Introduction to RF and End Launch Applications

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1. Introduction

Engineers choose wireless communication and protocols based on the end application demands of distance, power, and bandwidth. Traces or transmission lines carry RF signals from the RF devices or modules mounted on a PCB to an antenna. End Launch Connectors are used to connect coaxial cables from antennas or test equipment to the onboard transmission lines. In this article, we discuss RF communication fundamentals and some applications of end launch connectors.

2. Objectives

Upon completion of this learning module, you will be able to:

- Understand RF basics
- Explain RF Communication
- Describe fundamental analog and digital modulation techniques
- Discuss RF end launch applications

3. RF Frequency Bands

RF frequencies are part of the electromagnetic spectrum. They are divided into sub-bands, as per conventions provided by the International Telecommunications Union (ITU) and the Institute of Electrical and Electronic Engineers (IEEE). ITU has formed 12 sub-bands which range from Extreme Low Frequency (3-30Hz) to Tremendously High Frequency (300GHz-3THz). The IEEE naming convention includes additional definitions for C, K_u, K and $K_a$microwave bands.

RF frequency bands are subjected to regulation by regional governments based on their end-use applications. Governments reserve certain frequency bands for defense applications. Bands are also reserved for amateur radio communication, police, and fire safety services. Some bands are leased to telecom operators who provide commercial services such as mobile communication.

Some of the commonly used application-specific, RF frequency bands include:

- Air Band (118-137 MHz) for navigation and voice communication with aircraft
- Marine Band (156 and 174 MHz) for communication between ships and coastal bases
- ISM band (6.78 MHz, 13.56 MHz, 27.12 MHz, 40.68 MHz, 433.92 MHz, 915 MHz, 2.45 GHz, 5.8 GHz, and 24.125 GHz) for industrial, scientific, and medical applications. Some of the frequencies in the ISM band are subject to local acceptance. Popular consumer applications such as Wi-Fi and Bluetooth use ISM band frequencies.

4. How does RF Transmission work?

A typical RF communication system consists of a transmitter and a receiver. Free-space or air is the communication medium between the transmitter and receiver, with antennas being the interface. The transmitter includes a modulator and an antenna connected by a transmission line. On the receiver side, the modulator is replaced by a demodulator. Often the modulator and demodulator come in a single package as a modem. Figure 1 shows a typical communication system with one transmitter and one receiver. However, in practice, a receiver and transmitter are often used as a pair to achieve bidirectional communication.

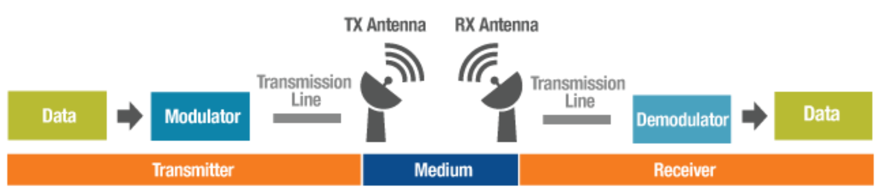

Figure 1: A simple RF communication system block diagram

The antenna converts the electrical signal to electromagnetic radiation and vice-versa. The size of the antenna is a factor of wavelength (λ), typically ($\lambda/2$ or $\lambda/4$). The size of an antenna increases as the frequency of the transmitted signal decreases. Transmission lines carry high frequency modulated signals between RF devices such as antennas and modulators/demodulators. Let’s now discuss modulation techniques, antennas, and transmission lines.

- 4.1 Modulation/Demodulation

In simple terms, modulation is the process by which the information signal (message) changes one or more fundamental characteristics of a carrier signal, such as amplitude, frequency, and phase. The carrier signal is a high-frequency bandpass signal with upper and lower cut-off frequencies. The information signal is also referred to as the baseband signal, since it contains frequencies near to zero (low frequency). The output of the modulator (modulated signal) is the carrier signal modulated by the baseband signal. On the receiver side, the received signal is demodulated to retrieve the original message. The demodulation technique depends upon the modulation scheme employed at the transmitter end.

