuning. The layout will be provided in DXF format as a starting point but the users are required to validate the performance of the matching circuit.

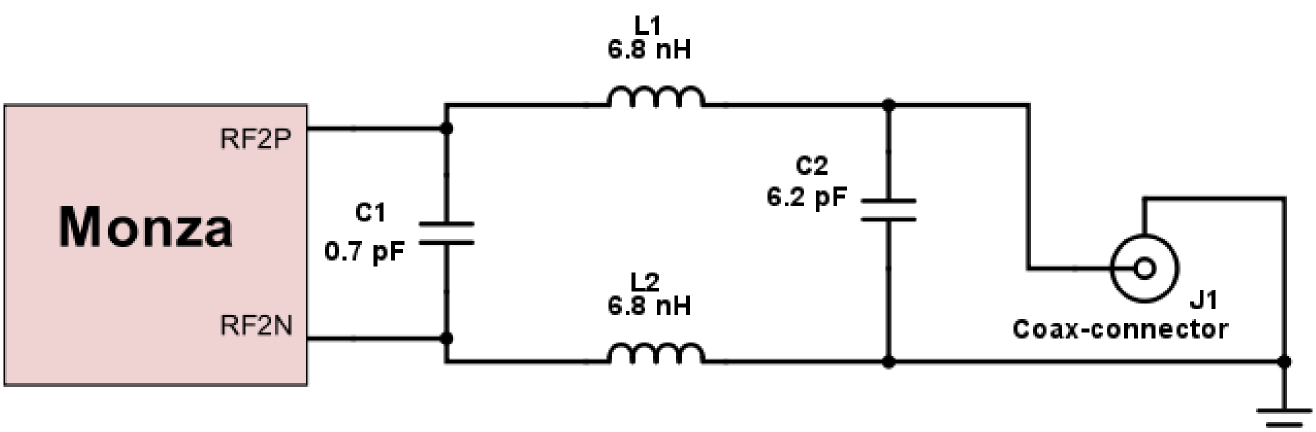


Figure 8 : Schematic diagram of pi-matching circuit

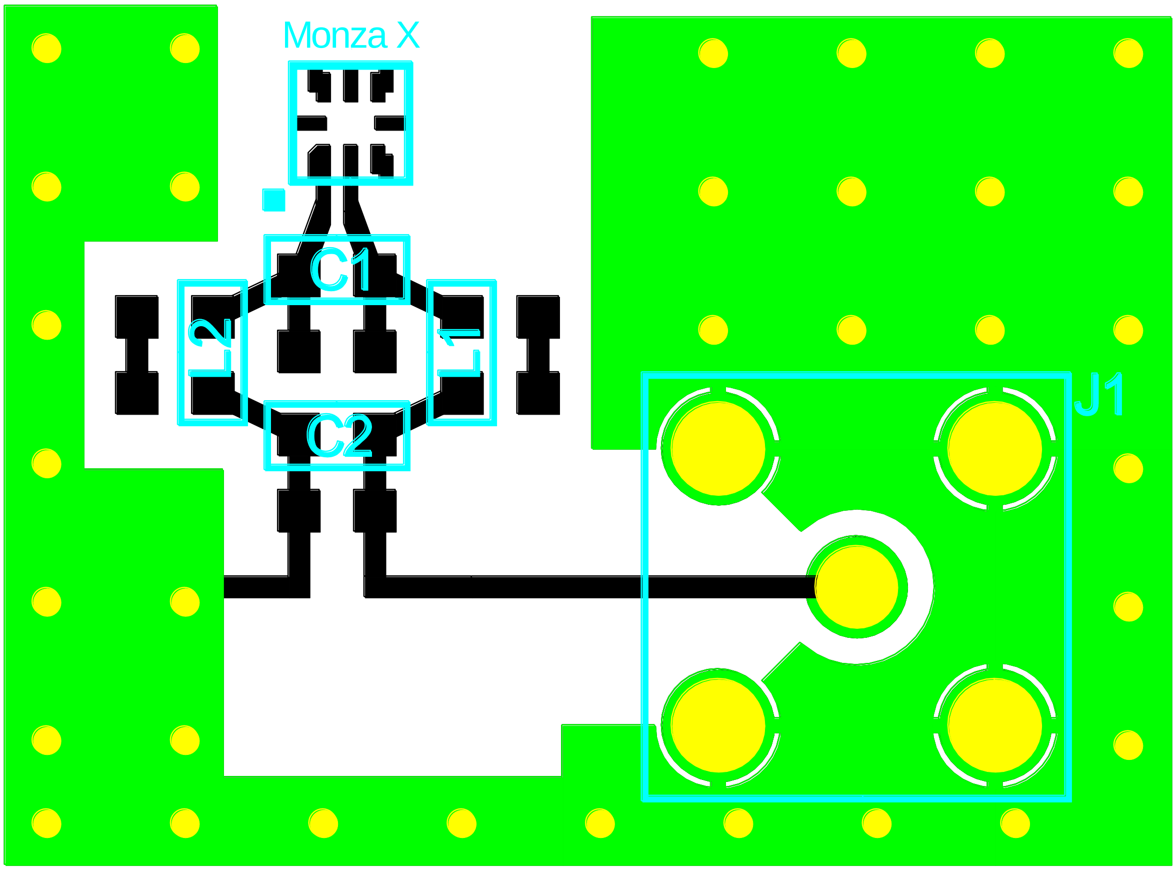


Figure 9 : Example of layout of pi-matching circuit

Another method of achieving impedance transformation and balanced drive from an unbalanced signal source is by using a microstrip balun. This well-known structure is based on coupled transmission lines and can be quite efficient. The evolution of a conventional microstrip directional coupler to a Monza X balun is shown in Figure 10, below. Using coupled lines, it is possible to implement the transformer with no lumped components. This structure has a further benefit of enabling near field contactless operation if an opening in all conductor planes (e.g. ground and power planes) is provided in the vicinity of the structure.

