Most important factors affecting radio frequency characteristics of microwave cable assemblies

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Abstract. The evolution of satellite communications systems results in more stringent on-board and ground equipment specifications for gain/temperature, performance variations, impedance matching quality. The use of cable assemblies capable to meet the increased requirements is essential for signal transmission between the units without any performance degradation. Taking into account the variety of microwave cables and connectors it is necessary to establish the selection criteria for parts and techniques of manufacturing microwave cable assemblies for satellite communications systems. This paper contains the analysis of the technological aspects of cable assemblies manufacturing which impact the radio frequency characteristics of end items.

Taking into account the existing variety of microwave RF connectors and cables it is necessary to distinguish the definitions of “cable” and “cable assembly” in order to avoid the ambiguity when selecting the components of a communications system. A cable is a product based on per-unit-length parameters which can be equipped with different kinds of connectors and external shields. A cable assembly should be interpreted as an end item comprising a cable of the required length as well as connectors and reinforcement of the required type. Therefore, the parameters of a cable assembly are bound to depend on the applicable parts (cables, connectors) and on the assembly techniques.

From the perspective of radio wave propagation a microwave cable assembly is a coaxial transmission line with the characteristic impedance:

$$Z = \frac{138\Omega}{\sqrt{\varepsilon_r}} \log \frac{D}{d},$$

where: $\varepsilon_r$ – relative permittivity of dielectric (dielectric constant);
$D$ – inner diameter of cable braid (connector housing);
$d$ – diameter of cable center conductor (connector).

The most widespread products are cables and cable assemblies with the characteristic impedance $Z=50\Omega$ which is common for radio technical systems and $Z=75\Omega$ which is used for broadcasting.
That’s precisely the characteristic impedance which defines one of the two key parameters crucial for the use of the cable assembly – the return losses $S_{11}$, $S_{22}$. In the field of engineering the return losses are generally represented as the voltage standing wave ratio (VSWR) for convenience:

$$\text{VSWR} = \frac{1+10^{\frac{S_{11}}{10}}}{1-10^{\frac{S_{11}}{20}}}$$  \hspace{1cm} (2)

where: $S_{11}$ – return losses, dB.

Taking into account the representation of a dipole S-parameters and Equation (2) it is obvious that ideally there should be no return losses, i.e. $S_{11} \rightarrow -\infty$, VSWR=1, which is not feasible in practice [1].

Apart from the mismatching induced by the design imperfection of cables and cable assemblies there is also a contribution of losses in the cable. The contribution of the losses in mismatching is obvious if the characteristic impedance of the cable is represented by the per-unit-length electrical characteristics:

$$Z = \frac{l}{c}$$  \hspace{1cm} (3)

$$Z_{\text{lossy}} = \left(\frac{r+j\omega l}{g+j\omega c}\right)^{\frac{1}{2}}$$  \hspace{1cm} (4)

$$Z_{\text{lossy}} = \left(\frac{r+j\omega l}{j\omega c}\right)^{\frac{1}{2}}$$  \hspace{1cm} (5)

where: $l$ – inductance per unit length (H/m); $c$ – capacitance per unit length (F/m); $r$ – resistance per unit length (Ohm/m); $g$ – conductance per unit length (S/m); $Z$ – characteristic impedance for ideal case (excluding losses); $Z_{\text{lossy}}$ – characteristic impedance including losses.

Ideally $Z$ is defined only by per-unit-length capacitance and inductance (3). In reality the characteristic impedance depends on parameters $g$ and $r$ (4). In engineering calculations for a coaxial cable $g$ [2] can be neglected and $Z_{\text{lossy}}$ will be expressed by Equation (5).

Since the cable and the connector as parts of a cable assembly are both the components of the transmission line, the contribution in mismatching will be inevitably seen at the connector mounting places [3, 4] (figure 1).

