

Article

Characterization of Electromagnetic Wave Propagation on Coaxial Cables

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Abstract: This research work is about the propagation of electromagnetic waves on coaxial cables such that its resistive losses are minimized, and signal quality is improved. The resistive loss of a coaxial cable is caused by several things; impedance of the conductor, and the type of dielectric material used and the skin effect and causes the signal to be attenuated. In this research, various comparison was made on different coaxial cables in other to test their resistivity per length of the conductor and measure the losses per meter of the coaxial cables. The various properties of the conductor, the impedance, capacitance, and the velocity of propagations was taken into consideration. Measurements were carried out to derive our data, and MATLAB was used in analyzing the results and the behaviour of the LMR series, RG8, RG6A, Davis RF, and CQ110 coaxial cables. Based on the findings, it is concluded that for a better and improved signal quality and to reduce resistive losses in coaxial cables, the characteristic impedance of the cable should be 80 ohms as this will reduce the coaxial cable resistive losses.

How to cite this paper:

Elechi, P., & Obeta, O. (2022). Characterization of Electromagnetic Wave Propagation on Coaxial Cables. *World Journal of Electrical and Electronic Engineering*, 2(1), 11-24. Retrieved from <https://www.scipublications.com/journal/index.php/wjee/article/view/282>

Received: April 27, 2022**Accepted:** June 7, 2022**Published:** June 9, 2022

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Keywords: Coaxial cable, Attenuation, Propagation, Resistive loss, Electromagnetic

1. Introduction

A big advancement has been made over time in the transmission of radio frequencies, microwaves, and millimetre waves. However, despite the emergence of the fibre optics cables for big bandwidth and very rapid transmission of data, the coaxial cable has performed a great role in telecommunication and remains part of the industry. The coaxial cable is a kind of low loss transmission line that transports electric signals of very large frequencies [1]. The coaxial cable transmission line is utilized in cell phone trunk lines, wideband internet networking, Global system of mobile communications (GSM), cable TV etc. The coaxial cable has an internal conductor enclosed by a dielectric insulator. Above the dielectric material is a conducting shield that is concentric. Spread over this shield is an outer insulating sheath which protects it. The term coaxial pertains to the inside conductor and the outer shield having a geometric axis. [Figure 1](#) shows a coaxial cable.

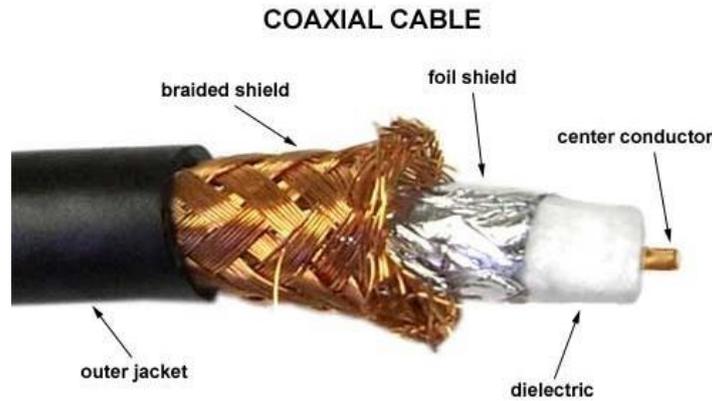


Figure 1. Coaxial Cable [2]

The concept of electromagnetic waves arose in the nineteenth century because of the rapid evolution of electrodynamics, and it has become as a unique type of electromagnetic field. Hans Cristian Oersted (1777-1851), a Danish physicist in conjunction with the Michael Faraday (1791-1867), an English physicist, at the start of the nineteenth century, came up with the concept of the indivisibility of the magnetic and electric fields. James Clerk Maxwell (1831- 1879), an English scientist expounded in 1846 the basics of magnetic and electrical phenomena in its entirety, and also produced a full thesis of the electromagnetic field. He exhibited mathematically the concept of the electromagnetic field in the form later referred to as the Maxwell's equations. [3]. These equations may be expressed in phrases in the following sentences: The field force lines of electric fields begin and ends in electric charges. The field force lines of the magnetic field are closed curves. Varying magnetic fields produce electric fields, while varying electric fields and chagnour. Hertz in his experiment was able to transmit electrical charge from one cable to another which were a few meters away from one another. [3].

Electromagnetic waves are oscillating electric and magnetic fields which propagate in free space at the speed of light (c) which is approximately 300,000,000 m/s. The electric and magnetic fields are oriented at right angles to each other. Energy is carried through space by electromagnetic waves, and their wavelengths vary, with each wavelength corresponding to a different kind of wave. The different types of the waves on the electromagnetic spectrum have different kinds of waves which move from longest to shortest wavelength and include radio, microwave, infrared, visible light, ultraviolet, X-Rays, and Gamma rays. Its wavelength is inversely proportional to its, frequency. Equation (1) illustrates this mathematically:

$$f = \frac{3 \times 10^8}{\lambda} \tag{1}$$

Where: λ is wavelength in meters, f is frequency in Megahertz.

