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MICROWAVE COAXIAL CONNECTOR TECHNOLOGY: A CONTINUING EVOLUTION

Mario A. Maury, Jr.
Maury Microwave Corporation

Introduction

Coaxial connectors are one of the fundamental tools of microwave technology and yet they appear to be taken for granted in many instances. Unfortunately, many engineers tend to overlook the lowly connector with resulting performance compromises in their applications. A good understanding of connectors, both electrically and mechanically, is required to utilize them properly and derive their full benefit. It should be remembered that performance starts at the connector.

Coaxial connectors provide a means to connect and disconnect transmission lines, components and systems at microwave frequencies. They allow accessing circuits, modularizing, testing, assembling, interconnecting and packaging components into systems.

There is a broad variety of coaxial connectors available today due to the various design trade-offs and applications that exist at microwave frequencies, including impedance (usually 50 ohms), frequency of operation, power handling, insertion loss, reflection performance, environmental requirements, size, weight and cost.

Precision connectors have played a major role in the evolution of microwave coaxial connector technology, as shown in **Figure 1**. It is through these connectors that our measurement equipment has improved and thereby connectors, in general, have improved. The foresightedness of the C83.2 and IEEE P287 connector committees in the early 1960s gave us the philosophies and concepts and paved the way to solutions for the fabrication of precision connectors that are in use today. The IEEE P287 committee has been re-activated and is carrying on this important work (see *IEEE P287 Committee*).

(a)

(b)

Figure 1: Precision coaxial connectors in use today; (a) 7mm and 14mm sexless connectors and (b) 3.5mm female and male, type N female and male.

This paper provides a brief history of coaxial connectors, gives an overview of coaxial connector technology today, cites sources of further information and takes a look into the future as connectors continue to evolve.

IEEE P287 Committee

In 1988, the sub-committee P287 for precision coaxial connectors under the IEEE/Instrumentation and Measurement Society was re-activated by the IEEE Standards Board to carry on the work originally begun in 1962.

The objective of this committee was to revise IEEE Standard 287 published in 1968 so that it represents the current state of the art in precision connector technology; to standardize both laboratory precision connectors (LPC) and general precision connectors (GPC) in a minimum number of transmission line sizes covering the frequency range from DC to 110 GHz; to standardize the means for transferring laboratory measurements to devices with field type connectors; to produce a standard that is useful and meaningful to the manufacturers and users of precision coaxial connectors; and to incorporate any other items deemed relavant and appropriate into the standard.

The committee is in the process of updating the standard that currently covers 7mm and 14mm sexless precision connectors. In addition, it has adopted pin socket type connectors in the line sizes and precision type N connectors for standardization, shown in **Table 1**.

TABLE 1
Adopted Pin Socket Type Connectors

Line Size (mm)	Maximum Frequency (GHz)
3.5	33
2.92	40
2.4	50
1.85	65
1	110

The committee is chaired by Harmon Banning of W. L. Gore & Associates, Newark, Delaware and consists of 25 members who provie a broad cross section of the microwave industry.

Terminology and Definitions of Coaxial Connectors

There are basically two distinct categories of connectors, sexless and sexed.

A sexless connector is a connector where both halves of the connector mated pair are identical. They are coplanar. The outer conductor coupling mechanism and the center conductor contacts are captive to the individual halves. There are sexed outer conductor coupling versions of sexless connectors. For example, 7mm GPC connectors typically are limited to precision connectors. These also are referred to as hermaphroditic connectors.

Sexed connectors have a female and a male configuration to form a mated pair. They can be coplanar or non-coplanar, and generally are sexed in both conductors. Type N and SMA connectors are examples of sexed connectors. This is the predominant category of connectors in use today.

The type of connector refers to a specific connector configuration that forms the basis of a family of connectors that mate with each other. For example, types N, BNC, SMA and 3.5mm are a family. It is also possible to have mating between families, for example, SMA and 3.5mm, 2.4mm and 1.85mm.

There are three grades of connectors; production, instrument and metrology. The production grade of connectors includes general purpose or field connectors for components and cables. The emphasis should be one assembly simplicity and low cost.

The instrument grade of connectors includes precision or test connectors for use with test and measurement equipment, meeting high performance standards, that is, low reflection and good repeatability, and moderate cost.

The metrology grade of connectors include high precision connectors primarily used on measurement standards where the highest accuracy is required and would allow traceability to national standards. The cost of these connectors is high.

Obviously it would be difficult for all connectors to meet this criteria. However, most can at least be made to meet production and instrument grade. New connectors, as they are designed, should follow these general guidelines.

Interface is the mechanical configuration (dimensions and tolerances) of a connector mating properties that must be clearly defined in order to insure mechanical mating compatibility and electrical repeatability. Different dielectrics present at the interface include air dielectric and dielectric.

Air dielectric simplifies connector construction and generally is used on precision connectors so accurate standards can be created. These connectors include type N, 7mm and 3.5mm.

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A solid dielectric like teflon usually is used and there are two basic configurations, flush and overlapping. Flush connectors are SMA and SSMA; and overlapping connectors are BNC, TNC, C and SC. Overlapping constructions generally are used for higher power application and to prevent voltage breakdown.

Reference plane is the outer conductor mating plane of a coaxial connector. It is desirable to have both the outer and center conductors coplanar at this plane, that is, in the identical plane, for electrical and mechanical reasons.

Coplanar connectors are connectors where the center and outer conductor mate in the same plane. These connectors include 7mm, SMA and 3.5mm.

Non coplanar connectors are connectors where the center conductors don't mate in the same plane. These connectors include N, BNC, C and TNC.

Coupling type describes how the outer conductors are connected. There are basically three types, threaded, twist or bayonet locks and snap-on. Type N, TNC, SMA and 7mm are threaded; type BNC and C are twist locks; and SMB is a snap-on.

All sexed connectors are of the pin-and-socket type, where there is a male contact (pin) and a female contact (socket). There are currently two types of female contacts slotted and slotless, used for precision applications. N, BNC, SMA and 3.5mm meet this definition.

Millimeter-wave coaxial connectors are coaxial connectors for use above 18 GHz. The term is appropriate because they operate in the mm-wave region. Generally these are pin-and-socket type connectors, such as SMA, 3.5mm and 2.4mm. Sexless connectors also have been made above 18 GHz.

As a general rule, a coaxial connector's electrical performance (SWR and insertion loss) must be defined based on a mated connector pair since this is the only way they can be measured; this is particularly true of non coplanar connectors.

There are many ways to describe connectors and usually a combination of these terms is involved. The following two important equations are helpful in defining coaxial connector parameters[1], impedance,

$$Z = \frac{59.9586}{\sqrt{\varepsilon}} \, ln \frac{D}{d} \; (\Omega)$$

cutoff frequency (TE_{11}),

$$f_c = \frac{7512}{\sqrt{\varepsilon}\,(d + D)} \, (GHz)$$

where

D = outer conductor inner diameter

d = center conductor outer diameter

ε = the dielectric constant in transmission line

air = 1.00059

teflon = 2.02

The predominant impedance of coaxial connectors used is 50 Ω (see *Why 50 Ω Connectors?*).

Connector electrical specifications are sometimes difficult to specify or verify because their performance depends on how they are assembled to the transmission line media, that is, flexible cable, stripline or microstrip. The only connectors that can be accurately specified are connectors for mounting or rigid coaxial lines.

Connectors covered in this paper are generally limited to those developed or in primary use in the United States. Also all dimensions are in inches unless otherwise specified.

Some helpful hints are: use the largest coaxial transmission line and connector possible for your application, as this will provide the best performance; check the manufacturer's specifications (both mechanical and electrical), sometimes they are better than military specifications and sometimes they are worse; and define the connector early in the project, not at the end of it.

Early History

An excellent historical perspective on coaxial lines and connectors has been published[2]. The evolution of connectors in the United States starting in 1940 is included. In 1940, the only coaxial connector in general use was the UHF connector that, interestingly enough, is still in use today in substantial quantities at lower frequencies. It was developed by E. C. Quackenbush of American Phenolic Co. (later Amphenol).

