A Comprehensive Guide to Coaxial Cables for Various Applications

White Paper

Abstract

This paper provides a basic overview of the different types of coaxial cables that are available along with the primary applications that use each cable type. The paper focuses on the following cable types and applications: coaxial test cables, low loss coax for wireless applications, low PIM coax interconnect and Hi-Rel military coax options including MIL-DTL-17 cable assemblies.

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A Comprehensive Guide to Coaxial Cables for Various Applications

Traditional RG cables and the Evolution of Coax

Military guidelines originally specified the “RG” or radio guide standards for coaxial dimensions to yield specific impedances ranging between 50 Ω, 75 Ω, and 92 Ω. These specifications are no longer used as these military standards have since been cancelled. However, commercial variants of these types of coaxial assemblies are referred to with similar construction and performance. Typically, the 50-ohm RG cables are leveraged for data applications such as WLAN, GPS, and cellular infrastructure. The 75-ohm cables are typically leveraged from audio/video (A/V) applications such as network video recorders (NVR), security camera systems, and CCTV. Typically, traditional RG cables are lossy since they are often constructed with a stranded center conductor, standard dielectric substrates, and one layer of braided shielding. For this reason, most cable manufacturers stray from these guidelines to optimize their cable construction for their particular application.

Coaxial Assemblies for Testing

Coaxial assemblies are necessarily leveraged in RF test labs with various equipment such as vector network analyzers (VNAs) and spectrum analyzers for a VNA, coaxial test cables effectively extend the testing plane of the VNA to the input and output ports of the device under test (DUT) when used with the appropriate calibration kit. Test ranges can vary from sub-GHz frequencies up to 110 GHz with VNAs. Therefore, the range of coaxial cables leveraged for these applications can vary significantly in construction.

Precision Coaxial Assemblies for Millimeter-wave Test

Precision cable assemblies are typically phase stable under flexure and are of a thin diameter for better flexibility and high frequency performance. As frequency increases, the wavelength decreases, causing dimensions of high frequency components to generally be smaller. Coaxial assemblies are no exception to this where precision connectors exhibit smaller cross-sectional dimensions (e.g., 7mm, 3.5mm, 2.92mm, 2.4mm, 1.85mm, 1mm) the higher up in frequency that is gone. Moreover, the skin depth -- or the portion of the conductor where signal propagation occurs - at millimeter-wave frequencies (beyond 30 GHz) is a fraction for that of lower frequencies. For instance, the skin depth of copper at 6 GHz is 08417μm. This number drops to 0.2662μm at 60 GHz: taking up only a third of the skin depth at 6 GHz. This means that less thickness is required for the inner and outer conductors of the high frequency, precision coaxial assemblies.

Ruggedizing Millimeter-wave Test Cables

Cable construction for assemblies operating up to 110 GHz involve very thin layers of dielectric and shielding. These thin layers greatly limit available constructions and manufacturing techniques as well as the subsequent handling of these assemblies when used in a test lab. Protecting these delicate layers of the transmission line is best accomplished by avoiding tight bends and constant flexure. Often, this can be accomplished by armoring the test cable with a spiraled stainless-steel sheath or armoring that inherently mitigates overexerting the cable with a tight bend. Armoring offers an additional crush resistance preventing any potential discrepancies in the cross-sectional dimensions of the coax from kinking or shear forces. Armoring methods can include the following:

- Additional foil and braided metal layers
- Light-duty armoring with rugged synthetics (e.g., Nomex®, PET weave, etc.)
- Crush Members
- External ruggedized metal armor
- Additional inner jackets.

Additionally, connector heads can be directly attached to this stainless-steel conduit providing torsion resistance during mating allowing for up to thousands of mating cycles. While these methods of cable protection tend to increase the size and weight of the coaxial cable, they improve rigidity of the cable while maintaining a degree of flexibility -- parameters that are critical in a test environment where cable handling (e.g., flexure, mating/unmating) are far more frequent. Ruggedized VNA test cables with proper jacketing and cable protection essentially fulfill the broadband, high frequency performance of semi-rigid/hand-formable coaxial assemblies without the need to ascertain the exact dimensions of the installation with both phase and amplitude stability.