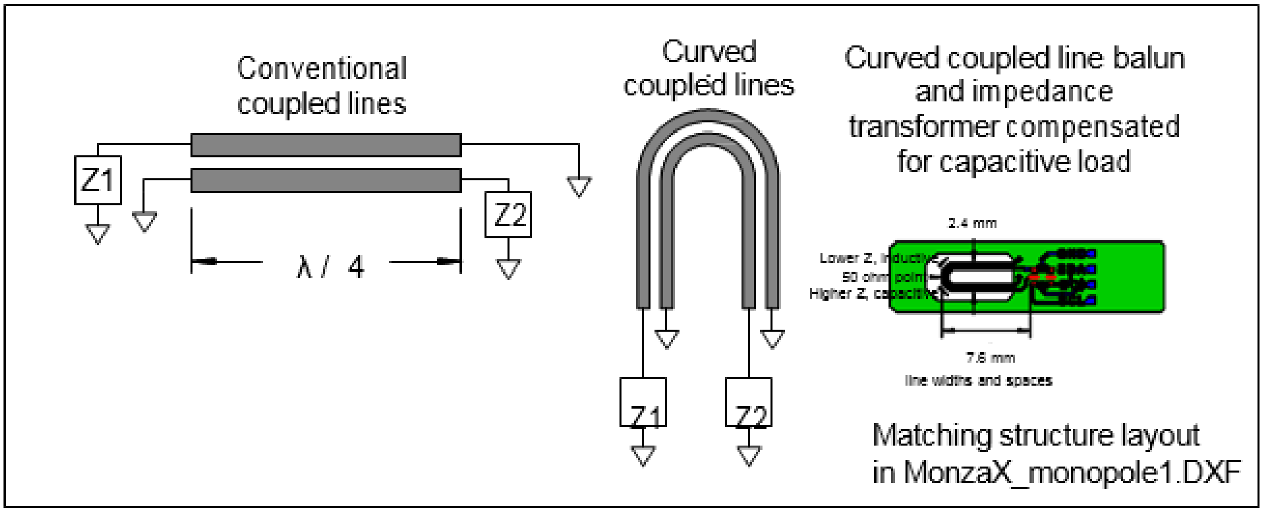


Figure 10 : Derivation of Monza X coupled line matching structure

The coupled line transformer can be used to match to a wide range of impedances by suitable choice of tap point. This tap point is defined by the location at which the feed signal is introduced into the transformer. See Figure 11 for more details. Moving the tap point electrically closer to the grounded end of the outer transmission line provides a lower impedance, more inductive feed point. Tap points electrically closer to the Monza X terminal but still along the outer transmission line have higher impedance, less inductive terminations.

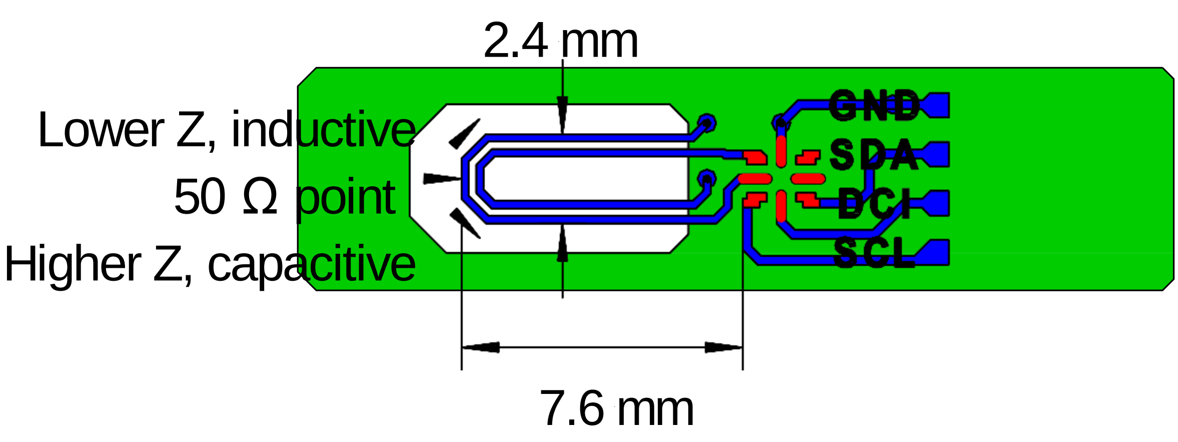


Figure 11 : Impedance matching by selection of transformer tap point

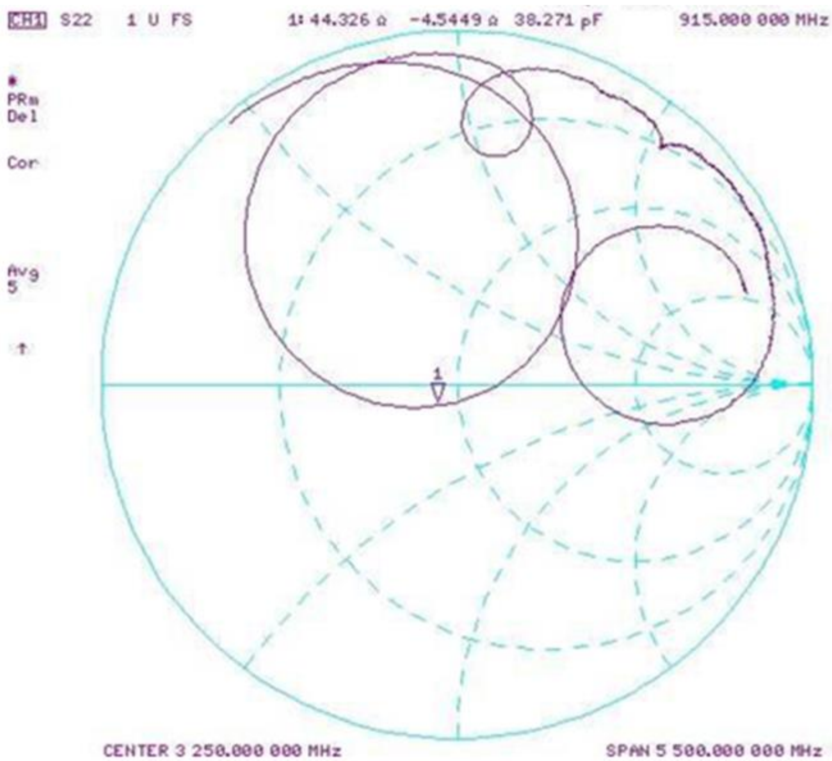


Figure 12 : Impedance looking into coupled line transformer at 50 Ohm tap point

4.3 Off-board Antennas

Placing the antenna near the pcb, but off the board can achieve good RF performance while avoiding the cost of coaxial cable and connectors. Two examples of off-board antennas are metal tabs soldered to the board and conductive features built into the enclosure, connected to the board by a spring-loaded contact. Such antennas can vary widely in electrical characteristics; it is up to the designer to implement impedance transformation suitable for his or her particular antenna. Structures used as off-board antennas often present an impedance that is rather high and capacitive. Such impedances can be matched by using the coupled line transformer of Figure 13, given suitable choice of tap point.