Figure 2 shows the signal representation of a baseband signal and a modulated signal in the frequency domain. In the figure, w is the maximum frequency component available in the message or the baseband signal S(f), and f_c is the frequency of the carrier signal. The message signal is spread between –w to w across the origin; hence, the name baseband signal. The modulated signal is spread between f_c-w to f_c+w and $-f_c$-w to $-f_c$+w centered on f_c and $-f_c$, respectively. The carrier frequency f_c is very high as compared to w.
The advantages of modulation include:

- Reduces the size of the antenna
- Signal separation or reduced interference, as simultaneous transmission of baseband signals by transmitters of different carrier frequencies, provides isolation
- Lower attenuation and thus more extended coverage
- Enables transmission of several signals over the same channel
- Improves the signal quality

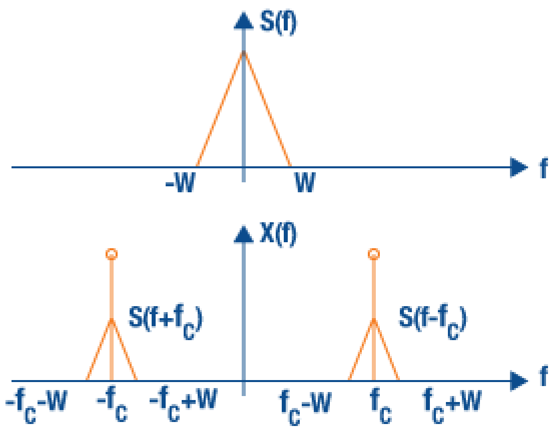

Figure 2: Baseband and Modulated signals

- 4.2 Modulation Techniques

Let us now discuss a few of the fundamental analog and digital modulation techniques.

Analog Modulation: When the modulating signal is of the analog type, the modulation scheme is called analog modulation. There are two types of analog modulation we will discuss here: Amplitude Modulation or Angle Modulation.

Amplitude Modulation (AM): In amplitude modulation, the amplitude of the carrier signal changes according to the amplitude of the modulating signal. The amplitude of the modulated signal is known as an envelope and depicts the modulating signal. Single Sideband (SSB), Double Side Band Suppressed Carrier (DSB-SC) and Vestigial Side Band (VSB) are some of the power-efficient versions of AM modulation. Figure 3 shows a typical amplitude modulated signal, demonstrating the modulating signal superimposed over the envelope of the modulated signal. Radio broadcasting uses amplitude modulation.

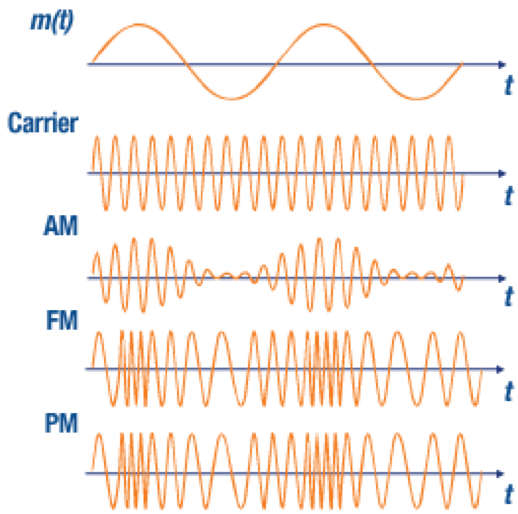

Figure 3: Output of AM/FM/PM Modulation Schemes

Angle Modulation: Angle modulation is achieved by varying the frequency or the phase of the carrier signal and is called either Frequency Modulation (FM) or Phase Modulation (PM), respectively. FM is used in radio broadcasting and for audio in TV signals. Figure 3 demonstrates Frequency and Phase modulated signals.

Digital Modulation: Digital modulation involves modulation of the carrier signal by using discrete digital signals (binary 1/0). Digital RF modulation comes in three forms:

- **Amplitude Shift Keying (ASK):** In ASK, the amplitude of the carrier signal varies according to the binary stream of incoming data. The basic form of ASK is called ON-OFF Keying (OOK), in which a carrier gets transmitted if the input bit is 1 and not transmitted if it is zero. ASK is widely used in transmitting data through optical cables.
- **Frequency Shift Keying (FSK):** In FSK, the frequency of the carrier signal varies according to the input binary data. The simple form of FSK, Binary

FSK modulation (BFSK), uses a pair of discrete frequencies to transmit bits 1 and 0. FSK is applied in audio lines and high-frequency radio transmission.