Ruggedized Amplitude and Phase Stable VNA Test Cables

Importance of Cable Amplitude and Phase Stability in VNA Testing

As stated earlier, bending a millimeter-wave VNA test cable can cause phase instabilities to occur ultimately affecting the integrity and lifetime of a calibration. In cases where the DUT is placed on a test fixture, the amplitude of phase stability of the coaxial cables used can have a more immediate impact on the accuracy of the test results. Calibration methods that bring the test plane to the ends of each port can vary. The relatively simple port extension technique, for instance, involves a vendor-specific algorithm that is used to calculate the delay (and sometimes loss) of the system to bring the test plane to the DUT. More complex methods involve fixture de-embedding where the fixture effects are removed through mathematical modeling based upon either simple lumped element models or full-wave 3D modelling. Additional calibration methods involve the use of a custom microstrip or coplanar waveguide (CPW) calibration kit.

Oftentimes, a simple port extension is leveraged. In this case, flexure in the cables that occur from basic handling of the DUT can cause phase and amplitude variations that negatively impact the accuracy of the algorithm used in the port extension calibration. This is due to the reliance of the coaxial line to calculate delay -- a value that is intrinsically tied to phase stability of the coaxial cables.

Understanding Amplitude and Phase Stability in Coaxial Cables

Amplitude variations can occur due to the physical expansion and contraction of the coax in temperature differentials. The increase in insertion loss is mainly due to the decrease in the conductivity of the metallic material with temperature where the electrical conductivity decreases with increasing particle velocity while the thermal conductivity increases (Wiedemann-Franz law).

Phase instabilities are a result of the changes in the “electrical length” of the coax -- a parameter directly correlated to the dielectric constant and physical length of the coax. This relationship is made evident though the equation for time delay (τ) in ***Equation 1.1***, where time delay can be obtained by unwrapping the phase response ($\angle S21$) of the transmission line.

$$\tau = \frac{l\sqrt{\varepsilon_r}}{c}$$

Equation 1.1

The length of the cable (l) and the dielectric constant (εr) are the two parameters in this equation that change under mechanical strain and temperature shifts. The change in electrical length is attributed to the linear coefficient of thermal expansion (CTE) -- a parameter that correlates to the expansion a material undergoes when experiencing increases in temperature. The metallic outer and central conductors of the coax will undergo much less expansion under increasing temperature drift. However, the dielectric material expands much more rapidly causing it to become compressed between the metals. This compression also occurs at low temperatures where the contraction of the shielding material compresses the dielectric causing changes in the electrical length.

The dielectric constant also changes with temperature, this change can be related to the temperature coefficient of the dielectric constant. Typically, there is a decrease in the dielectric constant with increasing temperature. In a way, this downward trend with increasing temperature works against the positive CTE with increasing temperature. However, it is not adequate to maintain phase stability over temperature and flexure. Therefore, foamed dielectrics are typically leveraged for phase stable cables as they are generally more stable with temperature fluctuations. ***Table 1.1*** lists the CTE and temperature coefficient of the dielectric constant for common conductor and insulating materials in coaxial cables. A coaxial cable undergoes minor physical changes in length under flexure, causing changes in the electrical length and therefore phase changes. Ruggedized VNA test cables can mitigate these changes through armoring and torsion resistant connector heads -- developing a buffer for the coaxial cable in the event of cable flexure.

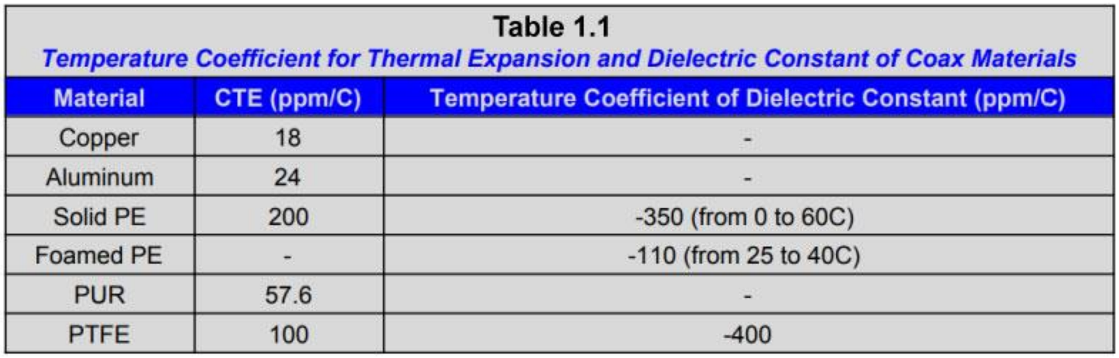


Table 1.1

Temperature Coefficient for Thermal Expansion and Dielectric Constant of Coax Materials