With the beginning of World War II, and the emergency need for higher frequency applications above 300 MHz, it was determined that the UHF connector was not suitable and that new connector designs were required. A joint Army-Navy RF Cable Coordinating Committee (ANRFCCC) was established in the early 1940s to develop standards for RF cables, rigid transmission lines and connectors for radio and radar equipment. The task of this committee later was incorporated into the Armed Services Electro-Standards Agency (ASESA) when it was established in the late 1940s and eventually was reorganized into the Defense Electronics Supply Center (DESC) that continues the important work of connector standardization for the military today.

Under ANRFCCC guidance, the type N connector was born in 1942 and featured a threaded coupling nut for connection and an air coupling interface. The N derived from Paul Neill of Bell Laboratories (New York) who was on the committee and worked on the connector. This was followed by the HN connector that was a high voltage version of the type N and featured an overlapping dielectric interface. The type C connector followed next with a twist-lock coupling mechanism for quick connect and disconnect. It was named after Carl Concelman of Amphenol. Then, as smaller coaxial cables became available, the BNC connector was developed jointly by Neill and Concelman, hence the N and C and the B for baby because of its size.

Another connector that originated in the early 1950s was the GR874, which was developed b the General Radio Company. It was a push-on sexless connector widely used in the laboratory. A later version added a threaded coupling for more stable operation.

Why 50 Ω Connectors?

In the United States, the predominant impedance for coaxial transmission lines and connectors is 50 Ω. The theoretical impedance for minimum attenuation is 77.5 Ω and for maximum power transfer is 30 Ω; the average of these two impedances is 53.75 Ω or rounded off to 50 Ω (see Figure 2 at right). Therefore, 50 Ω is a compromise between minimum attenuation and maximum power transfer in a coaxial transmission line, and that is why it was selected. There are connectors available with other impedances, the next most popular impedance being 75 Ω (approximate minimum attenuation performance) that is in fairly wide use internationally and in long line communication systems.

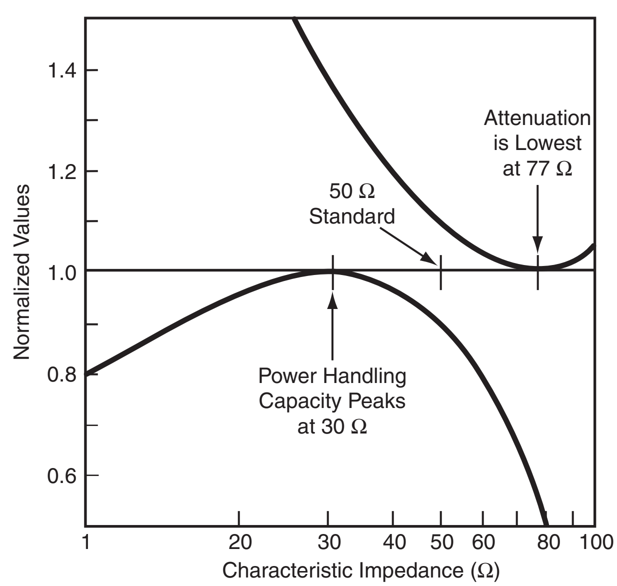

Figure 2: Power Handling – Attenuation Trade-Off

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In 1956 emerged the TNC connector that was essentially the BNC connector with a threaded coupling. This improvement was significant and produced a reliable and stable small connector suitable for systems applications. Its origin is difficult to pin down, however, Raytheon, Sandia National Laboratories and General R.F. Fittings have been mentioned.

A number of other connectors also were developed during this period but too numerous to mention here. **Figure 3** shows some of the early connectors. In the late 1950s and the early 1960s, connector development picked up the pace to improve performance and to operate at higher frequencies. Several major events occurred in this period that would have far reaching implications on coaxial connectors.

In the early days because of the lack of knowledge and the unavailability of accurate RF measuring equipment, military specifications for connectors were based on detail mechanical piece part drawings, which were non-optimum designs from a microwave standpoint, with no performance specifications. This limited manufacturers from making improvements or risk noncompliance.

(a)

(b)

Figure 3: Early coaxial connectors; UHF female and male adapters to BNC female, MIL-C-71 type N connectors female and male adapters to TNC female and GR874 connectors; (a) with and (b) without locking nut.

A major event in 1960 was the formation of the C83.2 Subcommittee on RF connectors under the American Standards Association (now American National Standards Institute). The formation of this subcommittee was instrumental in helping the military develop new specifications for coaxial connectors that specified

Chronological Introduction of Coaxial Connectors

Key chronological introduction of modern day coaxial connectors still being produced is sown in **Table 7**.

TABLE 7
Introduction of Modern Day Coaxial Connectors

Year	Connector	Year	Connector
1942	Type N	1964	7mm (APC7)
1944	Type C, BNC	1965	Precision type N
1950	GR874	1974	2.92mm (K)
1956	TNC	1976	3.5mm
1958	SMA	1983	K (2.92 re-introduced)
1960	SSMA	1986	2.4mm
1962	14mm (GR900, MPC14)	1989	1.85mm (V)

performance and mechanical interface information, which controlled mating compatibility and interchangeability. The specification was MIL-C-39012 and originally was issued in 1964. It made a major contribution to the evolution of coaxial connectors. Now manufacturers were able to make improvements on the connector design.

Another key event that occurred in 1960 was the start of the work that became the IEEE (P287) subcommittee on precision coaxial connectors in 1962 under the IEEE Instrumentation and Measurements Society. This committee formulated the design concepts and ground rules for precision sexless coaxial connectors primarily for measurement purposes. Two connector sizes, 14mm and 7mm, were standardized under the IEEE standard no. 287, which was issued in 1968.

Emerging during this same period was the SMA connector that changed microwave connector technology and eventually replaced the type N connector as the principal coaxial connector for microwave applications.

During the 1960s many improvements were made to the connectors that were started in the early 1940s pushing the technology to operate at frequencies up to 18 GHz. Also in this period, connectors operating at frequencies above 18 GHz started to enter the market.

In the 1970s, the frequency limits were pushed up to 40 GHz and then in the 1980s to 60 GHz and possibly 110 GHz.

Evolution of Type N Connectors

The type N connector originated in 1942. For many years it was the workhorse of RF (microwave) connectors, and it is still one of the most popular connectors in use today. The original type N connector was covered by Navy Bureau of Ships drawings that saw several improvements and then evolved into military specification MIL-C-71 that controlled type N connector specifications for the military until MIL-C-39012 was issued in 1964.

The major problem with MIL-C-71 type N connectors was that they were controlled by detailed mechanical drawings with non-optimum dimensions or design from a microwave performance standpoint. This forced various manufacturers in the late 1950s and early 1960s to develop improved performance type N connectors. The problems and the resultant evolution that took place during this period are summarized in a previously published work[2].

An early version of improved type N connector was produced by Maury Microwave Corporation in 1962 and was called Blue Dot. Several reports have been published by Jet Propulsion Laboratories[4]. The novel concept, introduced by Maury, was color coding connectors with a dot so they can be readily identified even though they look similar. This practice is still in use today.

A number of manufacturers, including Alford, Amphenol, Hewlett-Packard, Narda, Weinschel and Maury, contributed toward improving type N connectors during this period pushing the performance of the connector to 18 GHz. A variety of interfaces were generated and are summarized in an article[5]. The precision type N connector that is in use today emerged in 1965. It featured a solid outer conductor in the male connector and a uniform transmission line through a mated pair. **Figure 4** shows the interface configurations.

Currently, general purpose type N connectors (class 2) are covered by MIL-C-39012 and are rated to 11 GHz with a SWR of 1.3 (although this varies depending on the slash sheet) and the interface for these connectors is provided in MIL-C-390121/1 and /2. The class 2 interface is quite broad and allows a large amount of variation. For example, the MIL-C-71B connector interface can be built and comply with MIL-C-39012. A standard test connector with a tightly controlled interface also is defined in Amendment 2.