- **Phase Shift Keying (PSK):** In PSK, binary data bits get transmitted as a phase change in the carrier signal. In Binary PSK, a transition from 1 to 0 or 0 to 1 gets transmitted as a phase shift of the carrier signal by 180 degrees. If the binary stream is a continuous stream of 0 or 1, the carrier signal does not change the phase. Multiple bits can be transmitted using discrete phase shifting like Quadrature Phase Shift Keying (QPSK). RFID communications and Wi-Fi use the PSK modulation technique.

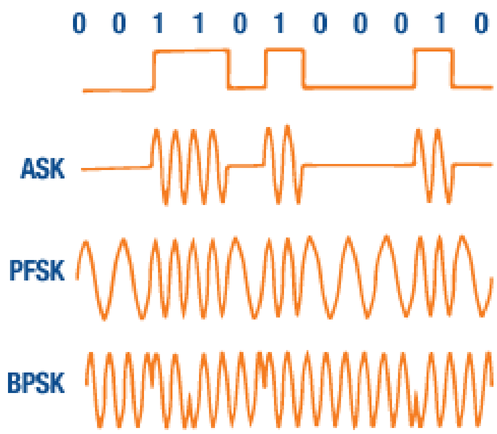

Figure 4: Output of ASK/FSK/PSK Modulation Schemes

- 4.3 Antenna

A single wire conductor can behave as an antenna if it obeys one of the following designs:

- If the current in the conductor is of uniform velocity, the transmission line has to be bent, truncated, or terminated.
- If the conductor is straight, it must have a current which accelerates and decelerates with a time-varying constant.

A moving charge through bent wire experiences centripetal acceleration, which helps in producing radiation. In a terminated transmission line, the abrupt change in impedance at the termination is responsible for radiation. Oscillating current gives rise to transverse electromagnetic waves moving away from the antenna. Two parallel conductors tapered at the open-end also radiate and behave like an antenna. On the reception side, the EM signals regenerate oscillating current in the antenna. The fundamental parameters of an antenna remain the same when it is used for transmission as well as reception. This property of an antenna is known as reciprocity.

Some fundamental parameters of an antenna are listed below:

- **Radiation pattern:** A graphical representation of the radiation radiated by the antenna into space.
- **Radiation intensity:** The ratio between power radiated by an antenna and a solid angle in a given direction.
- **Antenna efficiency:** The ratio of the power radiated by an antenna to the input power.
- **Beamwidth:** The angular aperture from which most of the power is radiated. Two beamwidths are observed in antennas: (a) First Null Beamwidth: The angular span between the first pattern nulls adjacent to the main lobe, which is called the First Null Beam Width. (b) Half Power Beamwidth: The angle between the two directions in which the radiation intensity is the one-half value of the beam.
- **Directivity:** The ratio of the radiation intensity in a given direction from an antenna to the radiation intensity averaged over all directions.
- **Gain:** The ratio between radiation intensity in a given direction and the radiation intensity of an isotropic antenna. An isotropic antenna is an ideal antenna which can radiate in all directions with equal power. However, it is not possible to design a practical isotropic antenna.
- **Bandwidth:** For broadband antennas, it is the ratio of the upper and lower frequencies of operation. For narrowband antennas, it is the percentage of the frequency difference over the center frequency of the bandwidth.
- **Polarization:** The curve traced by the end point of the arrow (vector) representing the instantaneous electric field when observed in the direction of propagation.
- **Input impedance:** The frequency dependent opposition (Resistance + Reactance) provided by the antenna to the current when a voltage is applied across its input. The transmission line and the antenna must have the same impedance (matched impedance) to avoid reflection loss.

We can classify antennas based on their operating principles:
Wire Antennas: These are constructed using a simple piece of conductor and are available in various shapes, including straight wire, loop, and helix. The circular loop antenna is widely used due to its simple design.

Aperture Antennas: Aperture antennas are a type that emit EM waves through an opening (or an aperture). These antennas have an aperture at the end. They are commonly used at microwave and the millimeter-wave frequencies. An open transmission line is a typical example of such an antenna. This antenna works in the UHF and EHF frequency bands. A waveguide is another example of an aperture antenna.