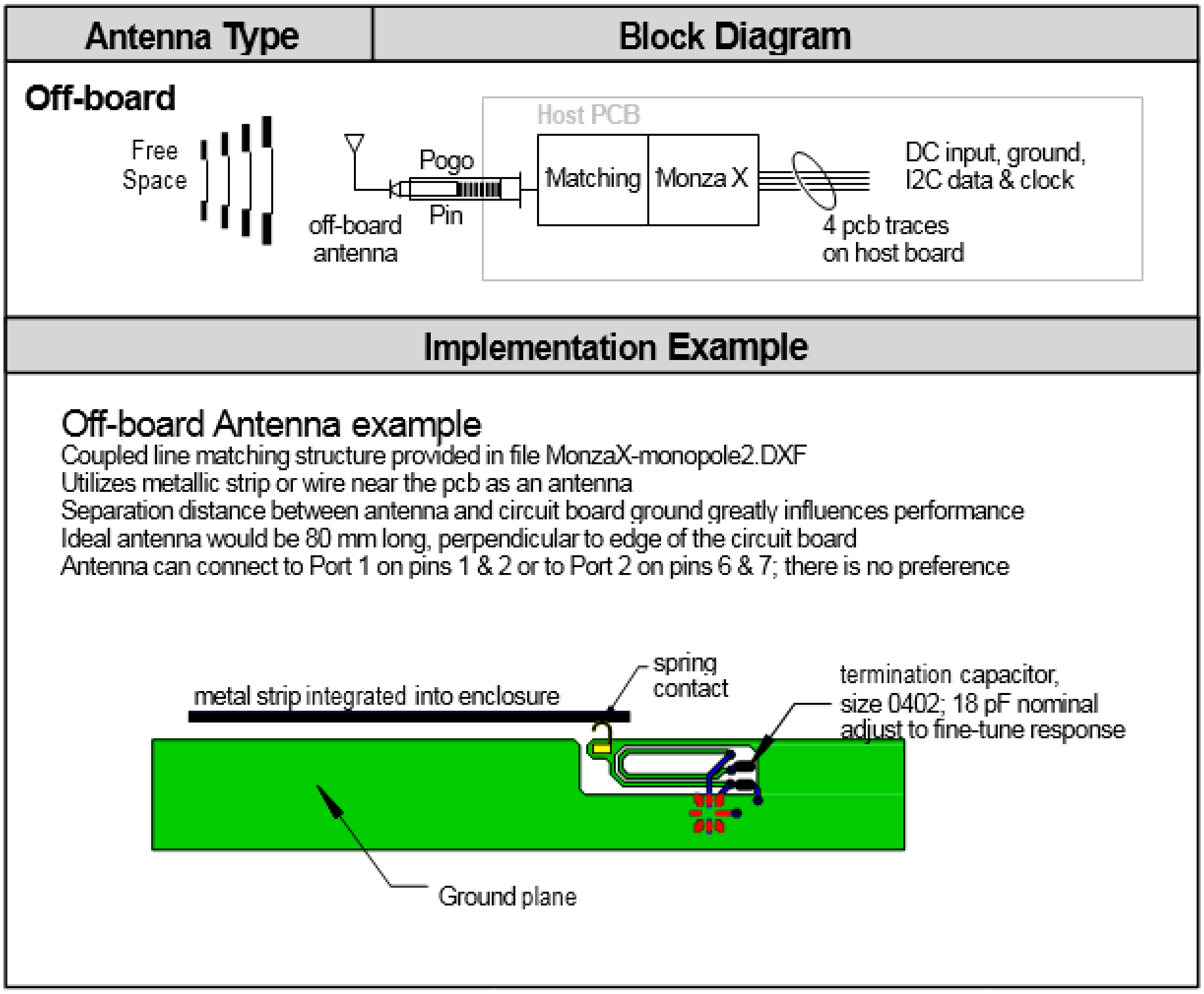


Figure 13 : Off-board antenna

4.4 On-board Antennas

On-board antennas can take many different forms – too many to explore them all here. We will examine three particularly useful topologies: the edge slot, the loaded loop, and the monopole.

The edge slot can be designed to provide inherent balance and an inductive terminal impedance, resulting in a simple and extremely compact implementation on the pcb. The evolution from a half-wave slot antenna in a conductor plane to the edge slot is shown inFigure 12 Figure 14, below. Each step of the evolution leads to a more compact antenna with the consequence of a loss in sensitivity.

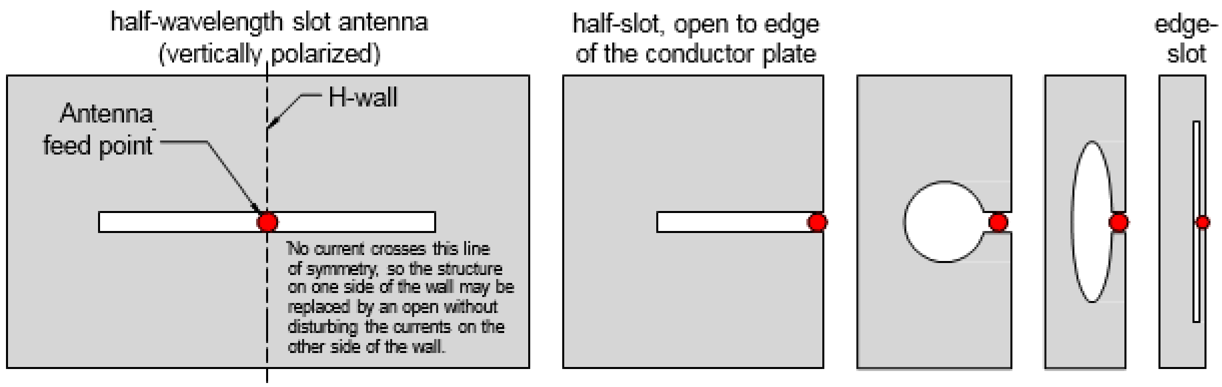


Figure 14 : Evolution of half-wavelength slot to edge slot antenna

The edge slot antenna has two critical dimensions: the length and the width of the circuit board region occupied by the antenna. Length is defined by the separation between the points at which the edge traces tie to the larger plane; width is the sum of the trace width and separation from the edge of the plane. Experiments have shown the best performance for equal trace width and space, e.g. a 1 mm wide trace with 1 mm separation from the ground plane for W_{total} = 2.0 mm.