The energy of the wave increases with increase in frequency and is shown in Equation (2).

$$E = hf \tag{2}$$

Where: E is energy of wave, f is the frequency and h is the Planck's constant.

Electromagnetic waves find wide use in many applications. For communication, Radio waves are used. Microwaves are used in heating and cooking food using the microwave oven. They are used also for communications, to extend the TV signals range to greater distances. Used in remote controls are Infrared and for night vision cameras which are heat-sensitive among many numerous applications. Ultraviolet (UV) waves are

very useful in destroying viruses, bacteria, and moulds in water, the air, and on surfaces. Used in imaging are X Rays, while Gamma rays are used to treat cancers and for geological applications.

A transmission line is a system of conductors, such as coaxial cables, waveguides, or wires that conduct electric power or signals efficiently between two terminals or more.” [4].

2. The Transmission Line

A transmission line is a cable or other structure specially designed to conduct electromagnetic waves between two or more terminals. When the conductors are long enough, it is called a transmission line and the wave nature of the transmission must be considered. A transmission line applies to a large range of power levels, frequencies, lengths of line, and construction modes.

The Telegraph was the earliest device that used transmission lines. It was built of mechanical parts, required little power to work, and its frequency spectrum was less than 100Hz. The first public message was sent in 1844 By Morse. Currently, there are several devices that use transmission lines. Many of these are more complex, requires wider frequency band, and have higher quality of sending and receiving end instruments.

In 1918 carrier frequency transmission was commercially introduced. This resulted in a great increase in the rate that any transmission line handles messages. In carrier frequency transmission, a sinusoidal wave of higher frequency is combined with a signal through the process of modulation. As a result, a band of frequencies that is close to the carrier is transmitted. At the receiving end through the process of demodulation, the signal is recovered.

The basic transmission line consists of two parallel conductors. These include the open wire line made up of two identical wires with air as the surrounding medium and a spacing of about 75 times the diameter of the conductor; the cabled pair having two twisted identical wires with solid insulation and a centre to centre spacing of twice the diameter of the conductor and encased; and the coaxial cable (Figure 2).

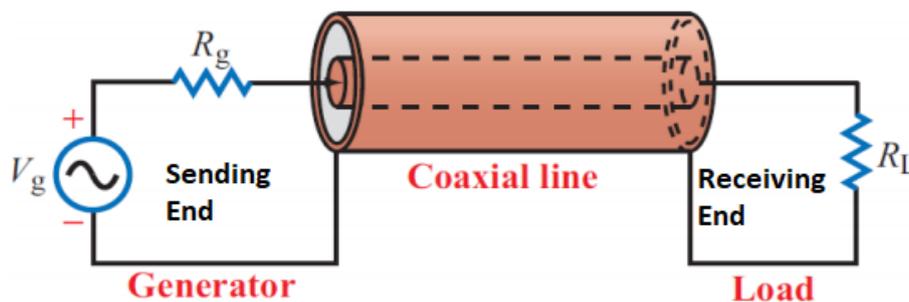


Figure 2. The Basic Coaxial Transmission Line [5]

To explain the signal on any line using Electric field intensity (E) and Magnetic field intensity (H) requires that the field distributions of E and H in transverse plane should be explained. The circuit state at any position can be fully explained using the current and voltage flowing in the circuit along a quasi-TEM (Transverse Electromagnetic) or TEM line [6]. This approximation should be understood and an awareness of the situations where it breaks down should be known. Transmission line models can be developed once the transmission line issues have been reduced to its resistance (R), Capacitance (C), Inductance (L), current, and voltage. Several models for transmission line are in use depending on the frequency of operation and accuracy needed.

Figure 3 can be used as a model for a segment of transmission line that is uniform, with steady cross-section along its length, regardless of the actual structure. The main

constants of this transmission line are “R = resistance/unit length; L = inductance/unit length; C = capacitance/unit length; and G = conductance/unit length” [7]. A good approximation which is useful is the lossless concept. However, when the resistance is large for example in the narrow on-chip interconnections, the lossless approximation is not valid.