Another version of type N also exists. It is defined in MIL-T-81490 and commonly is referred to as EWN. Precision type N is rated to 18 GHz and has a

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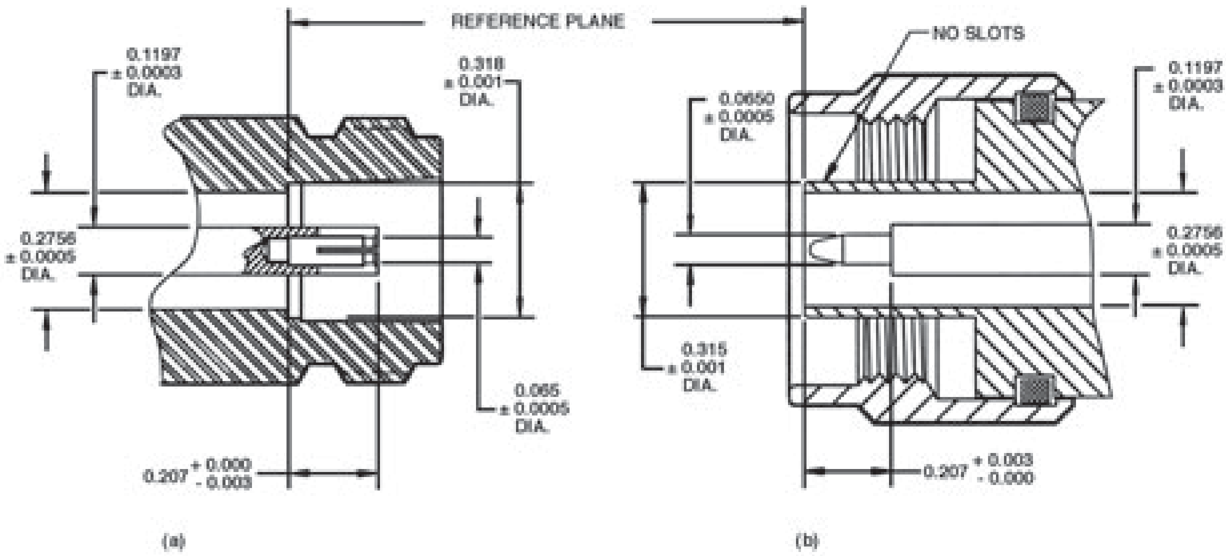

Figure 4: Precision type N connector generally accepted critical interface dimensions; (a) female connector and (b) male connector.

specification of 1.08 (maximum) SWR for a mated pair (Amphenol and Maury specification), as shown in **Figure 1**. There is also a high precision version of the type N connector with a slotless female contact and an SWR of 1.04 (maximum) to 18 GHz in a mated pair. They normally are supplied on test ports, air lines, and calibration devices (produced by Hewlett-Packard and Maury). The IEEE P287 Committee is in the process of generating a standard for precision type N connectors.

There is still a wide variety of type N connector interfaces in use today with corresponding performance limits. Type N has come a long way in almost 50 years and has proven its usefulness to microwave technology.

Type SMA and SSMA Connectors

The SMA connector is the most widely used microwave connector in the world today. It originally was designed at Bendix Research Laboratories by James Cheal in 1958 and began life as BRM connector for Bendix real miniature connector. Its development was continued in 1962 by Omni Spectra (now a division of M/A-Com) when the connector became known as OSM for Omni Spectra miniature. It became popular under that name. In 1968, it was incorporated into MIL-C-39012 where it received its current designation of SMA for subminiature A. A more detailed description on the early evolution of the SMA connector is described in a previously published work[2].

The SMA connector was designed to be a low cost miniaturized system connector. It is a coplanar pin socket connector with a dielectric interface. It is an excellent adaptation for use with 0.141 diameter semi-rigid cable in its simplest form. It found ready application for use with stripline and microstrip circuits because of its size. People have complained about their longevity in a measurement environment, but it was not intended for this application. The APC3.5 connector is a well suited test connector for SMA and is being used for this purpose on a regular basis[6]. The principle of interface error correction using software and a VNA was advanced[6] and later implemented[7].

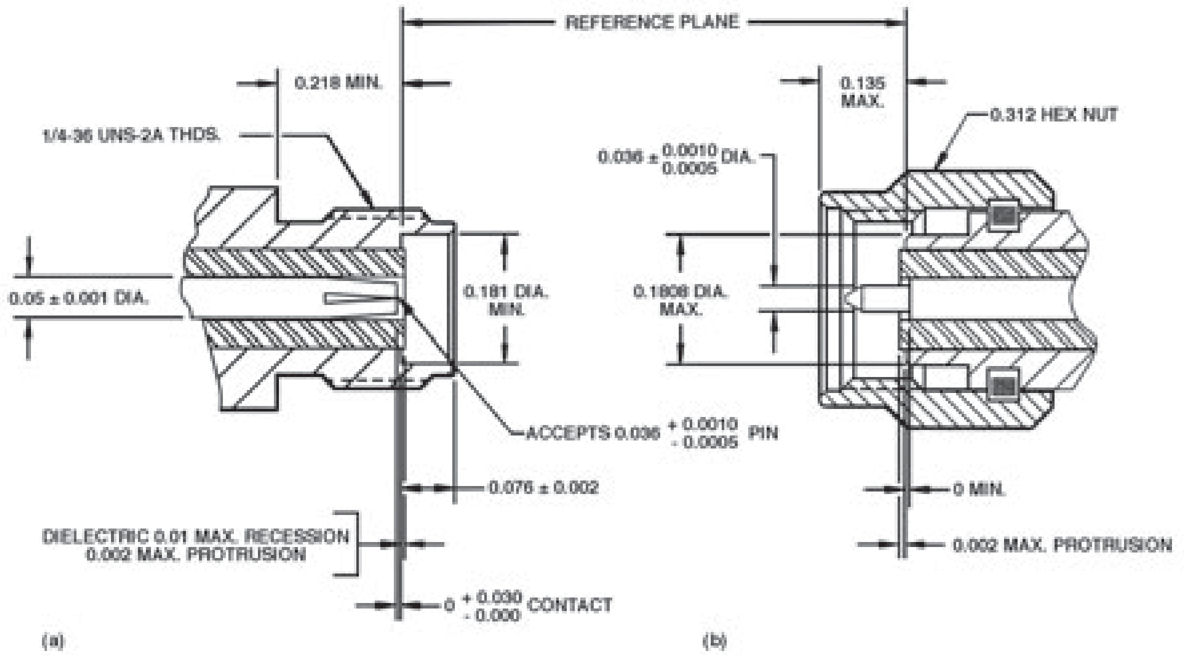

Figure 5 **SMA class 2 critical interface dimensions per MIL-C-39012/55 & /57; (a) female connector and (b) male connector.**

SMA connectors now are controlled by MIL-C-39012, as shown in **Figure 5**, for current class 2 interface information. Performance specifications vary depending on the slash sheet utilized. A standard test connector is specified in Amendment 2, however, it has a dielectric interface so it is not as good as an APC3.5 connector that has an air interface making the 3.5mm connectors more suitable from a measurement and calibration standpoint.

SMA connectors will operate mode-free to 18 GHz and certain versions to 25 GHz (higher order modes can exist in the 22 to 24 GHz frequency range). There is also an improved version available from Amphenol and M/A-Com that operates to 27 GHz.

The SMA connector has essentially spawned an evolution of its own. There are several higher frequency connectors that are SMA mateable, for example, 3.5mm and 2.92mm. Information on various SMA interfaces and some insight into coplanar interface compensation previously has been provided[6].

The SSMA connector (**Figure 6**) also was developed at Bendix in 1960 as BRMM and later improved and made popular as the OSSM connector. It was designed for use with 0.086 diameter semi-rigid cable and was basically a scaled down version of the SMA connector. Like the SMA connector, it is a coplanar pin-and-socket, dielectric interface connector. The SSMA connector has not been officially standardized so it is controlled by manufacturers specifications.

