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White paper

Design fundamentals for high-bandwidth BNC connectors

In the current world of high-speed internet connections, DSL telephony over twisted pair, coax modems, 500 channel cable television systems, and digital high-definition television, the venerable BNC connector has become the dominant connector choice for coaxial connections in the telephony, Cable, and broadcast markets. Part of the success of this decades old connector is rooted in the original design that dates back to the World War II era 1940's.

Some mystery surrounds the actual origin of the name "BNC." Some claim the connector was designed by the British, and the corresponding acronym stands for "British Naval Connector" while others prefer "Bayonet Naval Connector." Others claim that the name stems from the three engineers that designed the connector; Bayonet, Neill, and Counselman. Actually, two ingenious Bell Labs engineers named Neill, and Counselman originally developed the legendary BNC for the US military during the height of World War II. Therefore the BNC tag could either stand for "Bayonet Naval Connector" or "Bayonet Neill- Counselman" connector. Since the BNC is only a single member of a greater family of connectors that include the TNC, N, SMA, and SMB's, it is likely that Bayonet Naval Connector is the true origin. The TNC is identical to the BNC in interface dimensions, except that the bayonet is threaded rather than friction–fit. Again this could stand for "Threaded Naval Connector" or "Threaded Neill-Councilman." At any rate, Mssrs. Neill and Counselman's wisdom in design went far into the future. The design allowed the interface portion of the connector to be either 50 Ohms or 75 Ohms simply by adding or removing the insulator dielectric inside the front interface portion of the connector. In the past, 50 Ohm systems were the norm, and even today, 50 Ohm connectivity still dominates the RF world primarily because is offers superior power transfer characteristics for RF systems, whereas the 75 Ohm system offers lower loss characteristics for long distances.

While there are many ways to manufacture a BNC connector, the dominant standard that governs the design is specified in the military specification MIL-C39012. This specification sets critical interface dimensions, plating type and thickness, cable retention characteristics, and environmental requirements for the connector. Interface dimensions are fixed so that all connectors designed to meet the specification will interchange with any other regardless of the vendor that produces the actual part. There are many other "so called" BNC connectors on the market that look like a typical MIL standard BNC, but have interface dimensions (among other things) that are not compatible with connectors manufactured to meet C-39012. These typically low-cost alternatives may seem like a "good deal" on the surface until you realize that they may not work properly with connectors that meet C-39012. This can include things like oversized or undersized center conductors, improper length center conductors, improper chamfer angle of the center pin at the interface region, lack of, or improper plating on key parts such as gold center conductors, and connectors that are grossly out of tolerance for impedance. While C-39012 provides the key dimensions to ensure compatibility between vendors, it is flexible to allow for design differences that can have a dramatic impact on the quality of the signal going through the BNC.

In recent years, the data rates have increased to the point where maintaining constant impedance throughout the bandwidth of the signal has become a major concern. Drastic changes in impedance from capacitive to inductive creates regions in the connector where part of the original signal energy is reflected back to the source. Hence the measurement termed return loss (RL) is a measure of the amount of reflected signal energy relative to the source signal. The lower the number, the lower the amount of reflected signal energy. Another similar measurement called Voltage Standing Wave Ratio or (VSWR) measures the same criteria from a different viewpoint.

Changes in impedance create several problems in digital applications. First, high-speed super wideband digital signals such as SMPTE 292M 1.485 Gbit HD video are already sensitive to cable length due to the attenuation of the primary signal and odd harmonics. Poor return loss characteristics increase this attenuation and make it more difficult to recover the lost attenuation through the use of cable equalizers. This is due to the unpredictability of the signal being affected by poor connectivity components. Typical high-quality cable loss follows a predictable slope for attenuation that can be compensated for with quality cable equalizers and reclockers. These are typically built into distribution amplifiers (DA's) and router input/output modules. Signals attenuated by several poorly designed connectivity devices such as patching jacks or BNC's cannot easily be equalized and amplified because the radical impedance shifts within these devices do not allow all frequencies in the source signal to pass equally. This phenomenon known as group delay can play havoc with the quality of the digital signal. This leads to phase alignment problems and group delay of key information within the source signal. The most desired connectivity path is the one that provides the cleanest way for the signal to be transported. This can only be accomplished by using cable and connectivity devices that have been optimized for high-speed digital signals.