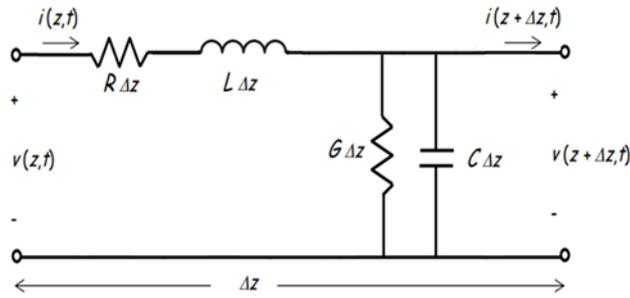


Figure 3. Lumped-Element Model of a Transmission Line [8].

When Kirchhoff’s laws applied to Figure 3 and the limit as $\Delta z \rightarrow 0$ is taken, the Equations of the transmission line are obtained.

$$\frac{dV(z)}{dz} = -(R + j\omega L)I(z) \tag{3}$$

$$\frac{dI(z)}{dz} = -(G + j\omega C)V(z) \tag{4}$$

These Equations (3) and (4) are referred to as the Telegrapher’s Equations. Solving further, the Characteristic impedance (Z_0) is obtained as:

$$Z_0 = \frac{V_0^+}{I_0^+} = \frac{-V_0^-}{I_0^-} = \frac{R + j\omega L}{\gamma} = \sqrt{\frac{(R + j\omega L)}{(G + j\omega C)}} \tag{5}$$

3. Properties of a Coaxial Cable

Coaxial cables have many characteristics or properties. These include Resistance of the Coaxial Cable, Resistance Per Unit Length, Coaxial cable capacitance, Inductance, Characteristic Impedance, Cutoff frequency, Velocity of Propagation, Skin Effect, and Attenuation. Several of these properties are calculated using the inner and outer conductor diameters illustration of a coaxial cable in Figure 4.

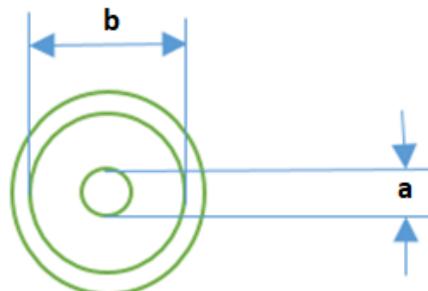


Figure 4. Diameter and Lengths Illustration of a Coaxial Cable

The coaxial cable has a shunt capacitance because of the space between inner and outer conductor of the cable. This capacitance per unit length C' in Farads per meter (F/m) is defined as [9,10]:

$$C' = \frac{2\pi\epsilon_0\epsilon_r}{\ln\left(\frac{b}{a}\right)} \tag{6}$$

As a result of the magnetic field that exists around the inner conductor as electromagnetic waves are propagated, the coaxial cable contains some inductance. The inductance per unit length L' (Henries per meter (H/m)) [9,10] is:

$$L' = \frac{\mu_0}{2\pi} \ln\left(\frac{b}{a}\right) \tag{7}$$

For a lossy coaxial cable, the characteristics impedance is defined by Equation 5 as:

$$Z_0 = \sqrt{\frac{(R' + j\omega L')}{(G' + j\omega C')}}$$

When the cable is lossless, line resistance ($R' = 0$) dielectric loss ($G' = 0$), this Equation becomes [6,10]:

$$Z_0 = \sqrt{\frac{L'}{C'}} \tag{8}$$

Substituting the values of C' and L' in Equations 6 and 7 we have:

$$Z_0 = \sqrt{\frac{L'}{C'}} = \sqrt{\frac{\frac{1}{2\pi\epsilon_0 c^2} \ln\left(\frac{b}{a}\right)}{\frac{2\pi\epsilon_0\epsilon_r}{\ln\left(\frac{b}{a}\right)}}} = \frac{\ln\left(\frac{b}{a}\right)}{2\pi\epsilon_0 C \sqrt{\epsilon_r}}$$

But

$$\epsilon_0 = \frac{1}{c^2 \mu_0} \tag{9}$$

Substituting we have:

$$Z_0 = \frac{c^2 \mu_0 * \ln\left(\frac{b}{a}\right)}{2\pi C \sqrt{\epsilon_r}} = \frac{4\pi * 10^{-7} * 299,792,458 * \ln\left(\frac{b}{a}\right)}{2\pi \sqrt{\epsilon_r}}$$

$$Z_0 = \frac{138.06 \log_{10} \left(\frac{b}{a} \right)}{\sqrt{\epsilon_r}} \approx \frac{138 \log_{10} \left(\frac{b}{a} \right)}{\sqrt{\epsilon_r}} \quad (10)$$

Where: $\epsilon_0 \approx 8.854187817620 \times 10^{-12} (F/m)$ is the permittivity of vacuum,

ϵ_r = relative permittivity of the dielectric,

$c = 299,792,458 (m/s)$ is the speed of light

b = outer diameter, and a = inner diameter of the coaxial cable.