SSMA connectors operate mode free to 26 GHz and certain versions to 36 GHz. Higher order modes can be excited at frequencies above 34 GHz. There is also an improved version available from M/A-Com that operates to 40 GHz. There are other SSMA mateable connectors with air interface available.

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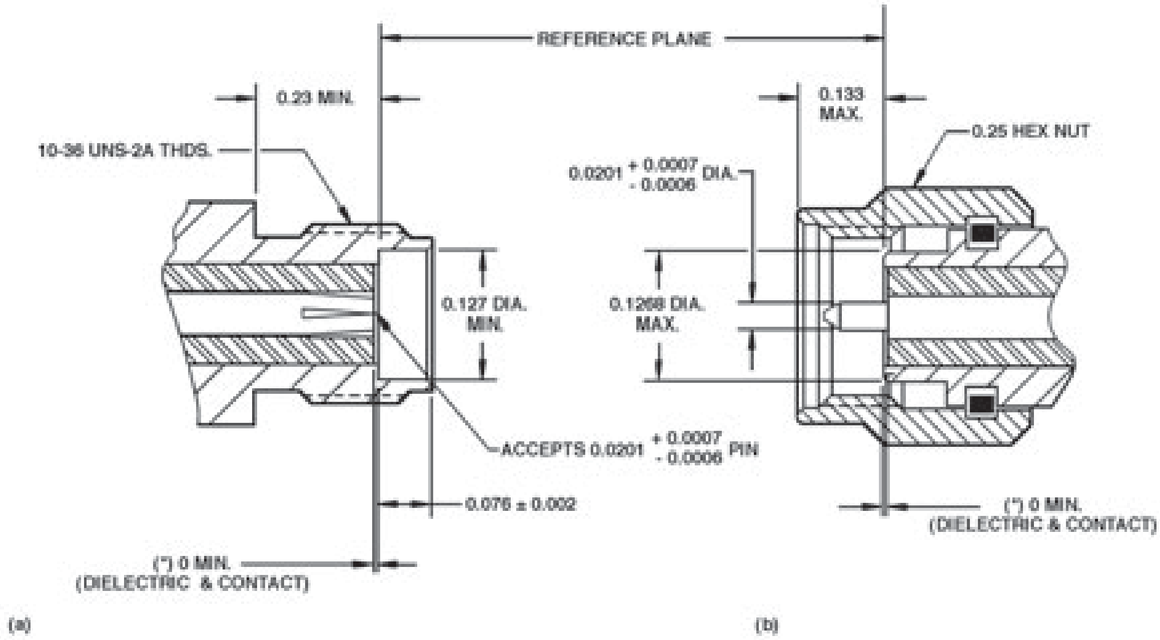

Figure 6: **SSMA critical interface dimensions; (a) female connector and (b) male connector (*) maximum limits depends on electrical specifications.**

General Purpose Connectors

This is a broad subject. There are as many connector types as there are applications, too many to cover in this paper. **Table 1** (on page 10) lists some of the more popular connectors covered in MIL-C-39012 and **Figure 7** shows their configuration. General purpose connectors are available in a multitude of types such as for flexible cables, semi-rigid cables, chassis mount and stripline launchers[8]. A recent article[8] provides some guidelines for connector selection and a 1990 survey furnishes a current list of coaxial connector manufacturers[9].

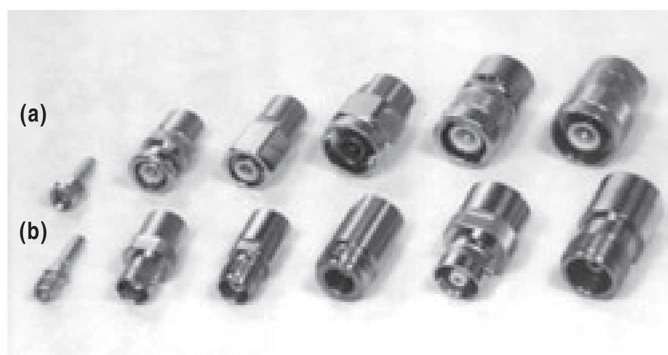

Figure 7: **General purpose coaxial connectors in wide use for systems application; SMA, BNC, TNC, N, C and SC; (a) male connectors and (b) female connectors.**

In addition to conventional coaxial connectors, there is a variety of other connectors available including high voltage connectors, like HN, that operate to 4 GHz per MIL-C-3643; high power connectors for large coaxial cables, like LT, per MIL-C-26637; and connectors for low loss, high power rigid coaxial line used in communications systems per MIL-F-24044 (EIA RS-225). **Figure 8** shows an example of these larger connectors. Some recent developments have been blind mate connectors for modular systems[10] (produced by Automatic Connector, M/A-Com and Selectro) and crimp-type, semi-rigid cable connectors that eliminate soldering[11] (produced by AMP Inc.).

TABLE 1
Some Popular General Purpose Coaxial Connectors For Use At Microwave Frequencies (All 50 Ω) And Covered By MIL-C-39012

Connector Type	Description	Frequency Range (*)	SWR (*)	Coupling Type	Interface Type	Size
SMA	Widely used system connector in military applications, popular use with 0.141 semi-rigid cables.	DC - 18 GHz (available to 26.5 GHz)	1.25	1/4 - 36 threads	Teflon, flush	Sub-miniature
SMB	Used for internal dense packaging applications, generally used with flexi-cables.	DC - 4 GHz	1.5	Snap-on	Teflon, overlap	Sub-miniature
SMC	Threaded version of SMB for higher frequency use.	DC - 10 GHz	1.6	10 - 32 threads	Teflon, overlap	Sub-miniature
BNC	Popular, used for small flexible cables with quick disconnect coupling.	DC - 4 GHz (useable to 10 GHz)	1.3	Twist-lock	Teflon, overlap	Miniature
TNC	Durable and reliable for aerospace applications (threaded version of BNC).	DC - 12.4 GHz (version available to 18 GHz)	1.3	7/16 - 28 threads	Teflon, overlap	Miniature
N	Rugged weather proofed connector for use with larger size cables.	DC - 11 GHz (version available to 18 GHz)	1.3	5/8 - 24 threads	Air	Medium
C	Weather proofed, quick disconnect connector for larger size cables.	DC - 10 GHz	1.35	Twist-lock	Teflon, overlap	Medium
SC	Threaded version of type C for aircraft and EW applications.	DC - 11 GHz	1.3	11/16 - 24 threads	Teflon, overlap	Medium

*Frequency range and SWR depends on style of connector, manufacturer, military specification, and is furnished as a guide only.

An interesting statistic is, "What are the most used coaxial connector types?" In 1985 based on shipments, the top seven coaxial connectors were SMA, BNC, N, UHF, TNC, SMC and SMB.

Precision Sexless Connectors

There are two precision sexless (hermaproditic) coaxial connectors in general use today in the United States, the 7mm (APC7) and 14mm (GR900, MPC14), see **Figure 1**. Both have 50 Ω impedance and primarily are intended for laboratory measurement applications.

These connectors employ the coplanar, butt-joint principle, in which the center and outer conductors are sexless. They also must meet these basic rules, the reference (mating) plane is electrically and me-

Figure 8: Large coaxial connectors for low loss and high power applications; 7/8 and 1-5/8 EIA rigid line connectors and LT female and male connectors, shown as part of adapter to 14mm.

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chanically the same, that is coplanar; air dielectric is used in the reference plane; all parts of the connectors are captivated to themselves; the coupling mechanism (center and outer conductors) must be detachable; and the butting electrical surfaces are protected by the coupling mechanism, in the case of 7mm, the threaded sleeve must be extended to accomplish this.

There are two types of connectors in each line size, the general precision connector (GPC) that has a self-contained dielectric support, in principle instrument grade, and the laboratory precision connector (LPC) that uses air dielectric only and provides high precision for maximum accuracy. The center conductor is supported by the mating GPC connector and typically is used on air lines and sliding loads, in principle metrology grade.