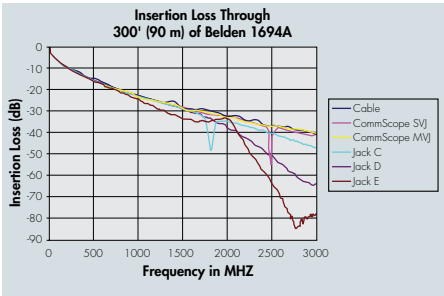

Figure 1: This graph illustrates the linear slope of cable loss (blue) versus various patching video jacks. Deviation from the cable slope indicates impedance fluctuations at different frequencies. The nonlinear patterns of jacks C, D, & E, cannot easily be corrected.

Optimizing a connectivity device starts with analyzing regions within the connector where impedance shifts might occur due to sharp transitions, or changes in materials. Similar to fluid traveling through a pipe, the speed, or velocity of electronic signals are affected by sharp bends and transitions within the cable or pipe just like with fluids. Interface regions, crimp areas, and transitions between metal and dielectric areas of the connector and cable must be carefully

balanced to provide the closest match to the optimum impedance in each area. While it is important to maintain a carefully impedance balanced component from end to end, large shifts in impedance, even when balanced by a corresponding offset will have a negative impact on the phase alignment of the digital signal passing through the component. The best design is one that minimizes the impedance variations throughout the connector or component.

Since coaxial cables come in a variety of sizes from .25" RG187 to .625" RG11, the diameter of the center conductor crimp, and transition area to the cable can vary considerably. Essentially, a change in impedance obstructs the electron flow creating resistance that reflects a percentage of the incident voltage back to the source. These obstructions vary by frequency, so not all of the energy reflected back is equal in bandwidth content. One measurement method called Velocity of Propagation (VOP) calculates the speed of a signal through a given dielectric material expressed as a percentage of the speed of light. The result is the Dielectric Constant for a given material.

The dielectric constant will vary widely for various materials, however Air is considered to be as close to perfect as possible and is given a value of 1.0. Since air alone will not support parts like center conductors, another non-conductive materials must be used.

There are many common dielectric materials used in connector design including ceramic, polypropylene, polyethylene, Teflon, and Ultem just to name a few. Teflon and Ultem are the best of the plastics, and are relatively easy to shape and form in production environments. Solid Teflon has a dielectric constant of 2.1, equating to 69% of the speed of light, whereas solid Ultem has a dielectric constant of 2.8, which equates to 59% of the speed of light. Unlike Teflon, Ultem can easily be molded into complex geometric shapes that contain mostly air. This reduces the amount of actual material and increases the amount of air, ultimately lowering the dielectric constant to a value much lower that what can be achieved with solid material alone. Teflon is very difficult to mold, tends to be hydroscopic (absorbs moisture) and is typically machined limiting the complexity of the part. The more air in the insulator (less material) the lower dielectric constant of the overall part (closer to air 1.0. Figure 2).

$$\frac{1}{\sqrt{\varepsilon_r}}$$

Figure 2: ε_r = The VOP of a material
1.0 = Air
2.1 = Solid Teflon (69% speed of light)
2.8 = Solid Ultem (59% speed of light)

The idea of adding air space to lower the dielectric constant and increase the VOP is most easily shown by comparing coaxial cables. Belden®, Inc. manufactures numerous cables under hundreds of part numbers. Two of their popular RG-6/U (Registered Government Type 6) cables; 8215, and 9248 and are similar in construction for the center conductor material and size, overall outside diameter, braiding type, and thickness. Yet the model 9248 is rated for a nominal VOP of 82% versus the 8215 at 66%. Why the 24% improvement in transmission speed?