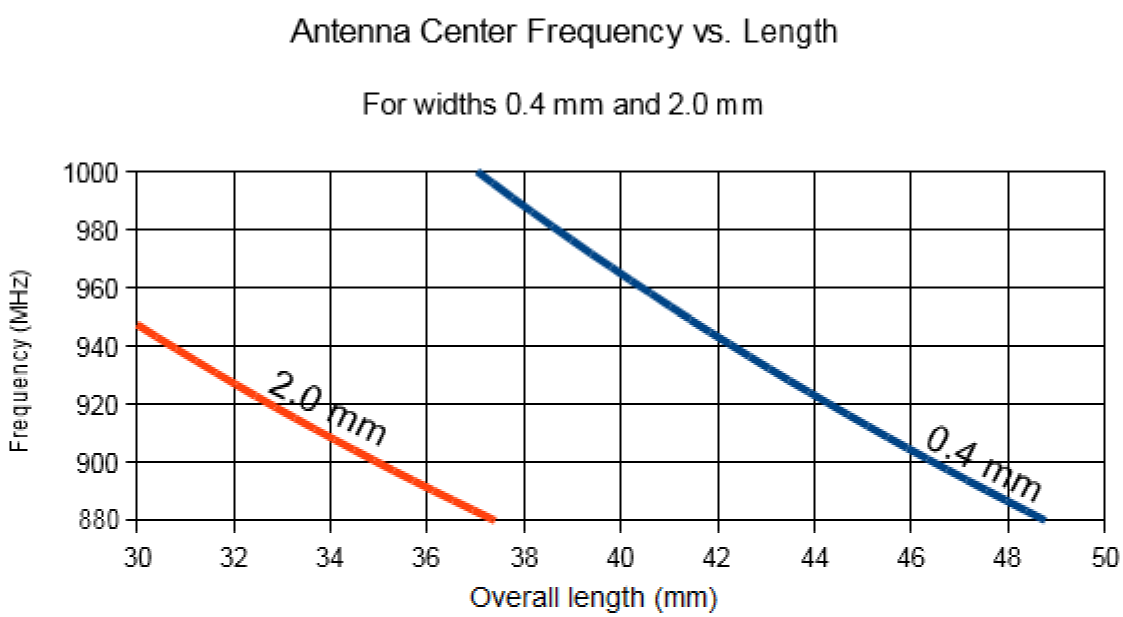


Figure 15 : Tuning curves for edge slot antenna for two selected widths

A compact edge slot antenna is shown in Figure 16, below. This antenna has a trace on the board edge of width 0.2 mm, with a 0.2mm separation from the ground plane, for 0.4 mm total width. Referring to Figure 15 (the ‘0.4 mm’ curve), we see that a length of 44 mm gives a center frequency just above 920 MHz.

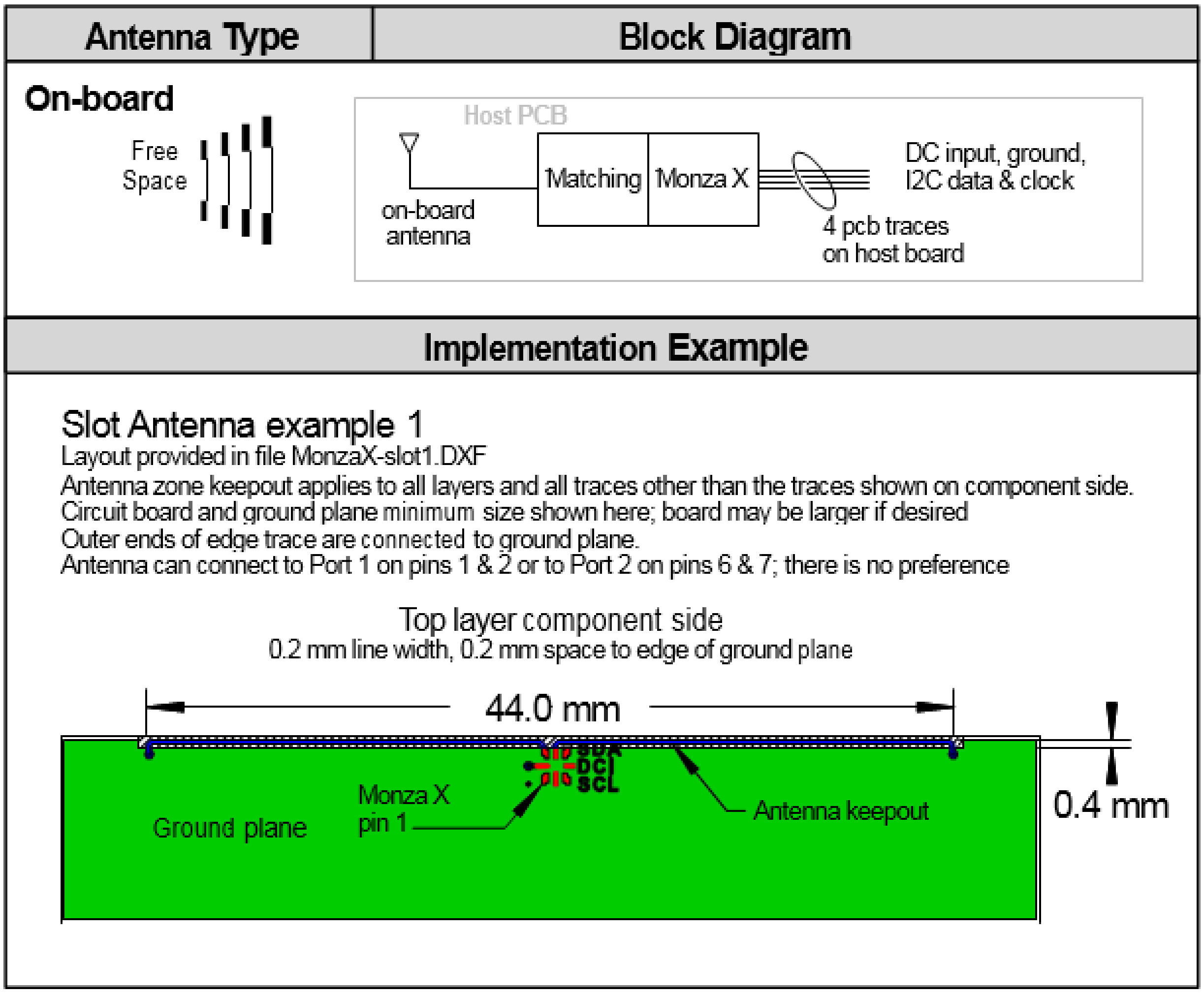


Figure 16 : Monza X slot 1 antenna layout

A prototype antenna fabricated to the dimensions shown in Figure 16 has a measured sensitivity of +7 dBm RIP at its center frequency of 920 MHz, for a range of approximately 70 cm when read using a fixed reader. This antenna occupies an area of just 17.6 mm2 and requires no further matching components or structures, as the antenna impedance is inherently matched for the Monza X port.