Table 2 provides the salient characteristics for these connectors. IEEE standard no. 287 provides complete information, including mechanical details for the coupling mechanisms.

The 14mm connector originally was developed in the early 1960s by the General Radio Company and known as GR900. It currently is being manufactured by Gilbert Engineering Company (G900) and Maury Microwave Corporation (MPC14). It has seen limited usage and primarily is used in military metrology and standard laboratory environments. It is probably the best coaxial connector ever built from a perfomance standpoint, that is, repeatability, low reflection and low insertion loss.

The 7mm connector was developed by Hewlett-Packard in the mid 1960s and opened the door for accurate measurements to 18 GHz. The design later was improved by Amphenol and became the APC7 connector. It is currently manufactured by Amphenol, M/A-Com and Maury[9]. It has seen wide usage and it is one of the most widely used instrumentation connectors in the U. S.

In the early 1970s, a 3.5mm sexless connector usable to 36 GHz was developed and marketed by Alford Manufacturing Company and American Microwave Industries (later acquired by Omni-Spectra). It was submitted to the IEC for standardization[12], however, it was not approved because of lack of support. This connector suffered the fate of being ahead of its time, a lack on test instrumentation in this frequency range and weak demand. It is currently not in use. An interesting perspective on the evolution of precision coaxial connectors has been reported previously[13, 14].

mm-Wave Coaxial Connectors

Frequencies from 18 to 220 GHz generally are referred to as the mm-wave region of the frequency spectrum and have up to recent years been the sole domain of waveguide transmission lines. This now is changing with the introduction of high frequency mm-wave coaxial connectors expanding into this frequency range. This is were the action is in coaxial connector technology today.

Coaxial transmission lines offer significant advantages over waveguides, including; broader frequency range (not band limited), and smaller size and weight

TABLE 2
Precision Sexless Connectors Per IEEE Standard No. 287

Nominal Line Size	Maximum Frequency	Maximum SWR		Actual Size	
		GPC	LPC	Center Conductor	Outer Conductor
14mm	8.5 GHz	1.001+0.001xF (GHz)	1.005+0.0002xF (GHz)	0.24425 (6.204mm)	0.5626 (14.288mm)
7mm	18 GHz	1.003+0.002xF (GHz)	1.001+0.001xF (GHz)	0.1197 (3.040mm)	0.2756 (7mm)

(allows denser, smaller and lighter packaging). The reason to expand into mm-wave frequencies primarily has been driven by electronic warfare (EW) and electronic countermeasure (ECM) military requirements, including radar surveillance, secure communications and smart munitions. However, there are a number of other applications, such as satellite communications and radiometry. Atmospheric absorption phenomena present unique opportunities at mm-wave frequencies.

Over the last decade, continuous development of mm-wave coaxial connectors ever pushing upward in frequency has been seen. There is now a 1mm connector proposed to go to 110 GHz. **Figure 9** shows various mm-wave coaxial connectors that are available at frequencies to 65 GHz (the 1mm connector is not yet commercially available).

The design of current mm-wave coaxial connectors began with the SMA connector. Its basic mechanical configuration has been the foundation of all mm-wave coaxial connectors that have followed regardless of size. The dielectrics have been removed and the coaxial dimensions have been changed to improve the integrity of the mechanical design. But fundamentally, it is the same basic SMA connector design.

Millimeter-wave coaxial connectors generally are described as sexed-thread coupled-coplanar-pin-and socket connectors and are available with either dielectric material or air at the reference plane. The mateability of these connectors is defined by the mechanical coupling dimensions of the interface not by the medium, that is, dielectric or air, at the reference plane, that is, SMA (dielectric) and 3.5mm (air) connectors mate.

The mm coaxial connectors described here have basically four mechanical coupling sizes:

- 1/4 - 36 thread coupling - SMA mateable (SMA, 3.5mm, 2.92mm will mate)
- 10 - 36 thread coupling - SSMA mateable
- M7 x 0.075 thread coupling (2.4mm and 1.85mm will mate)
- M4 x 0.7 thread coupling (1mm)

Figure 10 shows 3.5mm, 2.92mm, 2.4mm, 1.85mm and 1mm air interface connector dimensions. These interfaces currently are being considered for standardization by the IEEE P287 committee. SMA is shown in **Figure 4** and SSMA is shown in **Figure 5**.

A comprehensive listing of mm-wave coaxial connector manufacturers has been reported[9].

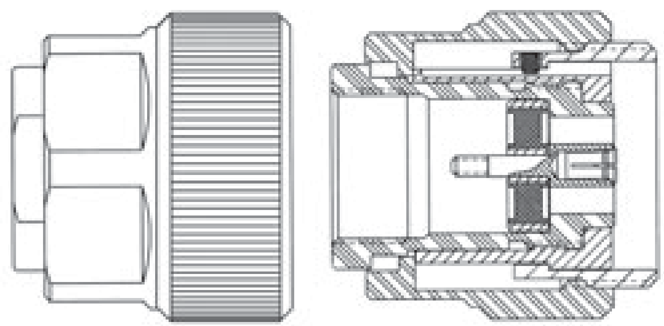

Figure 9: **Sexless 7mm connector GPC7 (APC7).**

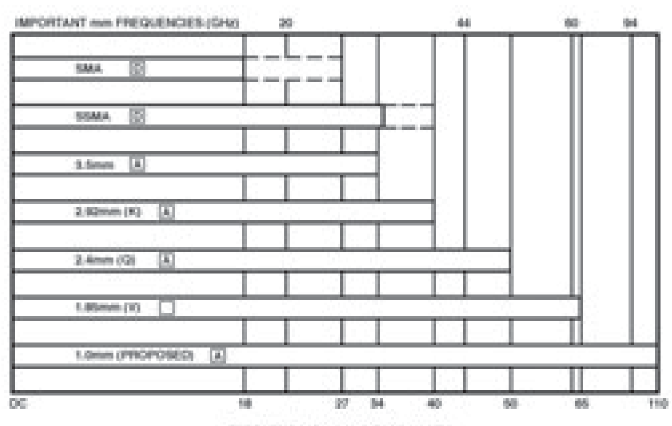

Figure 10: **Summary of mm-wave coaxial connectors vs. frequency.**

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History of mm-Wave Coaxial Connectors

The BRM/OSM/SMA connectors began the evolution in 1958 and were followed by the BRMM/OSSM/SSMA in 1960. These connectors extended the useful upper frequencies to 18 to 24 GHz and 26 to 34 GHz, respectively with mode-free operation.

In 1973, Maury Microwave Corporation, driven by Navy secure communications requirement, developed a new connector designated the model MPC2, with operating frequencies to 40 GHz. It was first reported at the 1974 Millimeter-Waves Techniques Conference sponsored by the Naval Electronics Laboratory Center (NELC) in San Diego[15] and later published in July 1975[16]. This was the first reported mode-free connector for use at frequencies to 40 GHz. However, it was not successful even though it was sold commercially for several years. Like the 3.5mm sexless connector, it was ahead of its time and did not mate with any connector then in existence. Because the connector did not mate with any connector then in existence, in 1974, Maury introduced a 2.92mm air interface connector that was SMA mateable and mode-free to 40 GHz. It was designated the model MPC3, shown in **Figure 11 (a)** on page 14. However, it was still ahead ot its time, which proves the point that without adequate instrumentation to utilize connector development, the connector will not succeed commercially. It did succeed years later when Wiltron re-introduced the 2.92mm interface as the K connector with the necessary instrumentation. Following the development of MPC2 and MPC3 connectors, Kelvin Microwave Corporation released an SSMA mateable air interface coaxial connector in 1975[17], designated KMC-SM, that also operated mode-free to frequencies of 40 GHz. This connector is currently being produced by Kevlin Microwave and Huber & Suhner and its interface is covered by IEC Standard 169-18.