Material	CTE (ppm/C)	Temperature Coefficient of Dielectric Constant (ppm/C)
Copper	18	-
Aluminum	24	-
Solid PE	200	-350 (from 0 to 60C)
Foamed PE	-	-110 (from 25 to 40C)
PUR	57.6	-
PTFE	100	-400

Table 1.1

Phase stable coaxial cables are manufactured with the careful selection of materials and construction between the use of foamed dielectrics and ruggedized cable construction. Moreover, extensive temperature conditioning is employed to ensure consistent temperature performance by essentially “breaking it in” before sending it out to a test lab. ***Figure 1.1*** shows the phase stability of a ruggedized coaxial assembly under flexure at 18 GHz.

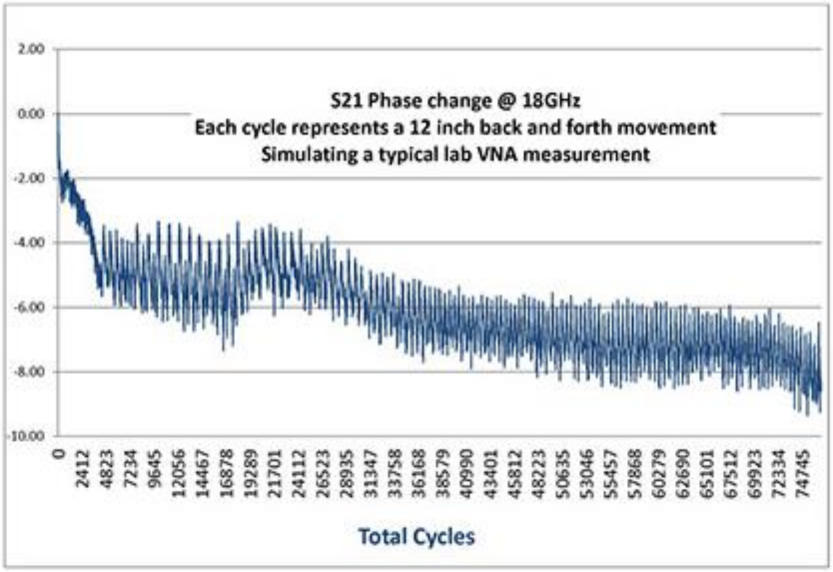


Figure 1.1: Phase stable coaxial assembly undergoing continuous flexure at 18 GHz.

Skew-Matched Test Cables for High-Speed Differential Signal Applications

Skew-matched cable assemblies can almost be seen as an extension of a ruggedized phase stable cable, closely matching the time delay of two coaxes. Skew-matched pairs of coaxial cables have utility in signal integrity testing applications where differential signaling is often used and the match between the test cables going to and from the test equipment intimately affects the accuracy of the test results.

Differential S-parameters generate the necessary parameters for understanding the signal integrity of a differential system with differential return loss (e.g., SDD11), differential insertion loss (e.g., SDD21), near-end crosstalk (NEXT) (e.g., SDD31, SCC31, SCD31), and far-end crosstalk (FEXT) (e.g., SDD41, SCC41), and differential-to-common mode conversion (SCDxx). ***Figure 1.2*** shows a 4-port differential system and the respective s-parameters required to best understand the SI of the system. In other words, an 8-port s-parameter matrix is necessary to adequately measure this DUT[1].