Microstrip Antennas: Microstrip antennas consist of a metallic patch over a substrate followed by the ground plane. The patch can take different configurations; however, rectangular and circular are commonly used since they come with low cross-polarization radiation and are easy to fabricate. A microstrip antenna also has a low profile and is inexpensive to manufacture, often etched over a PCB. These antennas can be used with frequencies above 100 MHz.

Array Antennas: Sometimes a single antenna element is not suitable to achieve the desired radiation characteristics. As such, multiple antenna elements can be arranged in an array.

Reflector Antennas: Parabolic and corner reflector antennas are part of the reflector antenna. Reflector antennas enable communication across long distances and are mostly used in the microwave frequency range.

Lens Antennas: Lens antennas use their curved surface for both transmission and reception. Lens antennas are made up of glass, where the converging and diverging properties of the lens are used to transmit and receive signals. The frequency range of usage of lens antennas starts at 1000 MHz, but they can be used at 3000 MHz and above.

- 4.4 Feedline and Transmission

This section discusses the transmission line (or feeding line), which connects the antenna and the modulator. Transmission lines are important because an imperfect transmission line can lead to losses.

Types of Feeder/Transmission Lines: Transmission lines are either multiconductor lines or waveguides. Different kinds of transmission lines are described below:

Open wire or twin feeder: Open wire, twin feeder, and ribbon transmission lines are commonly used for frequencies below 30MHz. They consist of two parallel wires; the current flows in opposite direction through the wires. These feeder lines are easily affected by nearby objects. They are used in VHF FM broadcast band antennas.

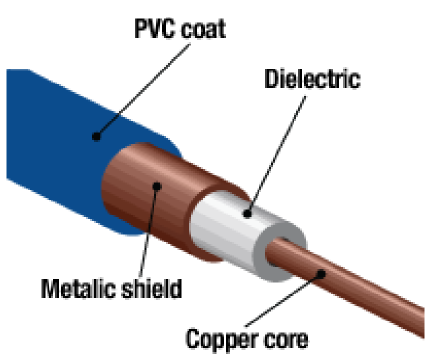

Figure 5: Coaxial Cable

Coaxial Cable: Coaxial cable is a widely used feeder in radio frequencies for domestic and commercial applications. It consists of a conductor, surrounded by an insulating dielectric, covered by an outer braid or screen, followed by an insulation cover. The braid/screen and the inner conductor carry current in the opposite direction, removing the possibility of radiation. The fields due to the conductors are also opposite and are confined in the cover. As the fields are not outside the cable, the coaxial cable is not affected by nearby objects. Coaxial cable is used in radio & television, commercial radio communications, broadcasting, and satellite antennas.

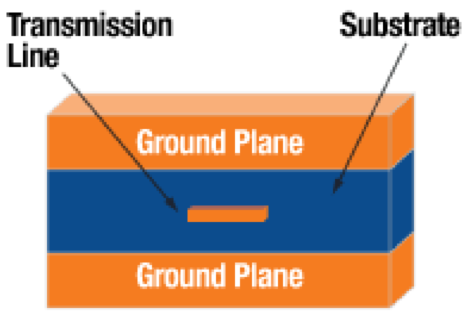

Figure 6: Stripline

Stripline: A stripline uses a flat strip of conductor sandwiched between two parallel ground planes. A dielectric insulator material is used to surround the central conductor. Stripline is often required for multilayer circuit boards because it can be routed between layers. However, grounding the stripline requires extra care.

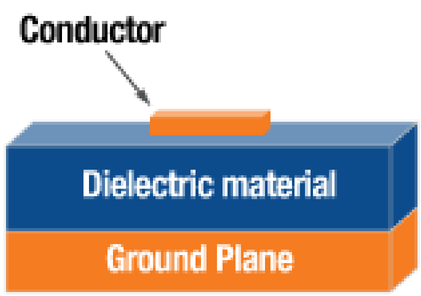

Figure 7: Microstrip

Microstrip: Microstrips are similar to striplines, but they are without the top plate, leaving only the strip and bottom plate with a dielectric layer between them to support the strip. A typical microstrip transmission line can be etched on a PCB.