The next major development was the 3.5mm connector developed at Hewlett-Packard in the mid 1970s and later marketed by Amphenol as the model APC3.5mm. The design was originated by Larry Renihan of the HP Stanford Park Division, reported on at the 1976 IEEE MTT-S International Microwave Symposium in San Francisco[18] and published in July 1976. The 3.5mm connector performed mode-free to 34 GHz, as shown in **Figure 11 (a)**[19]. It's an instrument grade connector that opened the way to improve microwave test instruments at frequencies to 26.5 GHz. It also satisfied an important need in creating a test connector for SMA devices[6]. The 3.5mm connector was successful because it was supported by a major instrument manufacturer and a qualify connector production house (a la APC7) and it satisfied a latent industry demand. The 3.5mm connector currently is produced by Amphenol, Maury and others[9]. It will be covered shortly by IEC standard 169-23.

In 1983, the 2.92mm connector reappeared and is now designated the K connector. Wiltron Company in conjunction with the development of a broadband automated scalar netowork analyzer system for measurements from 0.01 to 40 GHz introduced the K (2.92mm) connector in a paper at the 1983 IEEE MTT-S International Microwave Symposium in Boston[20] and later published the work[21]. The K connector development was led at Wiltron by Bill Oldfield and several improvements were made, including shortening the male pin to prevent connector damage and creating a novel microstrip launcher design[22]. The K connector is SMA mateable and has an air interface, as shown in **Figure 11 (a)**. The 2.92mm connector has been specified as being mode-free to 46 GHz, however, standardization efforts are limiting its upper frequency to 40 GHz. The K connector is currently available from Wiltron, ITT/Sealectron and Radiall[9].

The 2.4mm connector interface was conceived by Hewlett-Packard and jointly developed with Amphenol and M/A-Com Omni Spectra. It provides mode-free operation to 50 GHz and was introduced in early 1986[6], see **Figure 11 (b)**, for the 2.4mm air interface configuration.

The design of this connector was led by Julius Botka, Hewlett-Packard (Santa Rosa) and generated several new concepts. It satisfied the needs of all users by

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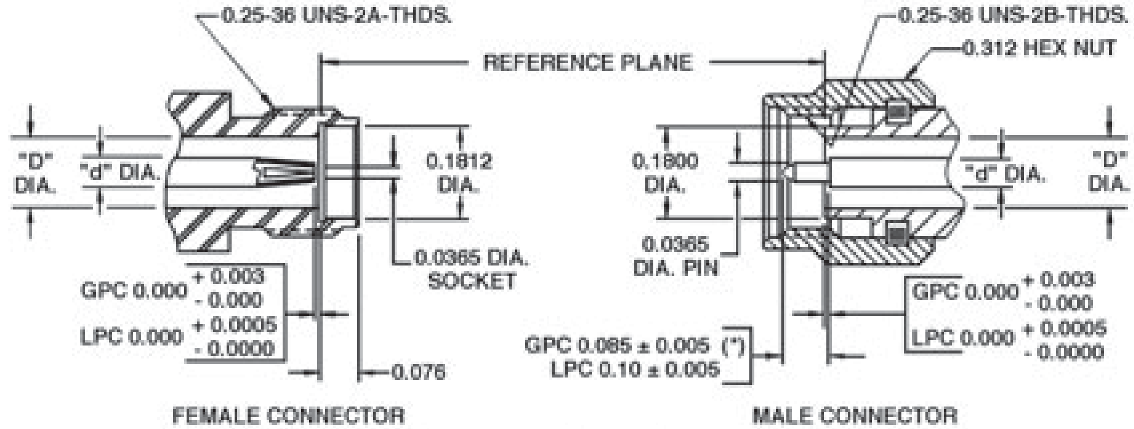
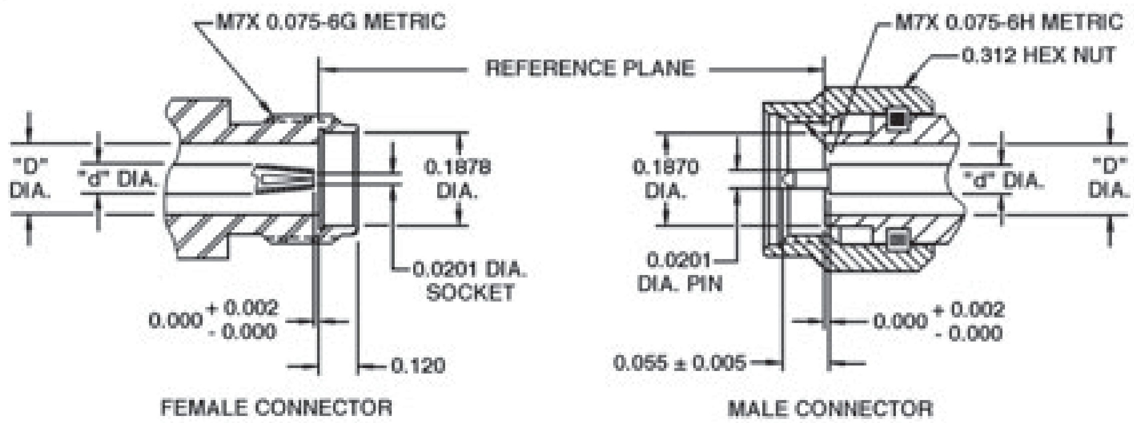


(a)

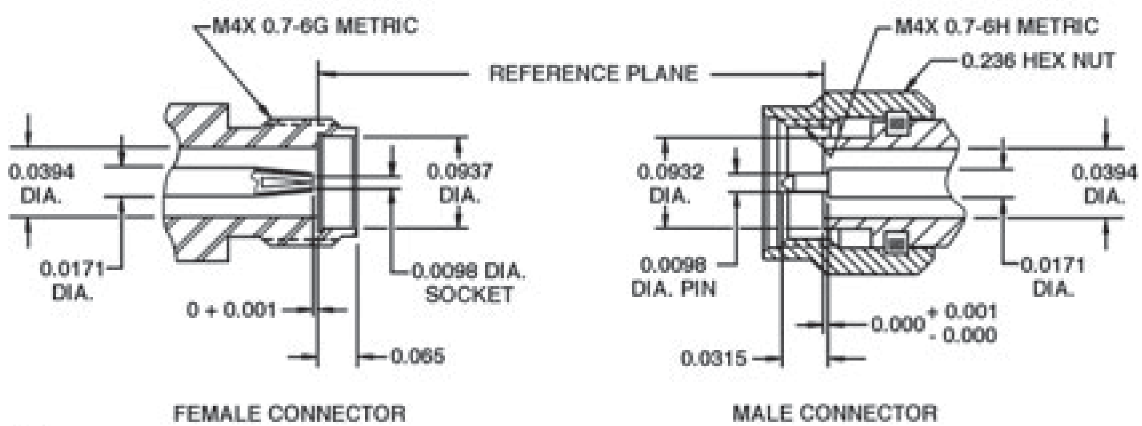
TYPE	MAX. FREQ.	REF.	d nom.	D. nom.
3.5mm	34 GHz	—	0.0598	0.1378
2.92mm	40 GHz	K	0.0500	0.115

(*) 0.063 ± 0.003 ALSO USED ON K



TYPE	MAX. FREQ.	REF.	d nom.	D nom.
2.4mm	50 GHz	Q	0.0410	0.0945
1.85mm	65 GHz	V	0.0316	0.0728

(b)



(c)

Figure 11: **mm-Wave coaxial connectors, pin and socket; (a) 3.5mm and 2.92mm connector interfaces; (b) 2.4mm and 1.85mm connector interfaces and (c) 1mm connector interface 110 GHz (maximum) frequency.**

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creating a family of connectors consisting of three grades, production (P); instrument (I); and metrology (M). It also created a totally new interface that eliminated the performance restraints of having to mate with an existing connector (like SMA) thereby allowing significant design improvements to be made. Also, HP and collaborators made provisions to extend the interface to 1.85mm in order to achieve the next jump in frequency. The 2.4mm connector is in process of standardization by the IEC, in addition to the IEEE P287 committee. The connector currently is being manufactured in P and I grades by Amphenol (APC2.4 and A050) and in P grade by M/A-Com (OS-50). The metrology grade is available only on calibration devices by Hewlett-Packard at present. Other manufacturers also are getting involved[9].