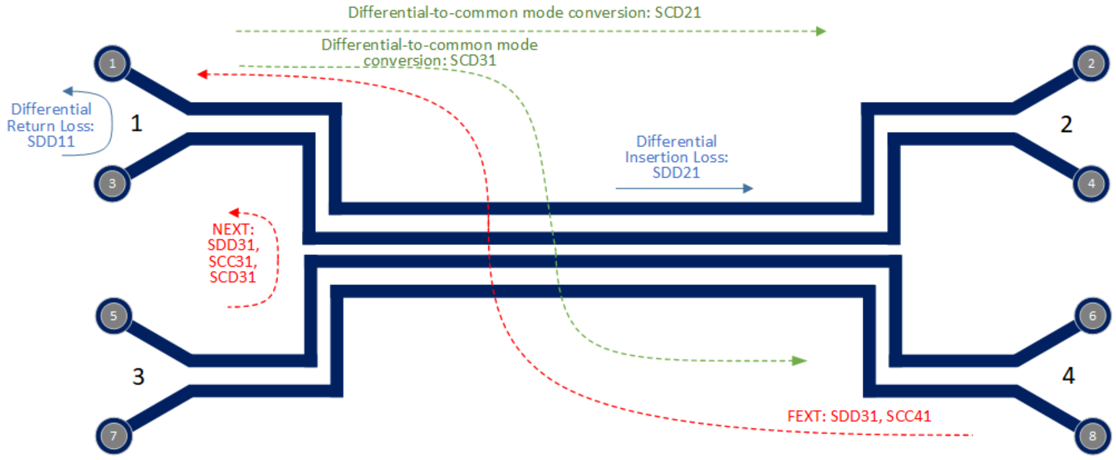


Figure 1.2: Differential s-parameters are used to analyze and assess a 4-port differential system. Various differential s-parameters illuminate the many pathologies within the system.

Test fixtures for high-speed differential systems often require short lengths of mini-coax and/or semi-rigid coaxial cables as they delay between these assemblies can be kept to a minimum. There is, however, a lack of flexibility when it comes to leveraging these types of coax -- they are often too short to reach test equipment or the DUT. This can limit testing capabilities severely. Skew matched coaxial cables leverage two, phase-stable coaxial cables and closely match the delay between with precise cuts and connector attachments. This is accomplished by observing the VOP values between the two dielectric materials and adjusting the length for the minor (1-2%) variations between the two assemblies. Further insurance of skew-matching over bending and temperature is obtained by closely matching the dielectric-constant behavior and ruggedizing each assembly to mitigate the phase changes during flexure.

Low Loss Cable

Coaxial cables in cellular installations and DAS will often require long runs of cable up the antennas on a tower or in a direct burial for WLL, GPS, WLAN, WISP, WiMAX, and SCADA applications. For base station installations, a tower mounted amplifier (TMA) is leveraged to amplify the incoming signal from the base station control all the way up the cell tower, to the antennas. A less lossy coax loosens design constraints around the link budget as the loss due to the coaxial feed to the receiver and transmitter is a necessary factor to consider (Equation 1.2).

$$P_{RX} = (P_{TX} + G_{TX} + G_{RX}) - (L_{TX} + L_{RX} + L_{FS} + L_M)$$

Equation 1.2

Where PRX/PTX is the power received and transmitted, GTX/GRX is the gain of the transmit/receive antennas, LTX/LRX is the loss of the transmitter/receiver, LFS is the free space loss, and LM are the miscellaneous losses (e.g., fading, multipath, etc.). This, in turn, loosens the requirements around signal amplification, allowing for more straightforward signal optimization, an improved signal-to-noise ratio (SNR) of the receiver, and ultimately the bit-error rate (BER) of the digitally modulated signals. In these long cable installations, attenuation becomes a critical parameter in order to ensure minimal loss over the length of the run. Insertion per unit length is optimized through a number of factors as discussed above including the following:

- A solid center conductor
- Thicker coaxial cross-section dimensions
- The use of a foamed or low-density dielectric
- Adequate shielding

Since frequent bending is not a major consideration in these installations, it is important that they remain thicker than the RG counterparts to minimize cable losses. With a solid center conductor, the losses due to the proximity effect are avoided and better higher frequency performance can be achieved. Foamed dielectric materials have an inherently lower loss tangent and dielectric constant causing them to exhibit less loss than higher density dielectric materials. Counter to most RG-based coaxial structure, multiple layers of shielding must also be employed to mitigate any losses that can occur from a lack of coverage -- generating a more robust coaxial assembly. Low loss cables for outdoor and large indoor installations also employ specific jacketing materials in order to prevent damage to cable. For direct burial applications a flooded cable, or a cable covered in a water-resistant gel, is leveraged to prevent any water ingress. In-building installations would require the use of a fire-retardant jacketing material in order to rapidly extinguish any flames.