The polarization of the edge slot antenna is linear, oriented parallel to the active edge. This result is anticipated from examination of the development of the edge slot antenna, shown in Figure 14.

A second edge slot antenna example is shown in Figure 17, below. This antenna has width of 2.0 mm and length of 34 mm. The tuning curve in Figure 15 (2.0 mm curve) indicates a center frequency of 910 Mhz

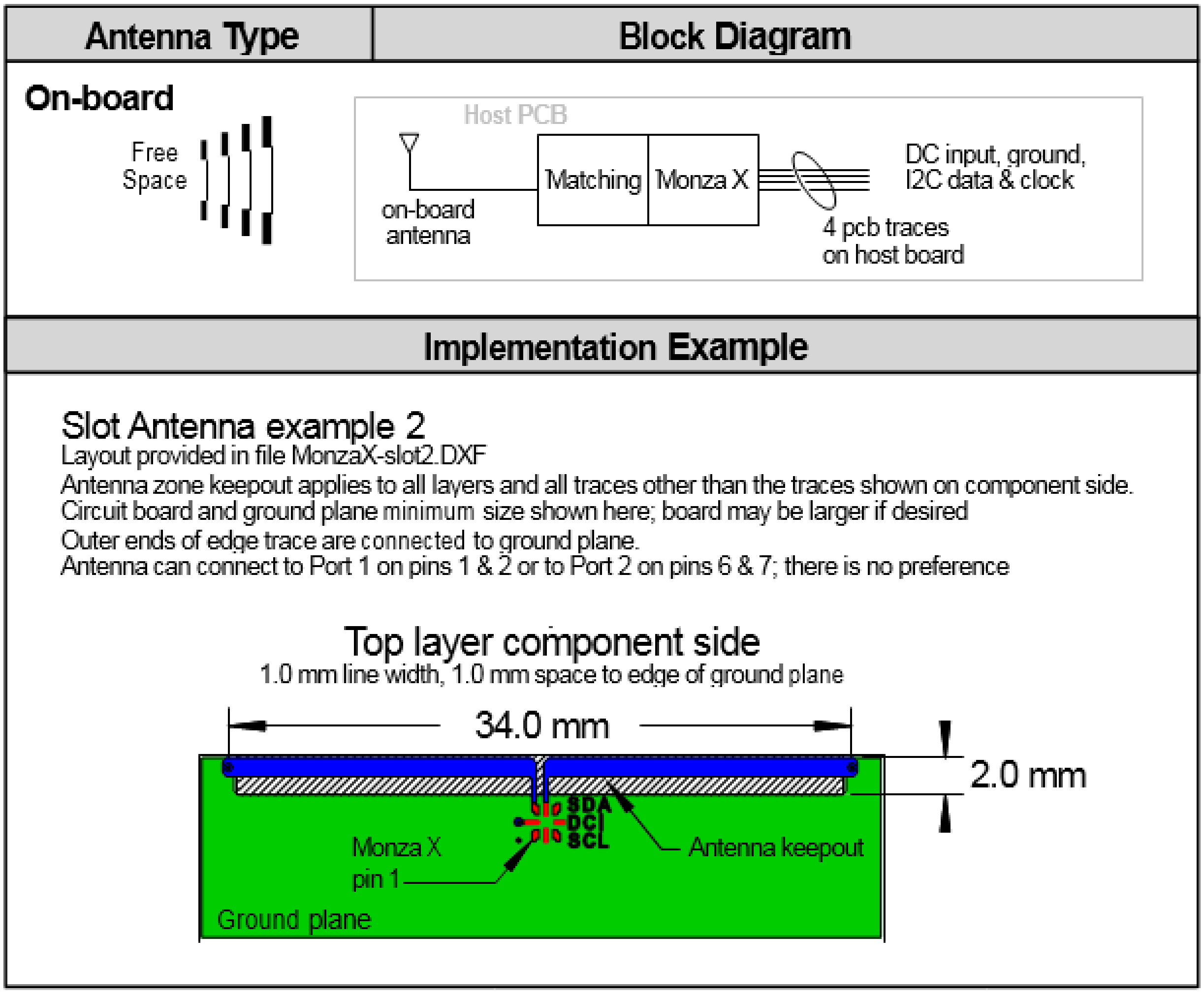


Figure 17 : Monza X slot 2 antenna layout

Monza X slot 2 has an occupied area of 2 mm x 34 mm = 68 mm2. This footprint is significantly larger than slot 1, and the sensitivity is better as a result. Measured sensitivity is approximately -2 dBm RIP at 910 MHz, resulting in a read range of about 2 meters from a fixed reader.

A point to note about any antenna of the edge slot architecture is that its resonant frequency is dependent upon the particular dielectric constant of the substrate used. Thickness of circuit board layers also has a secondary effect on tuning. For these reasons, it is important for the designer to be prepared to accommodate fine adjustment of the design, either iteration or by a set of prototypes fabricated with differing lengths. The tuning curves of Figure 15 are provided to inform the designer of the relationship between length and center frequency. If a design iteration is necessary, the tuning curve can provide guidance as to the amount of length adjustment needed to achieve the desired center frequency.

A loop antenna is an architecture which can have very good ultimate performance at its center frequency, although it tends to have a narrower bandwidth than the edge slot. One example of a loop suitable for use on a small substrate is shown in Figure 18. Loading the loop with a capacitor keeps the antenna relatively small while enabling frequency fine tuning by choice of capacitor value. The magnetic field established by currents in the loop excites the coupled line transformer driving the Monza X port.