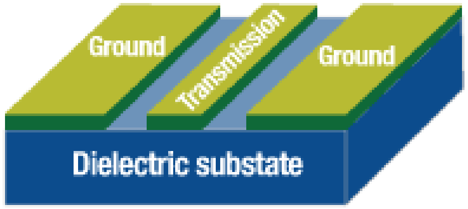

Figure 8: Coplanar Waveguide

Coplanar Waveguide: These are an alternative to microstrip and stripline, but the transmission line and ground plane are present in the same layer. A ground coplanar waveguide is used instead of a microstrip line with an additional ground plane below the dielectric layer in the coplanar waveguide. The top and bottom ground planes are connected using vias. These provide higher isolation as compared to microstrip.

Figure 9: Waveguide Cross section

Waveguides: These are pipes having rectangular or circular cross-sections. Waveguides are often used in higher (microwave) frequencies. The operating frequency determines the size of the waveguide. The signal is launched into the waveguide, and it travels along the waveguide. Waveguides feature low loss, but they are expensive and quite stiff. Flexible waveguides are available that allow flexing and twisting to deal with installation/misalignment problems posed by rigid waveguide structures.

- 4.5 Impedance Matching

When an RF transmission line is carrying a signal from a source to a load, some signals get reflected back towards the source instead of being carried to the load. This reflection is due to a mismatch of impedance in the transmission line or between components used in the line. The ratio between the forward wave amplitude and the reflected wave amplitude is known as the reflection coefficient. Impedance matching is necessary for any transmission line to have maximum power transfer and low loss.

The Voltage Standing Wave Ratio (VSWR) defines the level of matching of the transmission line. It is a function of the reflection coefficient, which describes the power reflected from the load. VSWR can vary from one to infinity plus. Lower

VSWR denotes a better-matched transmission line. The ideal value of VSWR is 1, considering there is perfect impedance matching, and the impedance of the line is known as characteristic impedance.
In microwave frequencies, distributed circuit behavior is considered, and thus inductance and capacitance in the transmission line are also considered. Although the transmission line does not include any capacitors or inductors, the impedance is always complex, having real and imaginary parts. Therefore, impedance matching involves a complex conjugate.

In unmatched transmission lines, quarter wave transformers or stubs are used for matching. Quarter wave transformers are transmission lines of length λ/4 with a known impedance termination. A stub is a length of transmission line or waveguide connected at one end to the unmatched transmission line with the other end either shorted (always in waveguides) or open. Quarter wave transformers are used only in cases of real impedance matching, whereas a stub can be used in any case. The length of the stub and the distance of the stub where it needs to be inserted depends on the mismatch. Whether the stub is inductive or capacitive depends on whether the transmission line has capacitive or inductive impedance. An inductive stub is achieved by using a short-circuited stub, whereas a capacitive stub uses an open-circuit one.

A typical single stub matching scenario is shown in the Figure 9. The stub can be inserted in series or parallel to the transmission line as shown.

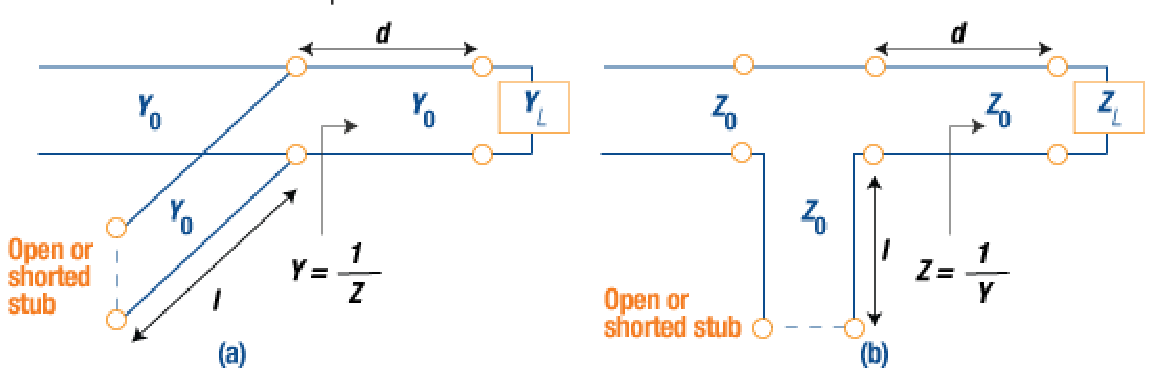

Figure 10: Single Stub Matching: Parallel (a); Series (b)