Fire Retardant Low Loss Cables

Fire retardant cables involve different levels of fire extinguishing properties for the cable jacketing material. ***Table 1.2*** displays the various fire-retardant coaxial cable ratings and their respective standards. Plenum rated cables undergo the more stringent tests in order to pass for a CATVP rating. This is due to the fact that plenum spaces are areas that facilitate air circulation throughout an entire building -- offering a potential avenue for the undeterred spread of a fire. The HVAC system, or the heating, ventilation, and AC system, is comprised of plenum spaces. The ductwork laid out in raised floors or throughout a ceiling for forced airflow is routed unimpeded through every room of a large building. Conveniently, cable runs can also be routed through an entire building via these structures with the proper fire ratings.

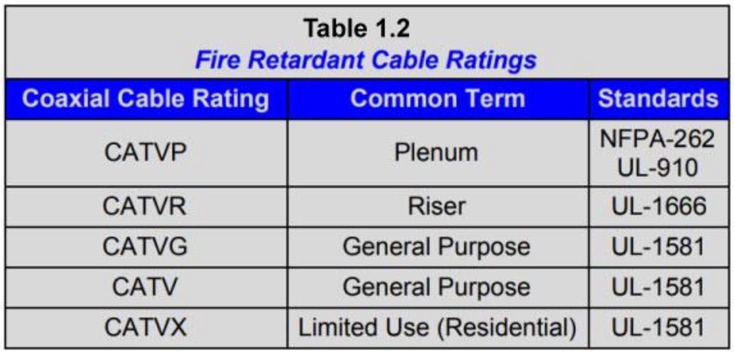
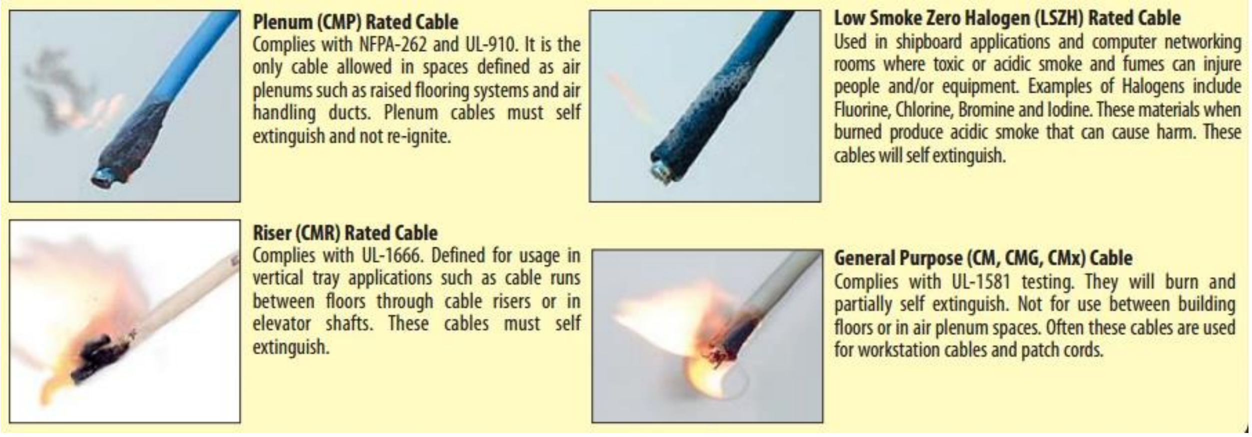


Table 1.2
Fire Retardant Cable Ratings

Coaxial Cable Rating	Common Term	Standards
CATVP	Plenum	NFPA-262 UL-910
CATVR	Riser	UL-1666
CATVG	General Purpose	UL-1581
CATV	General Purpose	UL-1581
CATVX	Limited Use (Residential)	UL-1581

Table 1.2

A general-purpose cable jacketing material would partially self-extinguish, doing little to stop the spread of flames. However, plenum or riser rated cables must be both fire retardant and self-extinguish. Plenum cables, however, cannot reignite once extinguished in order to qualify for a plenum rating (***Figure 1.3***).