The key difference between the two cables is that the 9248 has a Nitrogen gas injected Polyethylene dielectric core as opposed to the straight extruded Polyethylene core of the 8215. The Nitrogen gas injection process induces millions of tiny "air" pockets in the dielectric during the extrusion process effectively displacing Polyethylene and increasing the amount of air. This "Swiss Cheese" core contains more air and less material than the standard extruded Polyethylene core thereby increasing the velocity of propagation by 24%. The size, shape and dispersion of the gas bubbles within the Polyethylene core is an extremely precision process that must be carefully monitored during every aspect of the production process. Gepco International, Inc manufactures an RG6 HDTV cable (VSD2001) that is produced on one of the most advanced systems used in cable manufacturing today. Special computers, temperature monitors, tension meters, and numerous other status meters monitor the entire process of the cable line from core extrusion through final jacketing. Not only must the core be of the exact size, but the dispersion of the gas pockets must be uniform or the cable will produce "suck outs" and impedance variations that can dramatically affect the signal traveling through it.

With connectors and connectivity components, the same thing is true when comparing machined Teflon transmission conductor insulators, and geometrically arranged molded transmission conductor insulators.

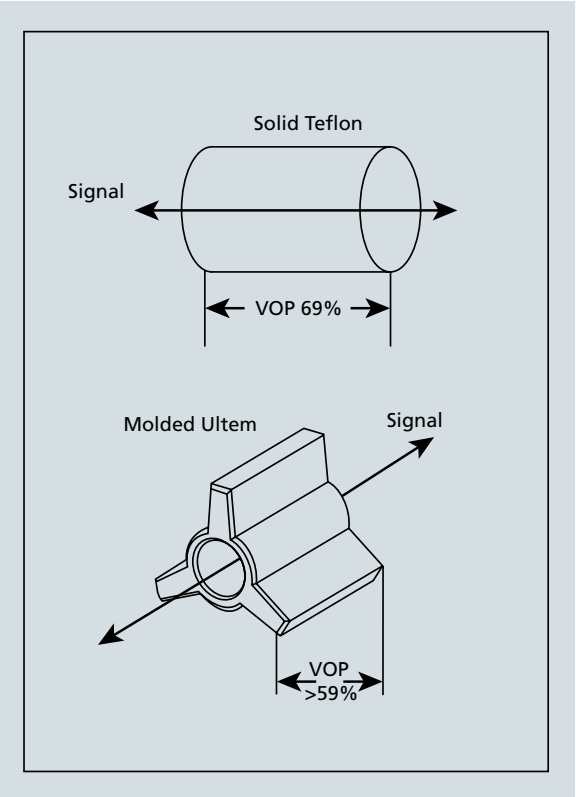

Figure 3: Solid materials act to slow the speed of transmission equal to their dielectric constant. Geometrically shaping the parts effectively lowers the dielectric constant by increasing the amount of air in the part and removing excess slower material.

Figure 4: Dimensions for all critical areas yet the unit with the molded Ultem center conductor insulator has a 10 dB improvement in return loss to over 2 GHz. The difference is the superior VOP of the molded part over the machined part.