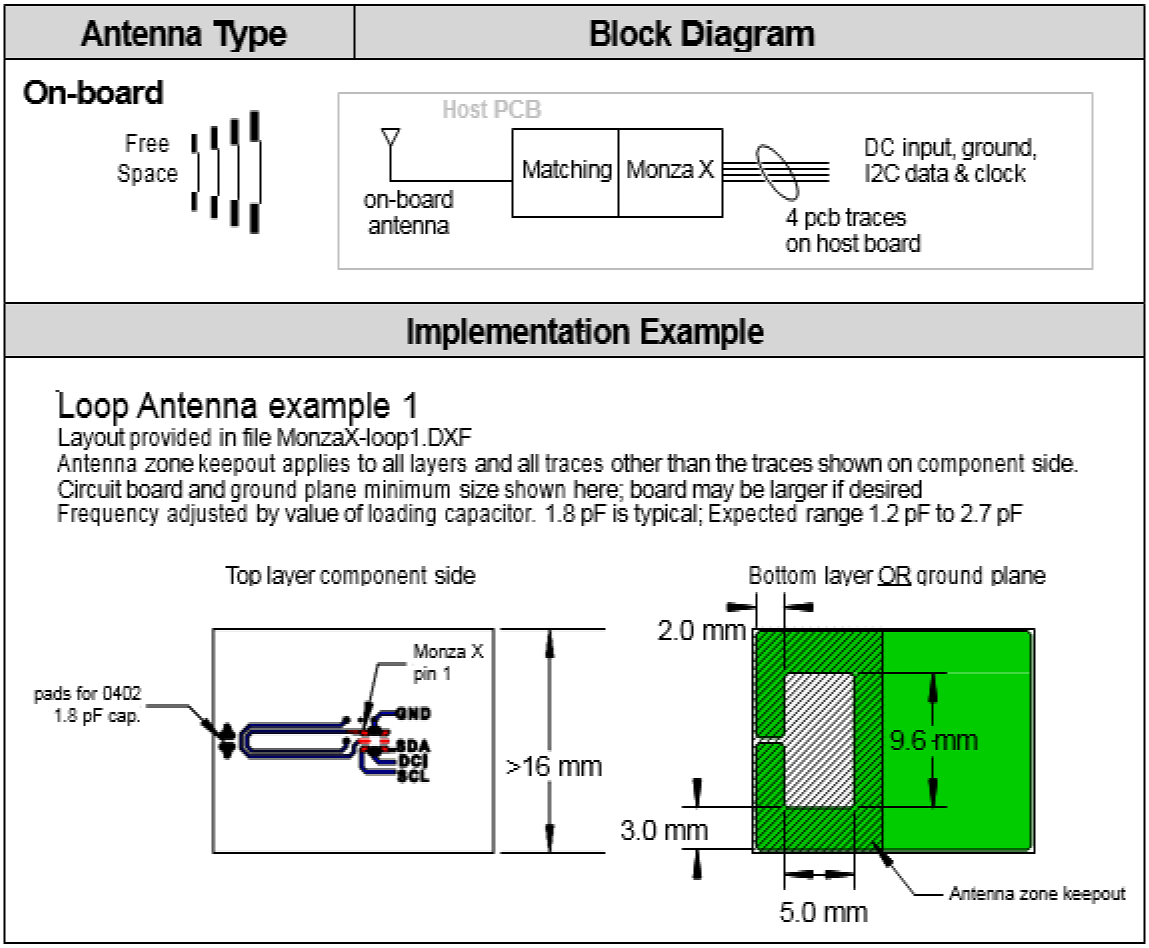


Figure 18 : Monza X loop 1 antenna layout

The loading capacitor can be viewed as the tuning element which is tailored to achieve the target center frequency and to compensate for circuit board materials or loading presented by the enclosure. For the geometry shown, a capacitor value of 1.8 pF centered the response at 915 MHz. Sensitivity at the center frequency was -3 dBm RIP, with a read range of about 2.5 meters.

The loaded loop is an antenna in the general category known as electrically small loops, defined as having current around the loop approximately uniform in phase and amplitude. Such loops have patterns that radiate in the plane of the loop, with polarization also in-plane. These radiation characteristics lead to a rather counter intuitive result that the far field response is minimized when the circuit board is oriented broadside to a reader.

However, any orientation that presents an edge of the board to the reader has good sensitivity. The loaded loop has very good sensitivity when read using a magnetic near field reader antenna.

Many minor variations on the loaded loop geometry are possible to accommodate constraints on the circuit board layout. A slightly flatter, longer loop is shown in Figure 19, below. The impedance transformer section is moved to the upper corner to illustrate options on placement of that structure; its only rigid requirement is that it most of it overlap the open window portion of the loop.