A 1.85mm connector, mode-free to 65 GHz, also originally was conceived by Hewlett-Packard as part of their 2.4mm connector strategy and was divulged by Julius Botka at the 1986 European Microwave Conference[24]. However, Wiltron was first to market this type of connector when the company released its 60 GHz vector network analyzer and the V (1.85mm) connector in early 1989[25]. The 1.85mm V connector mates with the 2.4mm connector, as shown in **Figure 11**. Currently the V connector is manufactured by Wiltron and Rosenberger. Several other companies have it under development[9].

A 1mm connector has been proposed by Hewlett-Packard useable to 110 GHz, as shown in **Figure 11 (c)**. This connector will push the limits of manufacturing capabilities in order to hold the required tolerances for acceptable microwave performance. The 1mm connector is not yet commercially available, although several manufacturers claim that it is under development in their plants[9].

High Frequency Coaxial Connectors

There is a variety of other high frequency connectors currently available. A microminiature size #6-40 threaded coupling connector, designated OSMM, operating to frequencies of 45 GHz is available from M/A-Com. Blind mate connectors also are moving higher in frequency. M/A-Com has several styles available, including OSP (22 GHz), OSSP (28 GHz) and OS-5OP (40 GHz). Kelvin Microwave also offers two blind mate configurations with a novel sexless center contact (the connector is still a sexed type) rated to 35 and 40 GHz (34). Lucas Weinschel also has produced several high frequency connectors that are SMA mateable with an interesting dielectric interface[35], designated WPM2 (26.5 GHz) and WPM4 (40 GHz).

Slotless Female Contact Connectors

Another major improvement in recent years has been the introduction of slotless female contacts for pin socket connectors.

Conventional female contacts (socket) have longitudinal slots that allow it to grasp the male pin upon insertion. The slots add a discontinuity that can't be totally compensated for plus the diameter over the slots is subject to tolerance accumulation that includes the variation in pin diameter.

A slotless female contact was developed by Julius Botka of Hewlett-Packard that solved this problem. It first was reported at the 1984 IEEE MTT-S International Microwave Symposium, in the paper, "High Frequency Coaxial Connectors – 40 GHz and Beyond"[28]. The paper was of considerable interest since a number of the attendees had been trying to accomplish this same objective for many years. A complete article was published in 1988[29] after the contact had been fully developed and a patent had been issued. **Figure 12** shows two configurations of the Botka slotless female contacts.

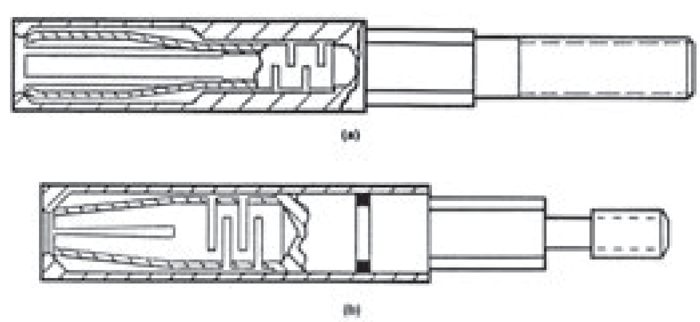

Figure 12: **Botka slotless female contacts; (a) type N and 3.5mm configuration with field replaceable inner contact and (b) 2.4mm version, inner contact is not field replaceable.**

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Slotless contacts of the Botka type have been designed for type N, 3.5mm and 2.4mm. Presently, they are only supplied in calibration standards using metrology grade connectors because of their relatively high cost. **Table 3** provides a comparison of slotted vs. slotless connectors that shows a marked improvement in repeatability, in addition, the reflection in a mated pair of connectors also is improved greatly. Slotless contacts have made a major improvement in measurement accuracy.

It is interesting to note that there has also been an evolution in slotless contacts. Weinschel Engineering originally introduced a slotless female contact in a type N connector configuration in 1965 and a patent[30] was issued in 1967. Wiltron used this same design under license from Weinschel to create a slotless contact for the WSMA (3.5mm size) female connector[31].

Connector Care

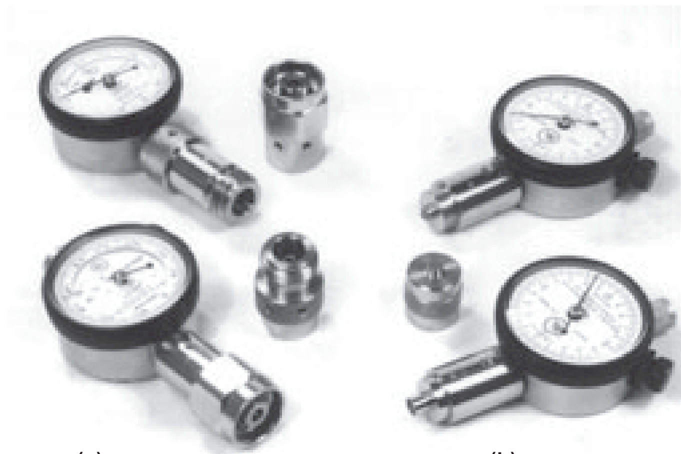
Coaxial connectors are the most likely to be mistreated part of a system. The most common causes of connector wear and damage are out of tolerance contacts; dirty mating surfaces; over-torquing; misalignment; and rotating during mating.

The most important aspect of a coaxial connector is its contact location. Protruding contacts beyond the specified tolerance can cause immediate damage to the mating connectors, while excessive recession may reduce electrical performance by causing high reflection. A connector gage should be used, as shown in **Figure 13**, to insure that connector center contacts meet their mechanical specifications. All connectors should be gauged after assembly and prior to making measurements.

The second most important aspect of connector care is torquing. Over-torquing and rotating connectors while mating accelerates connector wear and will damage mating connectors. **Table 4** presents recommended torque values. Additional information on connector care has been provided[32, 22].

TABLE 3
Connectors Repeatability Comparison

Connector Type/Frequency	Repeatability (dB)	
	Slotted Contact	Slotless Contact
Precision N @ 18 GHz	52	60
3.5mm @ 26.5 GHz	50	58
2.4mm @ 50 GHz	48	55



(a) (b)

Figure 13: **Connector gages; (a) type N — female and male thread-on connector gages and (b) 3.5mm female and male push-on connector gages.**

TABLE 4
Recommended Torque Values For Coaxial Connectors

Connector Type	Torque (in./lb.)
N	12
7mm	12
SMA	5
3.5mm	8
2.4mm	8

TABLE 5
Measurement Accuracy Possible With Current Vector Network Analyzers

Connector Type	Frequency Range (GHz)	Directivity (dB)	Source Match (dB)
N	0.04 - 18	42	32
7mm	0.04 - 18	52	42
3.5mm	0.04 - 26.5	44	34
2.92mm	0.04 - 40	40	34
2.4mm	0.04 - 40	38	33
1.85mm	0.04 - 60	36	29

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Coaxial Measurements

The ability to predict or control system performance depends strongly on the accuracy of individual component measurements. Small individual errors can add up and become large system errors. The accuracy depends on the choice of connectors, both from a production and test standpoint.

The new generation of vector network analyzers (VNAs) has focused on the connector as one of the potential limitations to measurment accuracy. The inherent resolution, dynamic range and accuracy of current VNAs, such as the HP8510B and Wiltron 360, meet most measurement requirements today. In addition, the high speed and resolution allows measurements to be made that were previously impractical, and has led to improvements in connector hardware.

Table 5 lists the measurement accuracy possible when different connectors are used with a VNA. The most important part of a good measurement is to have a well-defined reference plane that never changes. It should be consistent during calibration, measurement and application. To achieve this, the connectors should meet the general requirements, including rugged, stable test port adapters should be used[34], unlike connectors on a production device, the test port connectors must maintain the same performance for many connect and disconnect cycles; connectors used on calibration or verification standards must be stable and compare with well defined interface standards, calibration standards can be made from either instrument or metrology grade connectors depending on the degree of accuracy required[35]; and interface condition should be reproducible during the calibration, measurement, and use of the device under test (DUT).