As can be seen in figure 4, the critical dimensions for center conductor size (transmission conductor) crimp sleeve interior size, ferrule finger (ground path transmission) dimensions, etc. are identical for the graphed connectors. Yet the CommScope connector has a significant improvement in return loss and TDR plot (time domain reflectometer) over the other. The lone variable is the center conductor insulator. While the "Band X" connector uses standard machined Teflon technology, the CommScope employs a unique proprietary geometrically engineered molded center conductor insulator. The net effect is a smother transition in impedance performance from the interface region of the connector to the cable attachment region, resulting in a truer impedance match throughout the connector and better return loss especially at higher frequencies. This construction method also yields far superior unit to unit consistency due to the nature of precision molded parts. The "true 75 ohm" controversy in the industry is not in the interface region, but back inside the connector in the center pin crimp region. Many manufacturer's are still using a 50 Ohm .068" center pin crimp diameter. (The center pin gets wider as it goes into the body of the BNC) Since the I.D. of the crimp region of the BNC is fixed at .390, the only way to change the impedance is to alter the size of the center pin through that region. CommScope has optimized the entire connector from front to back for 75 Ohms. As a result, the center pin crimp is fixed at .042" crimp rather than the larger .068". This yields much improved impedance performance through that region of the connector. Others claiming to be "precision 75 Ohm" disguise their connector by making a hybrid that takes the .068" crimp of the 50 Ohm, and the dielectric free interface zone of the 75 Ohm, combine, and average the impedance for a "nominal 75 Ohms." In fact, the TDR plot shows that the impedance will swing from 52 to as much as 90 Ohms from 0 to 3 GHz. - Hardly a "precision 75 Ohm" device. Typically to specify a connector as "True 75 Ohms" it must not exceed +0/-3 Ohms from 0 to 3 GHz.

The effect of changing the insulator can also determine the overall impedance of the connector. The original design specification for BNC's (MIL-C-39012) allows for either a 50 Ohm or 75 Ohm connector by adding an insulator around the inside lip of the ferrule fingers for a 50 Ohm BNC, and removal for a 75 Ohm connector. Many common BNC's available today sold as "true 75 ohm" connectors still have this dielectric material in place, or often a Teflon shroud around the center pin. Naturally the impedance drops on such designs to as low as 50 ohms. The critical dimensions of the transmission conductor (ferrule fingers) do not change, yet the impedance decreases due to the drop in the VOP from the additional insulator material.

Once again, the standard used by every major connector manufacturer for BNC's both 50 Ohm and 75 Ohm is MIL-C-39012. This specification covers all of the interface dimensions of the connector, (the parts that mate with another BNC) the center pin of the male/female, ferrule fingers, and length of the connector etc. It does not specify things like insulator material, size, shape, crimp dimensions, etc. These details are left to the manufacturer's discretion. The center pin of the male BNC is specified at .053" +/- .001 at the interface point to the female. The ferrule fingers are .193 +/- .001 I.D., at the interface region, and .390 at the crimp region. The .053" center pin will result in a 75 Ohm impedance in the ferrule finger region without additional dielectric material, and 50 Ohms with the addition of dielectric (Teflon). The AVERAGE GATED RETURN LOSS -60 -55 -50 -45 -40 -35 -30 -25 -20 -15 -10 -5 0 0 250 500 750 1000 1250 1500 1750 2000 2250 2500 2750 3000 FREQUENCY (MHz) dB Molded Ultem Machined Teflon Both BNC's have identical dimensions for all critical areas yet the unit with the molded Ultem center conductor insulator has a 10 dB improvement in return loss to over 2 GHz. The difference is the superior VOP of the molded part over the machined part Figure 4. quickest way to spot a non 75 Ohm BNC is to look for insulator material around the center conductor or ferrule finger of the connector.

In the late 60's, before the invention of compounds like Ultem and Teflon, the easiest way to change the impedance of the BNC to 75 Ohms was to drop the center pin diameter to compensate for

the added dielectric material. The problem is that the smaller pin did not properly fit into 50 Ohm connectors using the .053" center pin opening, and worse, the female 75 Ohm units were blown out by the larger .053" interface pin of the 50 Ohm connector. Fortunately, good science and engineering since that time has done away with this practice, and standardized on the .053" interface center pin.

CommScope pioneered the use of geometrically shaped molded insulators for use in BNC's and connectivity components. Even though the VOP of Teflon is lower than Ultem, Using a solid machined Teflon center conductor insulator yields impedance violations that can go from 68 to over 85 Ohms! CommScope's proprietary design and molding process eliminates 90% of the dielectric material in insulator. Insulators are specifically shaped and contoured to "tune" the impedance of the region to +0/-3 Ohms from 0 to 3 GHz. To my knowledge we are the only manufacturer of BNC's that uses this process - It is expensive, but well worth it! Currently, the CommScope BNC has the best electrical performance in the industry.