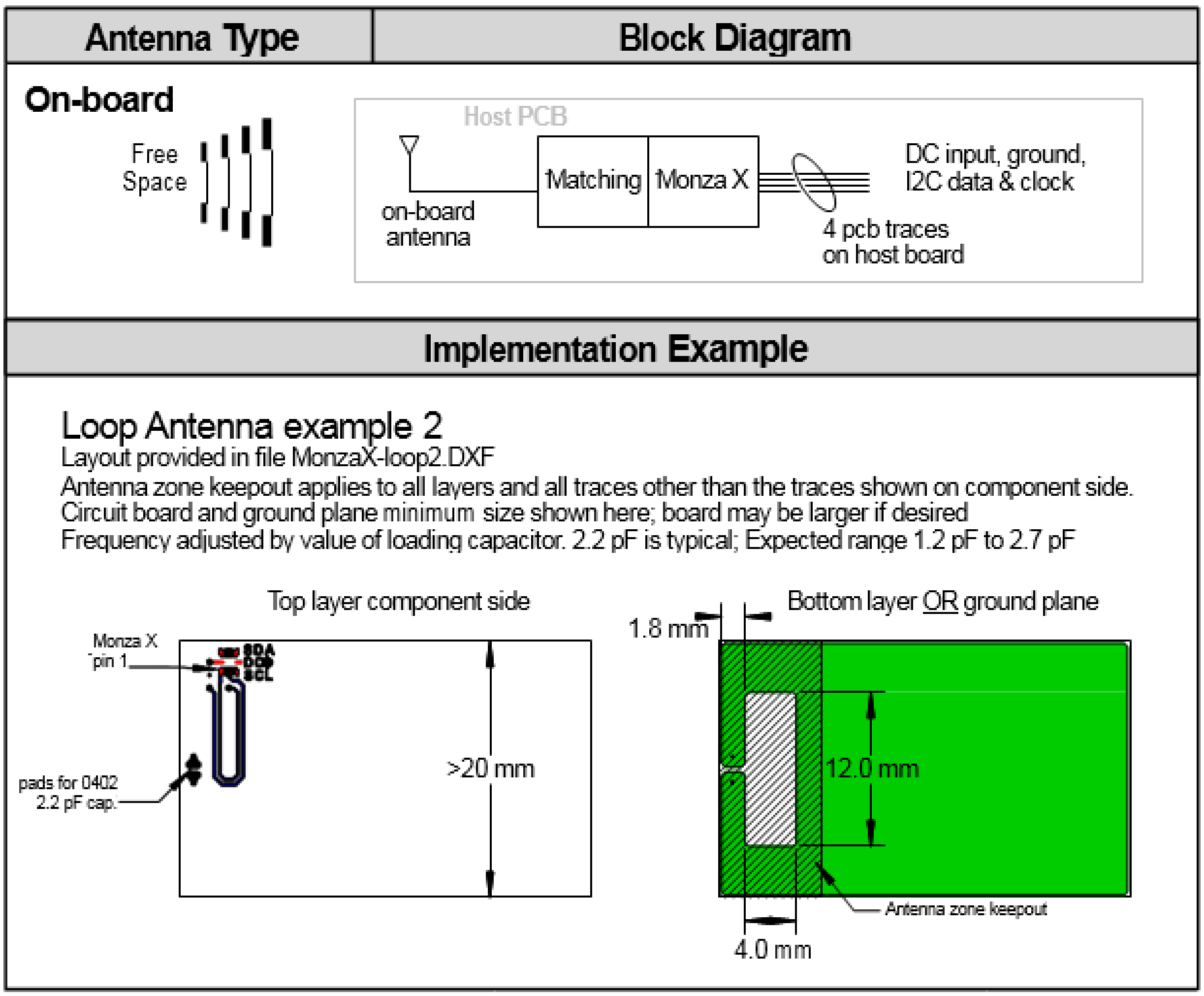


Figure 19 : Monza X loop 2 antenna layout

Of all on-board antenna types, the monopole offers the greatest potential performance. Like most antennas, the efficiency and bandwidth are strongly dependent on the electrical volume of the antenna – the region of space occupied by the electric and magnetic fields produced by currents on the antenna. A monopole with generous space for the radiating structure and its fields is shown in Figure 20, below.

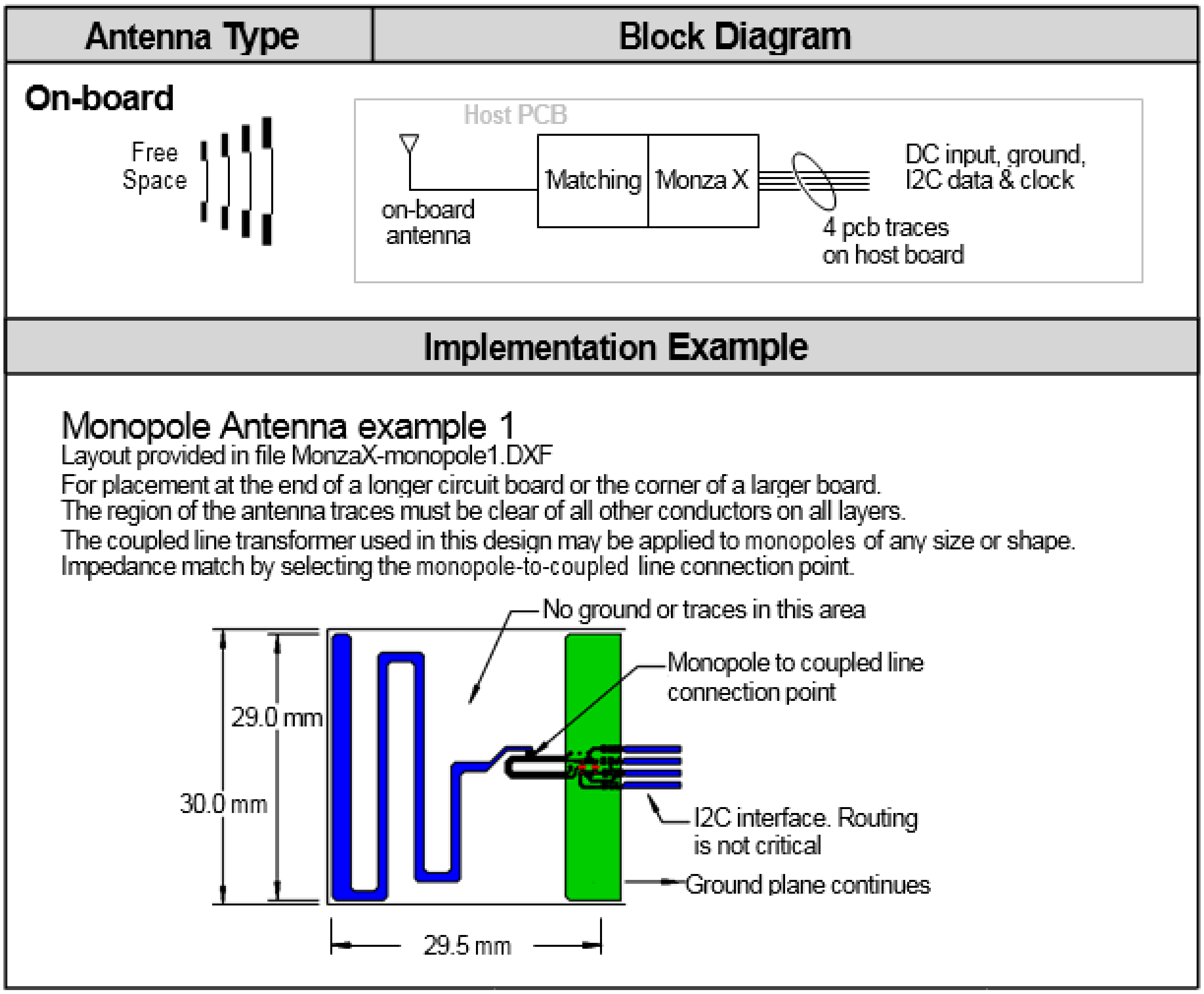


Figure 20 : Monza X monopole 1 antenna layout

The monopole 1 antenna was fabricated to the dimensions shown, with a ground plane extending 50 mm beyond the illustrated ground plane edge. This prototype operated at -11 dBm RIP, corresponding to a read range of 6 meters from a fixed reader.