$\mu_0 = 4\pi * 10^{-7} (H/m)$ is the permeability of vacuum or free space permeability.

$\ln(x) = 2.30259 \log_{10}(x)$

The expression for attenuation in a coaxial cable [11] is below:

$$\text{Resistivity Loss} = \frac{0.433}{Z_0} \left(\frac{\sqrt{\frac{P_d}{\rho c}}}{d} + \frac{\sqrt{\frac{P_D}{\rho c}}}{D} \right) \sqrt{f} \quad (11)$$

$$\text{Dielectric Loss} = 2.744 (Fp\sqrt{\epsilon_r}) f \quad (12)$$

The general Equation for attenuation loss in Coaxial cables is the combination of the Resistivity loss and the dielectric loss which is equation (13).

$$\alpha = \frac{0.433}{z_0} \left(\frac{\sqrt{\frac{p_d}{p_c}}}{d} + \frac{\sqrt{\frac{p_D}{p_c}}}{D} \right) \sqrt{f} + 2.774 (f_p \sqrt{\epsilon_r}) f \quad (13)$$

Where: D = diameter of the outer conductor

d = Diameter of the inner conductor

f = frequency

f_p = power factor of the dielectric

Z_0 = the impedance of the conductor

The resistivity of the centre of conductor material relative to copper $\frac{p_d}{p_c}$ and $\frac{p_D}{p_c}$ = the resistivity of the shield material relatively to copper.

ϵ_r = a foamed dielectric = 1.15

4. Experimentation

To measure the amount of electromagnetic field in a coaxial cable, the PCE electromagnetic (EM) field meter was employed. Also used is the EMF clamp meter. In

order to take an accurate measurement of the resistance of an LMR 400 coaxial cable and electromagnetic field present in the coaxial cable, the Airtel mast at AP filling Station Olu-Obasanjo Road and the Airtel mast at Air force base Port Harcourt Rivers State were used to carry out our measurements on an interval of 4 days. Several measurements were obtained at a Global System for Mobile Communications (GSM) Base Transceiver Station as illustrated in Figures 5 and 6.

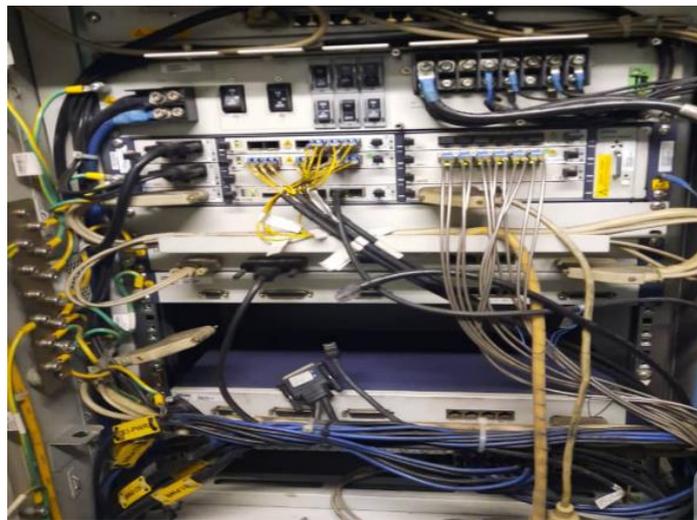


Figure 5. Base Transceiver Station



Figure 6. LMR 400 Coaxial Cable Attenuation Measurements

On this experiment we measured the level of attenuated GSM (Global System for Mobile Communications) signal from an LMR 400 coaxial cable connected to a Huawei base transceiver station. Also measured is the comparative characteristics of LMR400 Microwave cable, attenuation data for LMR series Microwave coaxial cables, and tests on other coaxial cables for Microwave Propagation. GSM attenuation measurement are shown in [Table 1](#), while [Table 2](#) shows the LMR=400 resistive loss data.

Table 1. Attenuation of GSM Signal Per Feet with Input Signal of 1900 MHz (LMR 400)

Freq. (MHz)	850-1900	850-1900	850-1900	850-1900	850-1900
Input signal	1900	1900	1900	1900	1900
Load SWR	1.5	1.5	1.5	1.5	1.5
Input power (Watts)	100	100	100	100	100
Length in feet	100	80	60	40	20
Matched loss in dB	5.825	4.66	3.495	2.33	1.165
SWR loss in dB	0.165	0.157	0.142	0.117	0.074
TOTAL loss in dB	5.991	4.87	3.638	2.448	1.24
Power out in Watts	25.177	32.982	43.275	56.917	75.17
Power loss in Watts	75	67	57	43	24

With a 1900 MHz GSM signal propagated at an input power of 100 watts, the graph in [Figure 7](#) illustrates the percentage of power loss and the output signal at different lengths of the coaxial cable. [Figure 7](#) was plotted using data from [Table 1](#).