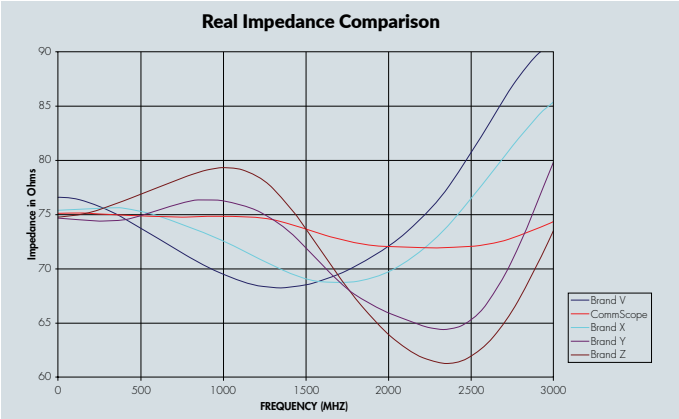

Figure 5: This is TDR (Time Domain Reflectometer) plot of a number of "true 75 Ohm" BNC connectors. Some vary as much as +15 ohms from 0 to 3 GHz leaving questions as to what true 75 Ohms means. Note that only the CommScope connector is within the +3 ohms required to be considered a true 75 Ohm device.

Why all the fuss and worry? Well, drastic swings in impedance reduce return loss performance by reflecting more of the incident wave back to the source. In digital systems, this can cause a dramatic rise in bit errors or BER (Bit Error Rate). Without sophisticated test gear like a digital signal generator and waveform VectorScope/bit rate tester, the user will typically notice a sizable reduction in the length of cable that can be used when using non-optimized components relative to optimized 75 Ohm components. With really poor cable and connectors however, you may be unable to resolve the BER at all.

Mechanical construction is important as well because it impacts the ability of the connector to stay on the cable especially when stressed in ways the connectors are typically not designed for. The MIL C39012 requirement for cable retention varies by the size of the coaxial cable from a low of 25 pounds for the mini coax RG187 types, to a high of 50 pounds for the larger RG59 and RG6 types. Cable retention can vary from manufacturer to manufacturer due to several factors. First, with all of the various manufacturers of coaxial cable, there are literally thousands of cable types. Typically there are a fixed number of cores (center conductor and dielectric) as well as a fixed number of outer braids and jacket sizes. Most of the differences between cables are related to jacket types or colors including plenum rated riser cables or soft pliable cables. The cores can differ by material type as well with the popular high-bandwidth foam polyethylene types being different from the standard polypropylene types. There are three primary components on any BNC; the center conductor, the ferrule finger/bayonet assembly, and the outer crimp sleeve. Each of these components must be uniquely sized to the cable type, although there are many common parts between various cables. Some manufacturers try to make large compromises between component sizes so that a few components will fit the greatest number of cable as possible. These compromises often lead to electrical performance reduction, as well as mechanical retention reduction due to the "one size fits all" approach.

CommScope also has many connectors for various cable sizes that share common components, however the goal of connector engineering is to always exceed the MIL requirements and always produce a "best in class" product that will consistently outperform the competition. CommScope uses a longer crimp sleeve and special "cross- hatched" diamond knurl pattern on the BNC ferrule to achieve the highest pull-off forces in the industry. Typically pull-off forces will range between 30-45 pounds for RG187, to over 85-100 pounds for RG59 and RG6. In addition, all crimp sizes are designed for industry standard crimp dies eliminating the need to purchase non-standard tooling.

Lateral stability of the connector is also a major factor in the overall mechanical reliability. Lateral forces on the cable can develop at installation, or afterwards if large cable bundles hang or drag on the connectors. The weight of a large bundle of cable can exert considerable force on the connectors. In cases where the connector is poorly designed, lateral forces can actually break the connector off at the crimp sleeve leaving the connector with little or no shield connection. Often times these poorly designed connectors use a thin stamped ferrule finger assembly to reduce cost. The sideward pressure (lateral force) snaps the ferrule finger off as it enters the bayonet sleeve. CommScope uses a one-piece all-machined ferrule finger, which has extremely high resistance to sideward or lateral force.