![Figure 1](image)

**Figure 1.** Cross-section view of coaxial cable connection with SMA connectors (at the top) and the curve of characteristic impedance variation along the cable length (at the bottom).

The contribution in mismatching due to the losses (5) and the imperfect ratio of diameters (1) will be seen even if other conditions given below are ideal:
all components of a cable assembly are ideal bodies of revolution;
no variation of dielectric constant along the cable length;
no air-filled sections due to the connector design.

All the above conditions are not feasible in practice. If the requirements for matching and variations are high (~VSWR=1.25 and variation of ~0.1 dB), those effects must be taken into account. Any deviations from the ideal scenario will generate the reflected wave propagating in the direction which is opposite to the incident wave and having the opposite phase (figure 2).

Figure 2. Reflections caused by the defects of cables and connectors:
1 – mounting of the 1st connector; 2 – nonuniformity of $\varepsilon_r$;
3 – local deformation of the cable; 4 – mounting of the 2nd connector.

According to figure 2 $\varepsilon_{r1} < \varepsilon_{r2}$, i.e. there is a change in dielectric density resulting in nonuniformities.

With regard to radio technical characteristics the effects of the reflections inducing the nonuniformities show up as local VSWR peaks and gain flatness. Figure 3 shows the results of VSWR measurement and gain measurement of the cable assembly with N connector. The measurement results contain the section with $Z \neq 50$ Ohm.

Figure 3. Effects of nonuniformities on radio technical characteristics of a cable assembly:
a) cable assembly with N connectors; b) cable assembly with SMA connectors.
As shown in figure 3 the significant nonuniformities result in simultaneous local degradation of VSWR and S21 [5]. It might seem that S21 dips are due to the increased reflections at those frequencies but it is not the case, and this can easily be proven by the backward Equation (2).

The most common dielectric materials applicable for existing microwave cables are given in Table 1.

| Designation | Material type      | $\varepsilon_r$ units |
|-------------|--------------------|-----------------------|
| PE          | polyethylene       | 2.28                  |
| PEF         | polyethylene foam  | 1.5                   |
| PTFE        | fluoroplastic      | 2.05                  |

The second key parameter of a cable assembly is the insertion losses. All manufacturers of cable assemblies seek to minimize the insertion losses since it is an obvious way to increase the gain/temperature and efficiency. Insertion losses are defined by the following equations:

$$\alpha = 10 \cdot \log \frac{P_{\text{out}}}{P_{\text{in}}} = (\alpha_c + \alpha_d) \cdot l + \alpha_{p1} + \alpha_{p2}$$

(6)

$$\alpha_c = \frac{11.39}{Z} \cdot \sqrt{F} \cdot \left( \frac{\rho_{rd}}{d} + \frac{\rho_{D}}{D} \right)$$

(7)

$$\alpha_d = 90.96 \cdot F \cdot \sqrt{\varepsilon_r} \cdot \tan \delta$$

(8)

where: $a$ – total insertion losses, dB;
$
\alpha_c$ – losses in cable conductors, dB/m;
$
\alpha_d$ – losses in dielectric, dB/m;
$
\alpha_{p1}$ – losses in connector №1, dB;
$
\alpha_{p2}$ – losses in connector №2, dB;
$
\rho_{rd}$ – center conductor resistivity, Ohm-mm$^2$/m;
$
\rho_{D}$ – conductor resistivity of cable shielding, Ohm-mm$^2$/m;
$\varepsilon_r$ – dielectric constant;
$tan \delta$ – dielectric loss tangent;
$P_m$ – input power (at the input of cable assembly), W;
$P_{out}$ – output power (at the output of cable assembly), W;
$l$ – length of cable assembly, m.