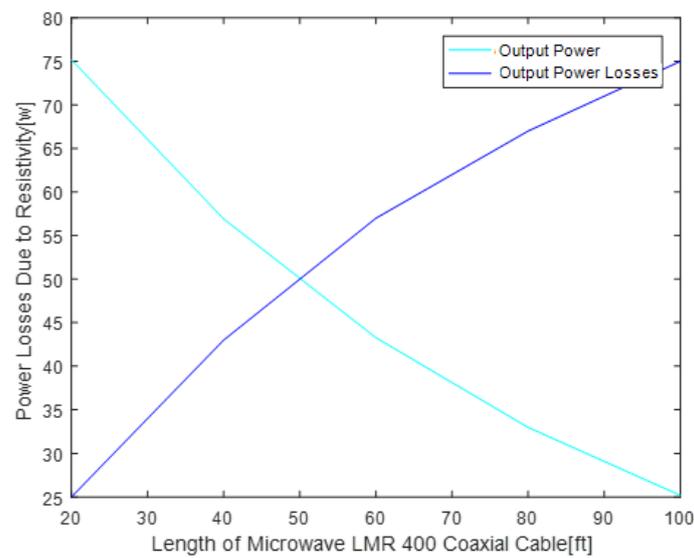


Figure 7. Losses in a LMR 400 Due to Resistivity

Table 2. LMR 400 Resistive Loss Data

Freq. (MHz)	Input Signal	Load SWR	Input Power (Watts)	Coaxial Length in Feet	TOTAL Loss in dB
850-1900	1900	1.5	100	100	5.991
850-1900	1900	1.5	100	80	4.87
850-1900	1900	1.5	100	60	3.638
850-1900	1900	1.5	100	40	2.448
850-1900	1900	1.5	100	20	1.24

Figure 2 shows the resistive loss per feet when a 1900 MHz GSM signal is propagated through the cable. Figure 8 was plotted using data from Table 2.

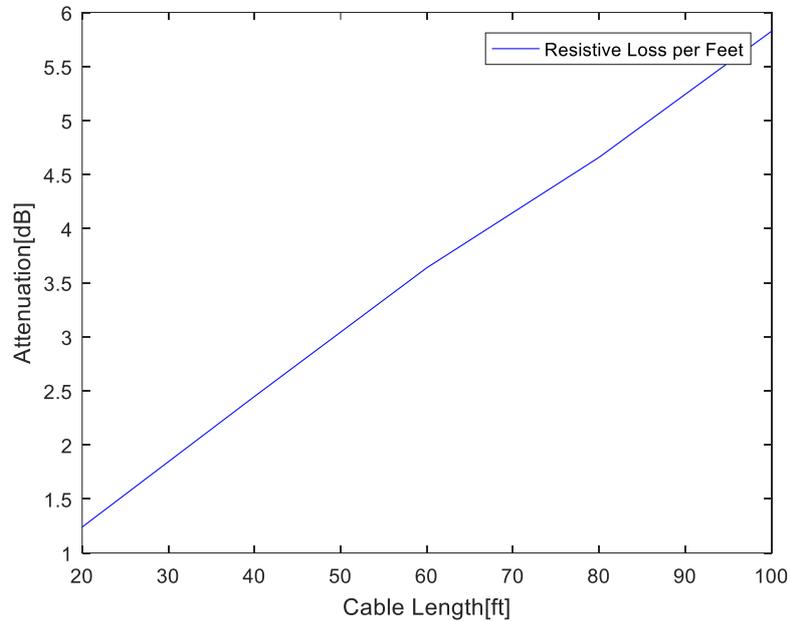


Figure 8. Resistive Loss of a Microwave LMR400 Coaxial Cable

LMR series coaxial cables were tested. The results in Table 3 shows the LMR 900 to be the best in the series because it has higher output power compared to others, lowest attenuation, and lowest power percentage loss at 30GHz. The next in line to be chosen after LMR900 is the LMR400 cable.

Table 3. Attenuation Data for LMR Series Microwave Coaxial Cables

Freq. (GHz)	30	30	30	30
LMR Cable	900	400	200	100
Input Signal	30	30	30	30
Load SWR	1.5	1.5	1.5	1.5
Input Power (Watts)	100	100	100	100
Total Loss in dB	2.67	5.991	14.799	34.385
Power Out in Watts	54.07	25.172	3.312	0.036
Power Loss in Watts	46	75	97	100

Figure 9 was plotted using data from Table 3.