Two crimp or one crimp design?

In recent years, some BNC manufactures have attempted to engineer single crimp designs to eliminate assembly labor. The conventional wisdom being that people will pay more for a connector that eliminates costly labor. These designs have taken two forms; the crimp center pin, friction cable fit type, and blind mate no-crimp center pin, crimped outer cable type. In each case, the result is a connector that saves little if any labor time, since most of the labor is in the cable prep, labor savings claims are questionable at best. The uncertainty of the "blind mate" of the center conductor, and the friction fit on the outer cable, often result in multiple connectors before success. Friction fit connectors rely heavily on the quality standards of the cable manufacturers. If the outer jacket thickness varies between cable reels, the result can be a fit that is either too tight, or not tight enough, and causes the connectors to come off the cable too easily. Cable manufacturers vary considerably in their ability to maintain unit to unit consistency. Some are way better than others, usually identified by the price of the product (you get what you pay for). Single crimp designs also normally require specialized tooling with is often very costly and can be difficult to obtain, especially in field installations.

Additional recommendations

The key to any connector is the installation process. The more precise the installation, the better the connector will perform. With BNC's it is extremely important to get the cable stripped to the right dimensions. Stripping the center conductor either too long, or too short can create problems in assembly. In addition, it is very important to avoid nicking the outer braid during the stripping process. This is because the braid provides the retention force for the cable to the connector. When you nick or cut braids off, you effectively change the holding force for the connector itself. This can also create voids in the braid leading to ingress/egress problems especially at higher frequencies.

The introduction or reception and radiation of unwanted signal energy is known as ingress/egress. BNC's that do not have a proper crimp on the center conductor and crimp sleeve can exhibit high amounts of ingress/egress especially after the cable center conductor or braid has oxidized and no longer makes a solid connection to a non-crimp style assembly. This seriously degrades the return loss characteristics of the connector, potentially affecting other equipment within the vicinity of the offending connectors.

Many high bandwidth coaxial cables include a foil wrapper around the dielectric just under the outer braid. Whenever possible, we recommend leaving the foil in tact rather than removing it. The reason is that unless the dielectric has an exceptionally tight fit into the ferrule of the BNC, the lack of the foil creates an area of impedance mismatch, and can degrade return loss by as much as 10 dB across the frequency range. Sometimes this is impractical because the stripping process often tears the foil making it impossible to slide under the ferrule. In cases like this, make sure the outer braid is very evenly distributed around the outside of the ferrule, and not bunched-up on one side. A little care at this point can save a lot of headache in the future.

Always select good quality crimp tools, and maintain the manufacturer recommended adjustment schedules. Dies that do not close completely will often "flash" at the crimp, leaving metal squeezed out where the crimp dies come together. If the flash becomes excessive, it can have a very negative effect on the electrical and mechanical performance of the connector. Never double crimp center pins and crimp sleeves! Double crimping no matter how carefully done will actually loosen the fist crimp leading to mechanical failure.

Maintain stripping tools as well, and replace the blades after the recommended stripping cycles. Remember that the quality of the initial strip can make or break the connector installation. Cable runs will usually vary somewhat between run to run, meaning that slight adjustments to stripping depths may be necessary. We also recommend checking the cable for internal shorts using a high-pot test prior to connector installation to prevent wasting connectors.

In cases where problems show up after the cable is put into place, and connectors are installed, a TDR (Time Domain Reflectometer) can be a useful tool in helping to identify where in the cable assembly the defect lies. The TDR sends a signal down the cable and measures the minute amount of reflected energy and the time it takes for the energy to return to the source. By knowing the time, it is possible to pin point the exact distance in the cable where the problem lies.

Our final recommendation is to always select quality cable, connector and tooling vendors. Saving a few cents on the cable or connectors can lead to bigger problems down the road.

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