Plenum (CMP) Rated Cable
Complies with NFPA-262 and UL-910. It is the only cable allowed in spaces defined as air plenums such as raised flooring systems and air handling ducts. Plenum cables must self extinguish and not re-ignite.

Low Smoke Zero Halogen (LSZH) Rated Cable
Used in shipboard applications and computer networking rooms where toxic or acidic smoke and fumes can injure people and/or equipment. Examples of Halogens include Fluorine, Chlorine, Bromine and Iodine. These materials when burned produce acidic smoke that can cause harm. These cables will self extinguish.

Riser (CMR) Rated Cable
Complies with UL-1666. Defined for usage in vertical tray applications such as cable runs between floors through cable risers or in elevator shafts. These cables must self extinguish.

General Purpose (CM, CMG, CMx) Cable
Complies with UL-1581 testing. They will burn and partially self extinguish. Not for use between building floors or in air plenum spaces. Often these cables are used for workstation cables and patch cords.

Figure 1.3: Various flammability ratings of cables.

PIM Considerations in Cell Tower and DAS Installations

For any high power, multi-band system passive intermodulation distortion (PIM) can cause interference and signal degradation in these highly sensitive systems. Caused by the passive components of an installation (e.g., antenna, interconnect, connector heads, diplexer, etc.), PIM occurs when two or more signals over the same transmission path mix, creating unintended modulation products.

The most common sources of PIM in a coaxial assembly are from the connector heads. These mainly stem from one of two issues:

- Irregular metal-to-metal junctions
- The use of ferromagnetic materials

Oftentimes the improper mating of the connectors (e.g., over-torquing, under-torquing) leads to a nonlinear metal contact and subsequent PIM generation. Any surface roughness and joints between dissimilar metals are also potential sources for PIM generation. Moreover, ferromagnetic materials commonly used in connector heads such as Nickel or Chromium can cause PIM and must therefore be avoided.

PIM can be mitigated through the use of low-PIM rated connectors that are specifically geared for cellular applications. Connectors heads such as the 7/16 DIN, 4.3-10, and NEX10 are specifically geared for low PIM performance with specific materials and construction, often with all brass bodies and with silver or white bronze plating. ***Figure 1.4*** shows these connector configurations along with a brief description of each of them. The connector heads get progressively smaller and function in higher frequency bands to best suit up-and-coming 5G applications.

These connectors also allow for a straightforward mate with hand screw and push-pull configurations for the 4.3-10 and NEX10 connectors. This allows for less human error in cellular Installations where antennas with a high port density are used such as passive MIMO (e.g., 4T4R, 8T8R, 16T16R) or, in a small cell application where there is little room to maneuver in order to accomplish a satisfactory mate.

7/16 DIN Connectors

Key Characteristics:
·Mating repeatability (~500 mating cycles)
·Mating configurations:
    ·Screw-type
·Up to 7.5 GHz frequencies

4.3-10 Connectors

Key Characteristics:
·40% smaller than 7/16 DIN
·Mating Configurations:
    ·Screw-type
    ·Handscrew-type
    ·Push-pull
·Low PIM performance
·Up to 12 GHz frequencies

NEX10 Connectors

Key Characteristics:
·53% smaller than 4.3-10
·Mating Configurations:
    ·Screw-type
    ·Handscrew-type
    ·Push-pull
·Low PIM performance
·Up to 20 GHz frequencies

Figure 1.4: Evolution in cellular connectors.

Coaxial Assemblies for High Reliability and Military Applications

Coaxial components for military applications require another level of tracking, testing, and certification over traditional commercial off-the-shelf (COTS) assemblies. More often than not, this level of processing has led the military to rely almost exclusively on a specific set of vendors with the proper infrastructure to provide components with a level of manufacturing transparency and proper testing practices to suit its mission-critical applications. There is, however, a higher cost of ownership for this type of procurement as these massive, long-term contracts can lead to excessive spending over a long period of time with the very real risk of an aging system that can be outdated by the end of the term. This lack of agility in obtaining contracts has led to a general push towards leveraging hi-rel COTS components. These build-to-print interconnects have the basic military requirements of durability, sub-component tracking, and testing transparency with the additional benefits of interoperability, quick turnaround time, and a higher vendor diversity[2].