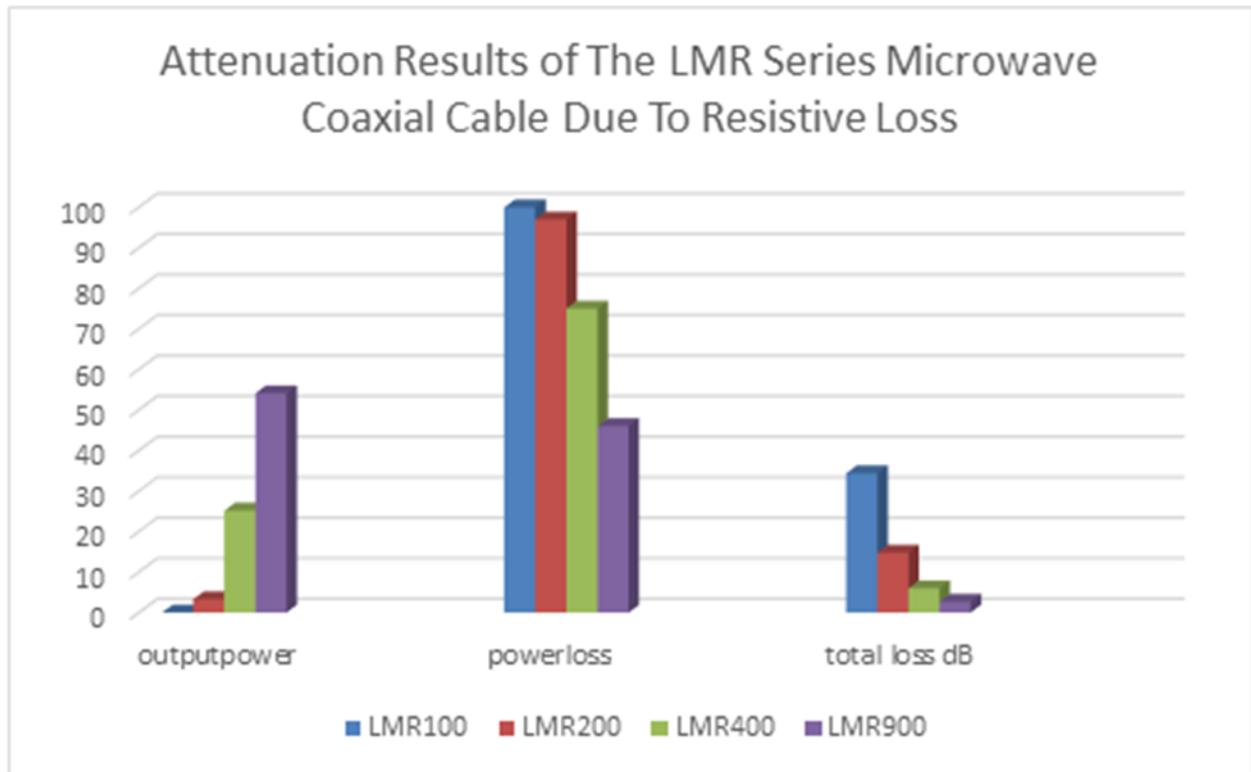


Figure 9. Attenuation Results of the LMR Series

Getting the best results during microwave propagation depends on the type of coaxial cable with its dielectric constant and how the resistance of the cable reacts to high frequency propagation through it. The results in Table 4 shows the various types of coaxial cables tested with their respective losses in decibels.

Table 4. Comparative Losses Data for Various Coaxial Cables

Freq. (GHz)	30	30	30	30	30	30
Wire type	LMR 900	RG6A	RG8	CQ 110	LDF 50	Davis RF
Input signal GHz	30	30	30	30	30	30
Load SWR	1.5	1.5	1.5	1.5	1.5	1.5
Input power (Watts)	100	100	100	100	100	100
Total loss in dB	2.67	14.659	11.43	13.127	1.392	6.89
Power out in Watts	54.07	3.421	7.195	4.867	7.567	20.467
Power loss in Watts	46	97	93	95	27	80

Figure 10 was plotted using data from Table 4.