The degree to which these three requirements are met limits the measurement accuracy. In practice these requirements cannot always be met simultaneously, so a compromise is needed. For example, the best measurements of SMA connector devices are accomplished using 3.5mm test ports and calibration standards[6]. 3.5mm connectors are much better than SMA for first and second requirements, but the air dielectric interface violates the third requirement.

Measuring Connector Repeatability

Connector repeatability is a measure of how well a connector junction will be reproduced after being disconnected and reconnected a number of times. Good repeatability is very important for good measurements.

Measuring connector repeatability is a good way to test (or learn) the techniques of making good connections. The best way to measure repeatability is by using a vector network analyzer, such as the HP8510B, so that both magnitude and phase changes can be seen from one connection to the next. The procedure is as follows:

- Calibrate the VNA for a one-port measurement.
- Connect a matched load to the calibrated port and take a frequency sweep of S_{11}; when finished, save this data in memory.
- Disconnect the matched load, then reconnect itagain; take another sweep of S_{11}.
- Find the magnitude of the complex difference between this latest data and the reference data saved in memory; this is the repeatability of S_{11} for that one reconnection; it may be left in format, but more often is converted to dB with the equation,

Repeatability (dB) =

$$20 \log_{10} (\text{magnitude of complex difference})$$

this conversion is done on the HP8510B VNA by selecting Log Mag format.

- Plot the repeatability vs. frequency; the first time, plot the entire rectangular chart, on subsequent sweeps, plot only the new trace.
- Repeat steps 3 to five at least 12 times, plotting the new value of repeatability onto the same graph each time.
- Trace a single curve along the top of the envelope of plotted data; this is the worst case repeatability measured.

However, this is a much better approximation than trying to make test ports and standards in SMA. The thin SMA outer conductor wall will wear too quickly to be an effective test port, and the dielectric interface makes it impractical for accurate calibration standards that can be mechanically characterized, that is, sliding load or air lines.

It is important never to use coplanar compensation at the connector measurement plane, that is, the test port connector in order to compensate for a mating connector. This would create erroneous results. Coplanar compensation at the reference plane also would prevent effective interface error correction modeling to be performed[6, 7].

Before any measurements are made, stable test port adapters should be set up[34]. Without good test ports, meaningless data may be taken. The main characteristics of good test port adapters are stability, ruggedness, good long term repeatability, ease of replacementand economy. Some typical test port adapters are shown in **Figure 14**.

Figure 14: Test port adapters that mate with HP8510 and Wiltron 360 network analyzers; 3.5mm-female, TNC-female, N-male and 7mm sexless shown.

The technique of making connections is also very important. The best way to learn and to evaluate a good technique is by making connector repeatability measurements. Measurement of verification standards right after calibration will provide a check on overall measurement accuracy[34]. Measurement instrumentation has been related closely to the development and commercial acceptance of coaxial connectors. In many cases, the instrument manufacturers have led the development efforts of new connectors. For example, the 14mm connector came from General Radio, the 7mm, 3.5mm, and 2.4mm connectors came from Hewlett-Packard, and the K and V connectors were made popular by Wiltron.

Connector Standardization

One of the most difficult tasks in dealing with connectors is the process of standardization[36]. Standardization is important in maintaining compatibility between different manufacturers' products. The 3.5mm pin socket connectors have been in use since 1976, yet a formal standard still does not yet exist. However, there is good news; IEC standard 169-23 is expected to be published shortly and will cover 3.5mm connectors.

In lieu of formal published standards, connector manufacturers should publish interface and performance specifications for the connectros they produce. Many quality connector manufacturers and instrument makers publish their own connector standards.

The primary connector standard in the United States is military specification MIL-C-39012 (connectors, coaxial, radio frequency, general specification for) that is generated by the Department of Defense through the Defense Electronics Supply Center (DESC), Dayton, Ohio. This specification consists of not only the main publication, but also of over 130 individual specification sheets, more commonly known as "slash" sheets, plus amendments and supplements.

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Another major specification in the U. S. is military specification MIL-T-81490 (transmission lines, transverse electromagnetic mode). This specification covers N, TNC and SC connectors for electronic warfare applications and these connectors are generally referred to as EWN, EWTNC and EWSC.

Another important standard, standards publication no. 287, is published by the Institute of Electrical and Electronic Engineers (IEEE). This standard covers general requirements and test methods for precision coaxial connectors and was published in 1968. Detailed performance and interface information is provided for 14mm and 7mm sexless connectors.

On an international level, the International Electrotechnical Commission (IEC), headquartered in Geneva, Switzerland, is the organization responsible for standardization in the electrical and electronics fields. The IEC works through national committees to develop their standards. The IEC subcommittee responsible for coaxial connectors, is the SC46D connectors for RF cables subcommittee, which is headed by Norb Sladek, Allied-Amphenol Products, Danbury, Connecticut. Under this subcommittee is the United States National Committee (USNC) headed by a technical advisor and comprised of 22 members. The current technical advisor is Ramon Jesch, consultant for the National Institute of Standards and Technology, Boulder, Colorado.

The two primary IEC standards on coaxial connectors are the IEC Standard Publication 169 and IEC Standard Publication 457. The IEC Standard Publication 169 covers radio frequency connectors, including the SMA, SMB, SMC, BNC, TNC, N and UHF. The IEC Standard Publication 457 covers a rigid precision coaxial transmission lines and their associated precision connectors, including the 3.5mm, 7mm, 14mm and 21mm rigid transmission lines and hermaphroditic connectors.

These IEC publications consist of multiple parts that have to be ordered separately. Additional information on the process of standardization in the IEC and a listing of published connectors and standards under consideration has been provided[37].

Obtaining Connector Standards

Military specifications and standards can be ordered from Standardization Document Order Desk, 700 Robbins Avenue, Building #4, Section D, Philadelphia, PA 19111-5094. IEEE standards can be ordered from IEEE service center, 445 Hoes Lane, Piscataway, NJ 08855-1331 (908) 981-0060. IEC standards can be ordered from American National Standards Institute Inc., 1430 Broadway, New York, NY 10018 (212) 354-3361.

What's Next?

The evolution of coaxial connectors made significant strides during the 1980s that included implementation of the K (2.92mm), 2.4mm and V (1.85mm) connectors and pushed the upper frequency of coaxial connectors to 60 GHz.

What will the 1990s have in store? I believe that there will be a consolidation and refinement period during which the connectors and capability that have been generated in the past decade will be utilized. During this time, cable technology may advance to produce low loss cables operating at mm-wave frequencies.

Other technologies will eventually impact microwave coaxial connectors, such as fiber optics and connectorless systems. Also the military market may diminish and some of the driving forces will not be there.

I am still bullish on coaxial connectors. I believe that advancements will continue in the 1mm connector, raising the operation frequency of coaxial connectors to 110 GHz. There also may be a return to the development of precision sexless connectors, probably in the 3.5mm and 2.4mm sizes, since test equipment is not a limitation. The evolution will continue!

Acknowledgment

This article is based on the efforts of many people who have contributed to microwave coaxial connector technology. Many of them are my colleagues. Over the years, we have had many discussions or heated debates; after all, aren't connectors a highly controversial issue? In recent years, Julius Botka and Bill Oldfield have made major contributions to high frequency connectors. Norb Sladek, Ramon Jesch and Tore Anderson have been major factors in connector standardization. The pioneering efforts of Bruno Weinschel, Andrew Alford, the C83.2 and original IEEE P287 committees. Also Harmon Banning, John Zorzy, Christian Staeger (Swiss PT) and to many others whom I apologize to for not mentioning them, they have all contributed to the evolution in connector design.

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Author

Mario A. Maury, Jr.

Maury Microwave Corporation
Ontario, California

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