Every military-grade, high reliability coaxial cable requires every part of the cable to be tracked along with transparency on the fabrication process. In other words, the materials purchasing and processing for the center conductor, dielectric, shielding, cable jacket, and connectors must all be readily available for looking up with respective serial numbers in an enterprise resource planning (ERP) system as well as the assembly of said materials. ***Figure 1.5*** shows the lot traceability process for a coaxial assembly, illuminating this involved process in order to be listed in the Qualified Products List (QPL) for military components.

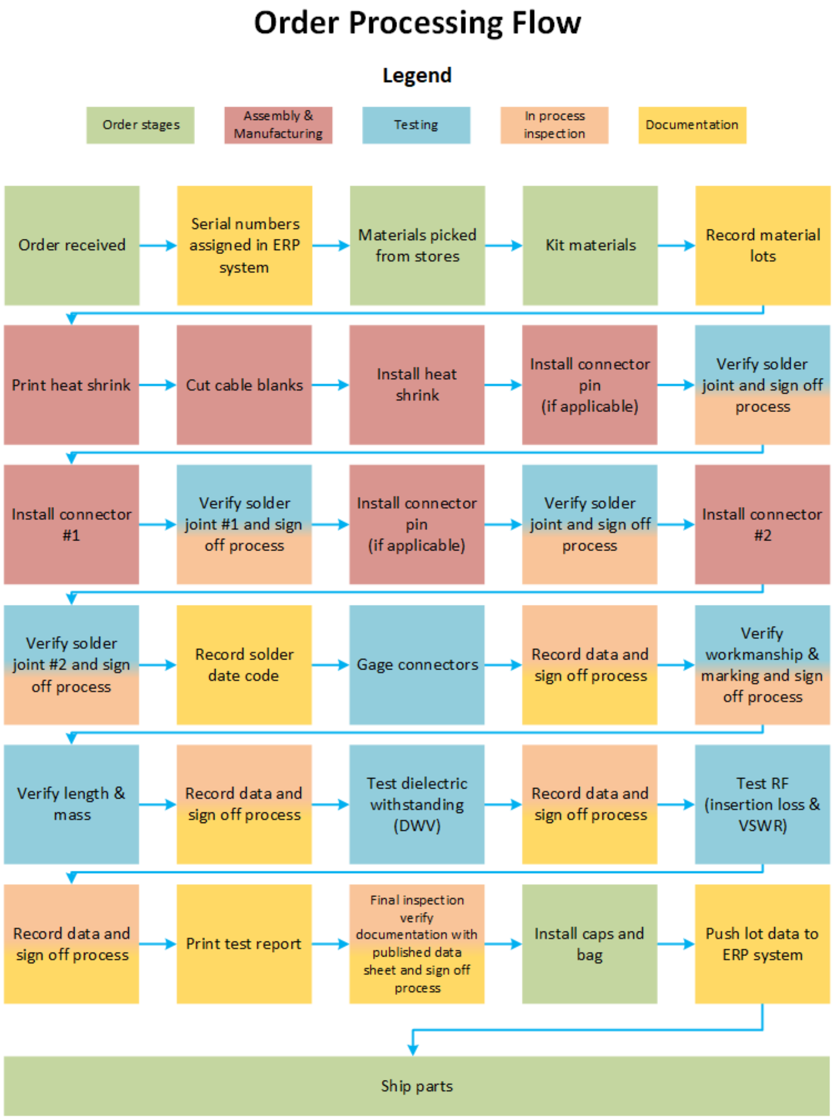
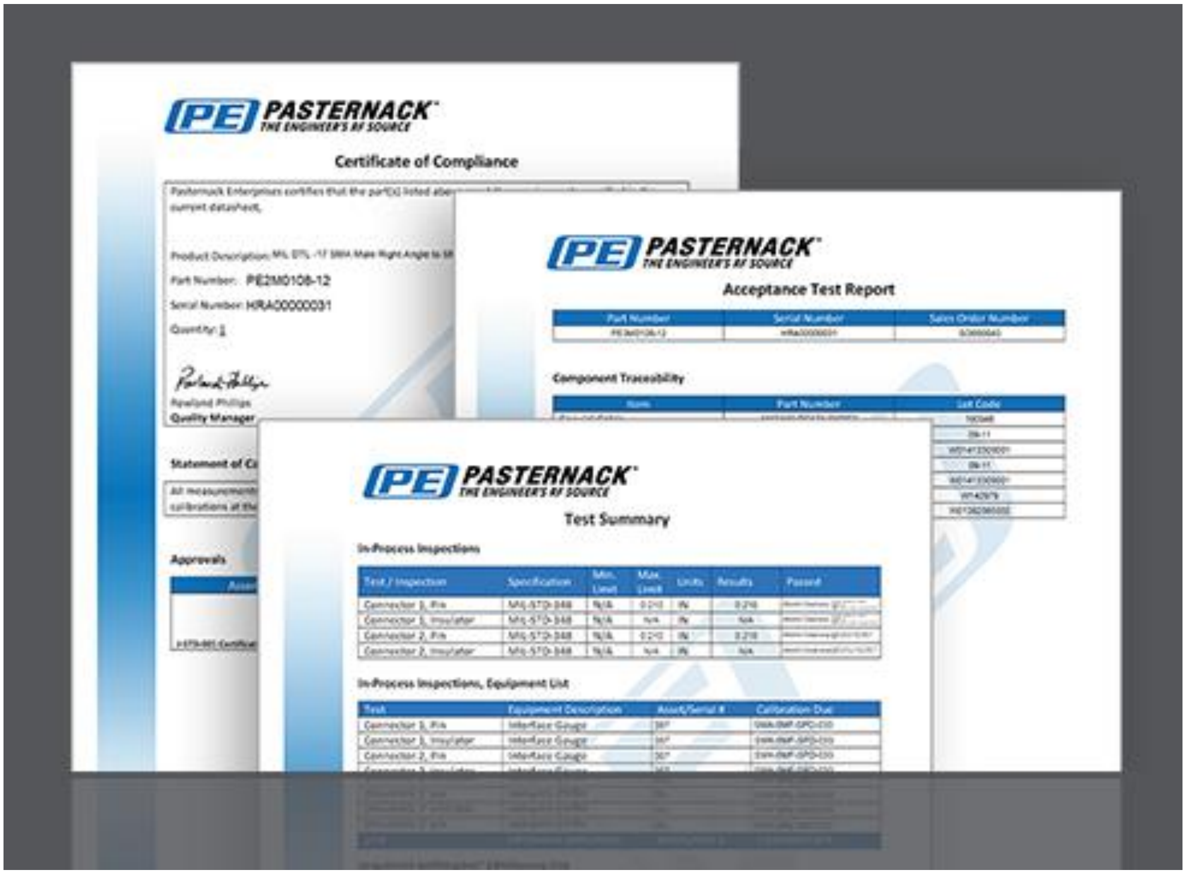