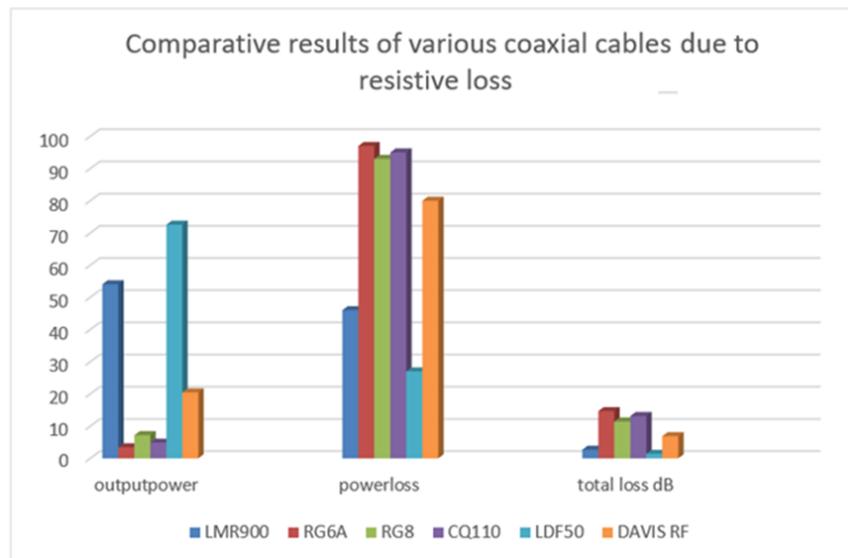


Figure 10. Comparative Results of Various Coaxial Cables Due to Resistive Losses

Table 5. Percentage Losses

Wire Type	Power Loss In watts (%)
LMR 900	46
RG6 A	97
RG8	93
CQ110	95
LDF50	27
Davis RF	80

Figure 11 illustrates the percentage power losses in each coaxial cable and was plotted from data in Table 5.

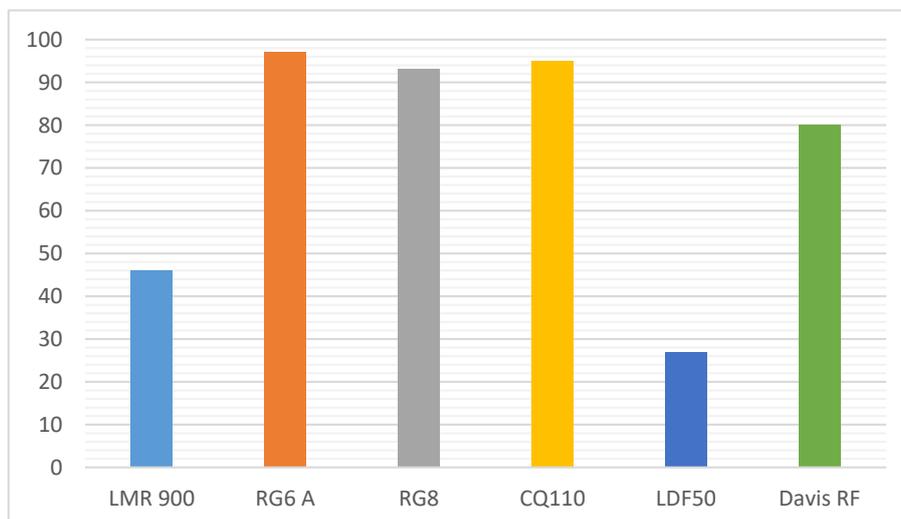


Figure 11. Power Loss at 30 GHz/ft

Equations 10 and 11 were used in calculating the Resistive loss of Coaxial cables as a factor of their characteristic impedance and frequency in MHz. With the dielectric of the Coaxial Cable chosen to be Polyethylene Solid (PE) with relative dielectric constant of 2.3 and Power Factor (PF) of 0.0003 [12], characteristics impedance chosen to be either 25Ω, 50Ω, 75Ω, or 80Ω, the inner and outer diameters of the coaxial cable was calculated using Equation 10. These values were then used in Equation 11 to calculate the resistivity loss for the various characteristic impedance of the Coaxial Cable. Since both the inner and outer conductors are both made of copper, the resistivity of the centre of conductor material relative to copper $\frac{\rho_d}{\rho_c}$ and the resistivity of the shield material relatively to copper $\frac{\rho_D}{\rho_c}$ are the same and have the value of $1.68 * 10^{-8}$ [13]. The results are in Table 6.