5. End Launch Applications

Transferring high-frequency signals from co-axial cable to microstrip transmission lines or coplanar waveguides is called an End Launch. End launch connectors are used to transmit RF Energy from the coaxial transmission line to planar transmission line structures. The success of applications involving end launch involves attention to connector design, mounting, and board launch layout. Factors such as PCB material, thickness, and connector selection are of utmost importance for minimizing reflection losses. In this section, we will discuss PCB or substrate selection, stripline design, connector selection, and installation procedure for efficient end launching.

- 5.1 PCB or the Substrate

The optimal performance of a system depends on making a smooth signal transition from the end-launch connector to the PCB planar with minimal reflections. The launch pin of the connector rests on the planar transmission line in order to have a shallow reflection. For higher frequencies, the dielectric loss also becomes an essential factor. As the frequency of operation increases, the thickness of the dielectric material or the PCB must decrease to avoid the generation of transverse modes on the transmission lines. However, the thin PCB material is mechanically unstable to support the connector and associated circuitries. Therefore, a hybrid circuit board consisting of high-frequency laminates and epoxy or glass substrate has emerged as an alternative. The other circuit paths, such as digital signals, are designed onto the low-cost epoxy or glass FR4 layer, and the microwave signals are carried on the top high-frequency layer.

Guidelines for Optimal Performance

For optimal high-frequency circuit board performance, a designer should consider the following fabrication guidelines when creating mounting footprints for end launch connectors on a PCB:

- Maintain a stable ground plane below the high-frequency substrate layer
- Minimize the pullback of the trace and grounds from the board edge
- Continue the grounded coplanar waveguide line beyond the ground pad area
- Place 16 mil diameter ground vias on both sides of the coplanar waveguide line, spaced at 50 mil gaps along the entire length of the line
- Use Immersion gold plate (ENIG) all high-frequency conductors as per IPC-4552
- Do not coat the signal trace or open ground gaps with solder mask

- 5.2 End Launch Connectors

Figure 11: End Launch Connector

End Launch connectors are available in surface mount, thru-hole, and self-fixture types, as well as both soldered and solderless. The Johnson Patented High-Frequency End Launch connectors from Cinch are designed to attach directly to high-frequency coplanar waveguide (CPW) circuit board transmission lines. Other transmission lines such as microstrip can be used with good results. The in-line connector design minimizes reflections as compared to a vertical mount PCB mount transition. It can be used on high-frequency PCB substrate layers as thin as 8 mils, and can operate at frequencies up to 26.5 GHz.

- 5.3 Design and Optimization

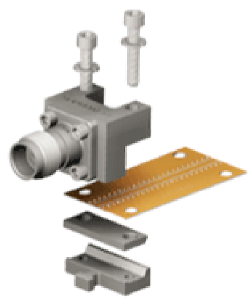

Figure 12: A typical compression fit end launch connector

Lower-frequency applications, up to 6 GHz, are usually terminated by soldering the launch pin to the board. For frequencies above 12 GHz, termination is achieved by compressing the center contact onto the circuit pad while the connectors are screwed down to the board. The benefits of solderless termination include reduced installation time, faster inspection, and the ability to remove/reuse the connectors without being reworked.

Small differences between the connector and PCB in the ground return path, such as the surface resistance or conductivity difference between solders used to join different parts, have little to no impact on lower RF frequencies. However, at higher frequencies, these cause significant performance issues.
The length of the ground return path influences the launch achieved with a given PCB and connector combination. A simple way of optimizing signal launch is to minimize the impedance mismatch in the launch area. If the conductor of the Microstrip line is broader compared to the conductor of the connector used, it can lead to a capacitive spike. The spike can be avoided by tapering the conductor of the Microstrip line at the junction of the conductor and the connector.
Narrowing the PCB conductor makes it more inductive (or less capacitive). A taper occurring over a long distance provides a greater inductive effect at lower frequencies than a shorter taper. For example, in the case of a signal launch with poor return loss at lower frequencies and having a capacitive impedance

spike, a longer taper may be suitable. Conversely, a short taper has a more significant effect on higher frequencies.