Figure 1.5: Order processing flow chart for a military-grade, hi-rel coaxial cable.

These cables also have a series of military specifications that must be met in order to pass for military-grade. Standards include MIL-DTL-17 (conformance requirements for connector and cable), MIL-PRF-39012E (testing for connectors), and MIL-STD-348 (interface dimensions for connectors). It is critical the vendor can properly demonstrate that in-house testing adheres to the specification requirements (***Figure 1.6***). The additional ability to view test reports allows a system designer to be better aware of the performance of a coaxial assembly and its subcomponents over its operational frequency.



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Certificate of Compliance

Part Number: PE2M0108-12
Serial Number: HRA00000031
Quantity: 1

Rowland Phillips
Quality Manager

Statement of C

Approvals

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Acceptance Test Report

Part Number | Serial Number | Sales Order Number

Component Traceability

Item | Part Number | Lot Code

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Test Summary

In-Process Inspections

Test / Inspection	Specification	Min. Limit	Max. Limit	Units	Results	Passed

In-Process Inspections, Equipment List

Test	Equipment Description	Asset/Serial #	Calibration Due

Figure 1.6: Test reports of a coaxial assembly on a QPL can provide additional insight on its performance.

Conclusion

The coaxial cable is a desirable transmission line for broadband, high frequency applications due its mode-free performance well into the W-band. The myriad of use cases for these assemblies all come with their respective choice of materials, constructions, and manufacturing considerations. Understanding these variations and applicational considerations can greatly help the process of choosing the right coaxial assembly.

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