Table 6. Comparative Data of Some Ideal Coaxial Cables

Freq. (f) MHz	25 ohms ideal coaxial Resistive loss dB/100 feet	50 ohms ideal coaxial Resistive loss dB/100 feet	75 ohms ideal coaxial Resistive loss dB/100 feet	80 ohms ideal coaxial Resistive loss dB/100 feet
10	1.09E-05	2.69E-06	2.59E-06	1.93E-06
20	1.54E-05	3.81E-06	3.67E-06	2.73E-06
30	1.88E-05	4.66E-06	4.49E-06	3.35E-06
40	2.18E-05	5.38E-06	5.18E-06	3.86E-06
50	2.43E-05	6.02E-06	5.80E-06	4.32E-06
60	2.66E-05	6.59E-06	6.35E-06	4.73E-06
70	2.88E-05	7.12E-06	6.86E-06	5.11E-06
80	3.08E-05	7.61E-06	7.33E-06	5.46E-06
90	3.26E-05	8.08E-06	7.78E-06	5.80E-06
100	3.44E-05	8.51E-06	8.20E-06	6.11E-06
200	4.86E-05	1.20E-05	1.16E-05	8.64E-06
300	5.96E-05	1.47E-05	1.42E-05	1.06E-05
400	6.88E-05	1.70E-05	1.64E-05	1.22E-05
500	7.69E-05	1.90E-05	1.83E-05	1.37E-05
600	8.42E-05	2.09E-05	2.01E-05	1.50E-05
700	9.10E-05	2.25E-05	2.17E-05	1.62E-05
800	9.73E-05	2.41E-05	2.32E-05	1.73E-05
900	0.0001	2.55E-05	2.46E-05	1.83E-05
1000	0.00011	2.69E-05	2.59E-05	1.93E-05

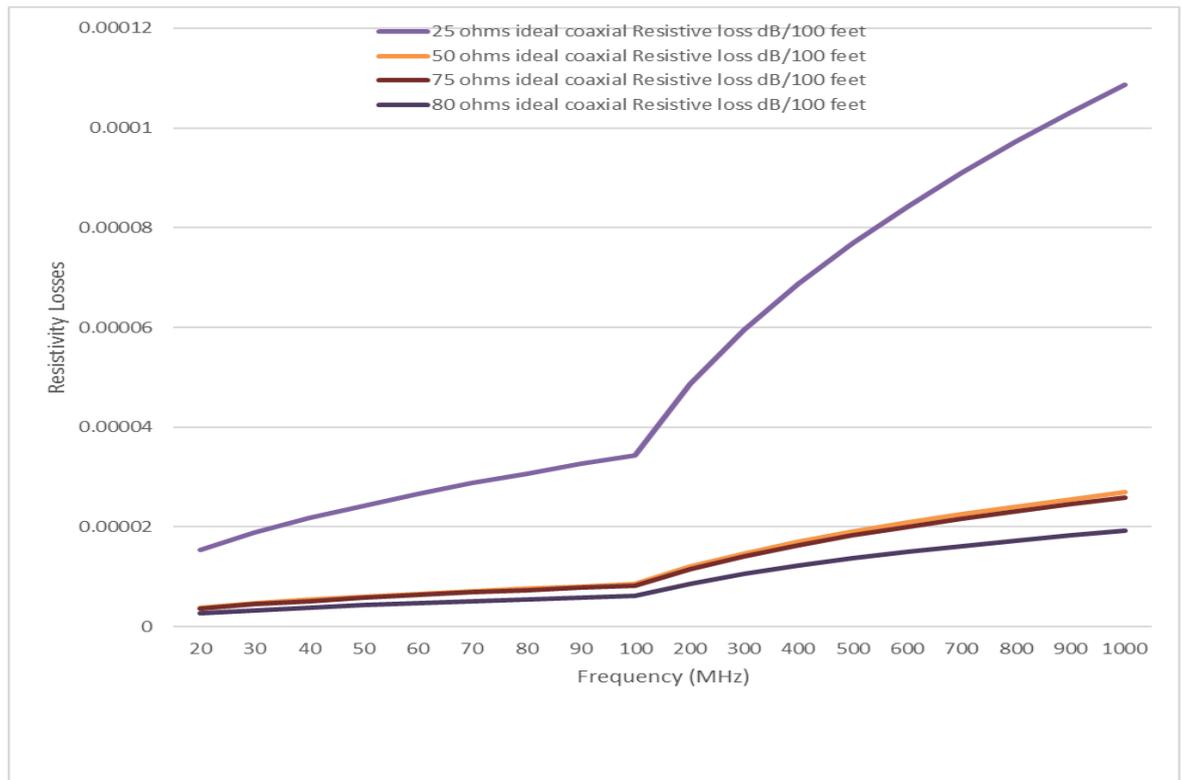


Figure 12. Ideal Coaxial Cable Resistive Loss

5. Conclusion

One of the fastest ways to transmit electromagnetic signals after the fibre optics medium, is the use of the Coaxial Cable. However, the issue with the coaxial cable is the attenuation loss on the cable particularly, the resistive losses which is the focus of this research.

Based on the findings, it is concluded that for a better and improved signal quality and to reduce resistive losses in coaxial cables, the characteristic impedance of the cable should be 80 ohms as this will reduce the coaxial cable resistive losses.

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