A monopole antenna routed along an edge of the circuit board is shown in Figure 21, below. This is a variation on the inverted-F antenna, employing the coupled line balun as an integral part of the antenna feed. As expected, the proximity of the antenna to the ground plane severely limits its performance; incident power in the range of 0 to +5 dBm RIP is typically required for operation. This antenna topology has an aspect of simplicity in its design in that the tuning is somewhat decoupled from the antenna size. The length of trace along the board edge may be increased for substantial range improvement, or it may be reduced all the way down to the point that the response is purely near-field.

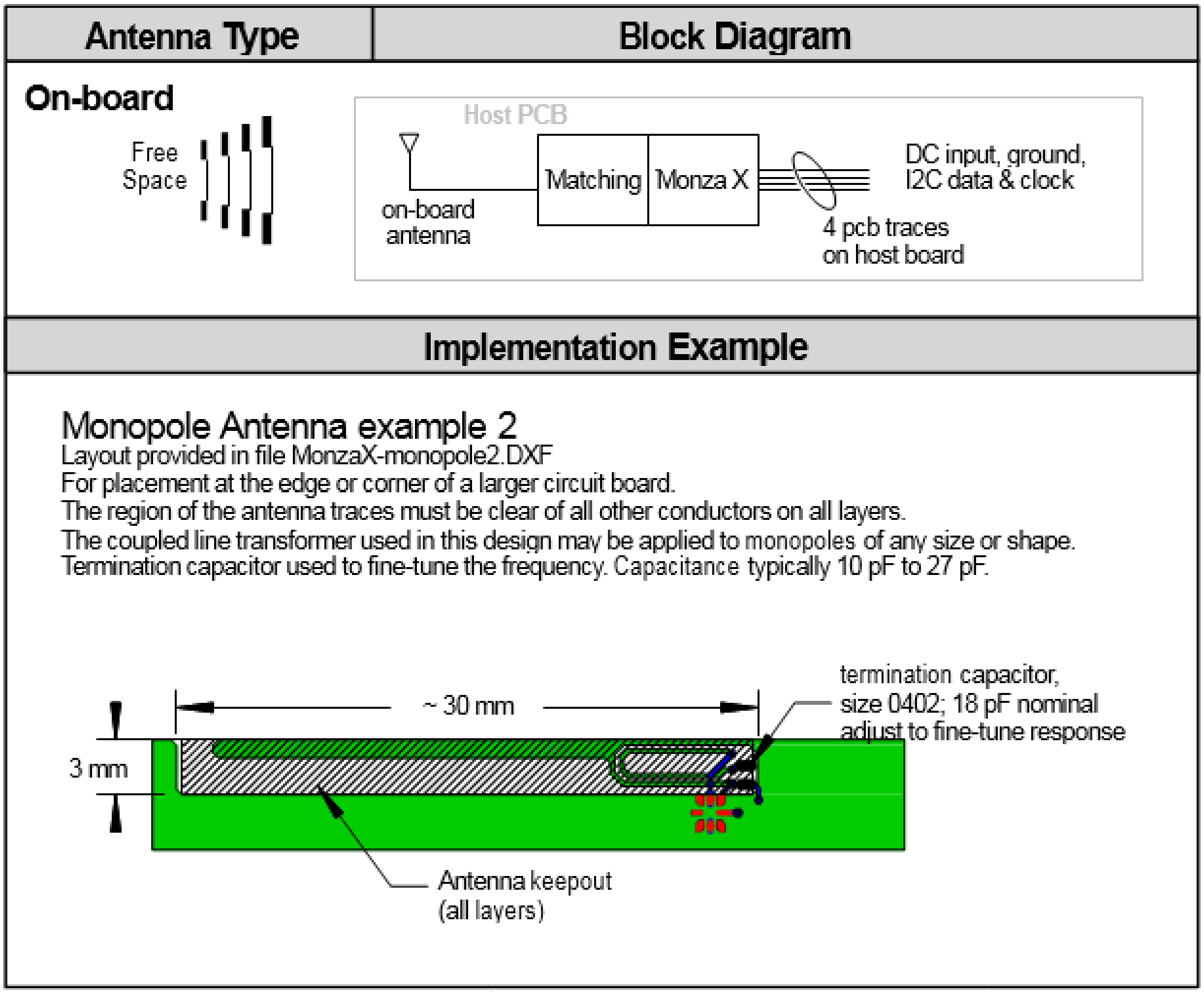


Figure 21 : Monza X monopole 2 antenna layout

The design of Monza X monopole 2 incorporates a feature for added tuning flexibility: the terminating capacitor on one of the lines of the balun transformer. The addition of this capacitor in the design allows compensation for circuit board loading effects or other detuning effects. It serves a similar purpose to the loading capacitor in the loop antennas presented earlier. This termination capacitor may be added to any of the designs using the coupled line balun.

4.4.1 PCB Antenna Guidelines

The following are some general guidelines applying to on-board antennas.

- It is recommended that the traces be on the outer circuit board layer, component side, if possible. If necessary, the antenna traces can reside on a lower layer as long as the keepout zone is respected within all other layers.

- The keepout zone applies to all metal layers other than the antenna layer. Where applicable, keepout zones are marked in the DXF artwork file with a hatched polygon on layer 'ground-notes'.
- The example designs are sized for FR4 circuit board material with a thickness of 1.57 mm (1/16 inch) with soldermask. The optimum dimensions may be different for other materials or thicknesses. The effective dielectric constant of FR4 is known to vary depending on layer thickness and composition. The designer should be prepared to make adjustments to the geometry and/or component values to achieve optimum performance.
- The antenna must be laid out on one of the PCB edges for proper operation.

5 FURTHER READING

The following texts contain valuable background information and are highly recommended for anyone designing RFID antennas, particularly antennas on circuit boards. Many of the concepts presented in this app note draw from material found in these books.

Balanis, Constantine. *Antenna Theory: Analysis and Design*. Wiley, ISBN 978-0471667827

Volakis, John; Chen, Chi-Chih; and Fujimoto, Kyohei. *Small Antenas: Miniturization Techniques & Applications*. McGraw-Hill, ISBN 978-0071625531

Chen, Zhi Ning and Chia, Michael Y. W. *Broadband Planar Antennas: Design and Applications*. Wiley, ISBN 978-0470871744

Pozar, David M. *Microwave Engineering*. Wiley, ISBN 978-0470631553

Mongia, R. K.; Bahl, I. J.; and Bhartia, P. *RF and Microwave Coupled-Line Circuits*. Artech House, ISBN 978-159693156

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