- 5.4 Connector Mounting

Ensure that the center pin of the connector has no additional space in relation to the PCB edge, as any extra space can cause an increase in the signal reflections, reducing VSWR performance. It is also critical to maintain positioning of the center pin to the center of the trace on the PCB. There can be improvements to the design by tapering the trace to reduce the reflections of the signal. Connector mounting can be done horizontally or vertically. In horizontal mounting, the mating cable is parallel to the board plane, whereas in vertical mounting they are perpendicular. Horizontal mounting is being replaced by vertical mounting in many applications due to its lower footprint and cost. The positioning of connectors in mid-board locations is avoided by using angled and vertical launch connectors.
High-frequency end launch performance is dependent upon proper mounting. The contact pin should be centered on the circuit board signal trace. Use a minimal amount of solder between the contact pin and signal trace. Do not allow excess solder to build up or flow down the trace. Clean all excess flux and other residues from the launch area, especially between the trace and ground.

- 5.5 Mounting End Launch Connectors

The steps required to mount the end launch connectors to a circuit board are as follows:

a) A Fixture should be used as an aid during manual soldering. The fixture maintains the proper location of the connector’s insulator and contact. It protects the connector from damage during clamping.

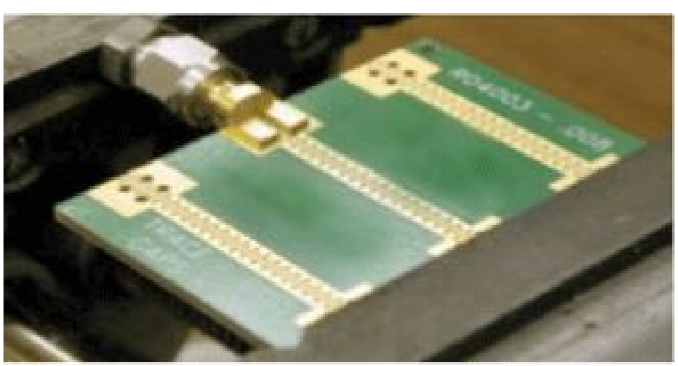

Figure 13: Use of Fixture

b) Position the connector on the circuit board and ensure that the contact pin is aligned with the center of the signal trace as shown in Figure 14. Make sure that the connector legs and contact pin are held flush against the top of the circuit board, keeping the axis of the connector parallel to the plane of the circuit board.

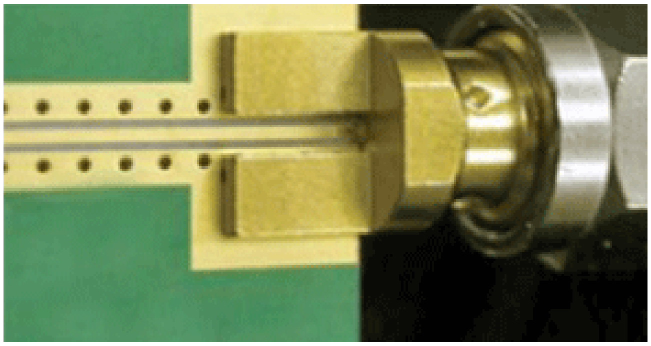

Figure 14: Connector Legs and Contact Pins

c) A small portion of the Teflon insulation projects out from the rear mating plane of the connector. It acts as a seal while soldering the center conductor pin to the trace. Clamp the connector tightly against the edge of the board. This action compresses the insulator seal against the board edge and effectively creates a barrier between the inner and outer conductors, preventing the bridging of solder.
d) While ensuring the connector is held in the correct position, solder the ground legs and ground posts to the top and bottom of the board before bonding the center pin to the trace.
e) Once the connector body is adequately grounded to the board, the center contact pin can be bonded to the trace by using a minimal amount of solder. It is essential that solder flows along the length of the exposed pin, creating a good electrical and mechanical connection. Remove any excess solder that is not required for a stable joint.

f) Clean all flux and other residues from the trace area between the signal side ground legs, as any flux present between the signal trace and ground affects performance. The completed mounting assembly looks like Figure 15.

Figure 15: Clean Flux and Residues

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