As it follows from Equation (6) if a cable assembly is not a jumper, $\alpha_{p1}, \alpha_{p2}$ are not significant contributors (for 2.92 mm connectors $\alpha_{p1,2} \leq 0.1$ dB at frequencies up to 26.5 GHz). Equations (7) and (8) show that the only efficient way for a manufacturer of cable assemblies to reduce the losses is the decrease of the loss tangent $tan \delta$. Since the loss tangent $tan \delta$ is a function of $\varepsilon_r$, it seems appropriate to use the cables with PEF dielectric (see Table 1), but this is not quite correct. The melting point of polyethylene foam is 102 °C, it makes the soldering of connectors very difficult and often results in nonuniformities (figure 2) due to the overheating.

As follows from Equations (7) and (8) the manufacturers of cable assemblies should seek to minimize $tan \delta$ and $\varepsilon_r$. However this calculation should not be used as it is, given the fact that most of the microwave cables (foreign and domestic) use as a dielectric some forms of fluoroplastic-4 (PTFE). For this group of materials the loss tangent $tan \delta$ varies from 0.0001 to 0.0004 and increases together with the frequency, therefore the effective value of $tan \delta$ should be based on the measurements performed at the cable operating frequencies. The parameters of a cable applicable in satellite communications systems (table 2) can serve as an example.
If data from Table 2 are used to calculate $a$ according to Equations (6)–(8), e.g. for frequency 26.5 GHz, the result will be better than the value specified by the manufacturer. This is due to the effective value of $\tan \delta$ at the frequency 26.5 GHz which is difficult to predict by calculation.

The design of a cable assembly which shall be used in high power channels (e.g. output section of a repeater) shall take into account not only the insertion losses and VSWR but also the frequency-related limitation of the maximum transmitted power (figure 4).[6,7,8]

**Table 2.** Example of cable specified parameters.

| Insertion losses, dB/m vs frequency | 4.0 GHz | 1.05 |
|------------------------------------|---------|------|
|                                    | 8.0 GHz | 1.54 |
| Dielectric outer diatmeter, mm      | 12.4 GHz| 1.96 |
| Dielectric material                | 18.0 GHz| 2.45 |
| Dielectric constant $\varepsilon_r$| 26.5 GHz| 2.98 |
| Center conductor material          | 40.0 GHz| 3.48 |

**Figure 4.** Typical plots of insertion losses (attenuation) and maximum transmitted power versus frequency.

The correlations shown in figure 4 are easy to explain given the fact that the power dissipated in the cable assembly transforms in the heat and heats up the cable and its connectors.

The selection of a connector type is as important as the selection of a cable type. The most common types of connectors used in the existing satellite communications systems are given in table 3.

**Table 3.** The most common threaded connectors.

| Connectors                     | Thread type | Recommended torque, N*cm | Upper frequency, GHz |
|--------------------------------|-------------|--------------------------|----------------------|
| 1mm (APC-1.0, RPC-1.0, W)      | M7x0.75     | 45                       | 110                  |
| 1.85mm (APC-1.85, V, OS-65)    | M7x0.75     | 90                       | 70                   |
2.4mm (APC-2.4, OS-50) M7x0.75 90 50
2.92 mm (K, SK, OS-2.9 and others) 0.250-36-UNS 90 40
SSMA
3.5mm (APC-3.5, PC3.5) 0.250-36-UNS 70 40
SMA
0.250-36-UNS 90 26.5
(non-hermetic connectors), 100 18/26.5
(hermetic connectors)
SMC
0.190-32-NF 35 10
TNC
7/16-28 UNEF 56 10
N, UHF, APC-7 0.625-24 UNEF 135 10

Some design features of main types of connectors should be mentioned [9]. 2.92mm and 3.5mm connectors are mechanically compatible and their mating is acceptable [2], but mating of 3.5mm male with 2.92mm female could result in damaging female connector pins. The same is true for 1.85mm and 2.4mm connectors. Therefore if the cable assembly under construction provides for several options of connection, it makes sense to opt for 2.92mm connectors. TNC connectors are mostly used in the output section of the repeater equipment (where the high power transmission is required).

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