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Original Research Article

# Error estimation of the free space propagation model for humidity based mediums using Taylor's series

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**Abstract:**

The Taylor's Series is a conventional method for analyzing errors when model verification is required. This paper discusses the errors approximation when signals are transmitted from foggy or humid medium and when the transmitting and receiving points are located at far distances. Due to foggy environment at morning or rain fall, the signal strength is deteriorated and power of the received signals does not remain the same as when air is present in the atmosphere. This research paper estimates the error associated with the power of received signals calculated in decibels or decibels mill watts when the weather is rainy or moisten. The research methodology adopted is quantitative. By the application of Taylor's Series to the Free Space Propagation model for Humidity based mediums, considering the free space distance of 100 meters from antenna, by increasing distance from 10km to 20 km, the power of the received signal decreases, from 107.57161*10 raised to power -5 to 75.74335*10 raised to power -5, and the percentage of error or decrease is -42.02118 percent. As the distance increased, the power of the signals decreased with a factor of 31.82826, a factor indicating the effect of humidity on the received signal power in decibels.

**Keywords:** Derivative, Relative permittivity, Permittivity of free space, Dielectric, Signal strength, Wavelength, Transmitter gain, Receiver gain, Distance, Path loss.

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## 1. Introduction

As the fields of Artificial Intelligence and Machine Learning have been growing rapidly it has become essential for us to move towards the improvement of the mathematical models used for telecommunication systems and engineering. One of the most famous models are Friis Free Space Propagation Model which calculates the power of the signals communicated from the transmitter to the receiver through a line of sight composed of moisture or fog. The line of sight medium has a prominent significance in estimating the power of the received signals, the errors associated with the power of the received signals. The effects of line of sight medium on the might of signals has a profound importance which has been developed in the form of a new mathematical model of Free Space Propagation for Humidity based mediums (Faraz *et al.,* 2024).

I can define Humidity as the water vapors vaporized in the environment when the water cycle moves through different stages and the water is converted from sea water form to gaseous form through exposure to heat (Sadeghioon, *et al*., 2017). Humidity is measured in terms of concentration of water vapors obtained through moisture, fog, rain water, drizzling, water melted from ice pellets and snow (Ladan, 2017). Humidity also appears in the form of dew. The dew is defined as the water vapors collected at the thin metallic plates or surfaces exposed to air. The water vapors condensed at the surfaces of objects because of the radiation of heat from the surfaces and snow or rain fall from the clouds during the morning time on the surfaces. The surfaces can be metallic or can be made up of sand or cement. It is obvious that when there is water in the form of water vapors the signal quality parameters change (Cho *et al.,* 2019). The one of the signal quality parameter is power of the received signal. The power of received signal can be measured in decibels or in decibels milli watts. I will measure the power of received signal in decibels milli watts because of the suitability of the unit with the collected data since the collected data is in very small figures (Boukalov *et al*., 2002).

The Free Space Propagation model, proposed by Friis for measuring the signal strengths at transmitting point and receiving point for telecommunication systems, is only applicable when air is the medium of communication (Shaw, 2013). When the medium of communication changes from air to humidity as the weather changes from hot to rainy weather, the updated Free Space Propagation model for Humidity based mediums can be used. The error estimation of the updated Free Space Propagation model is essential for me, I selected Taylor's Series for error estimation of the updated Free Space Propagation model for Humidity Based medium.

### 1.1. Research objective

The research aim for this research work is to investigate the effect of humidity on the power of signals with computation of errors in the received signal power using Taylor's Series. Taylor's Series is a conventional numerical method, which has not been used for calculating errors for power of signals using Free Space Propagation model. Taylors's Series computes the errors in fractions or decimals which gives a clear picture of error estimation in received signal strength measured in decibels or decibels mill watts.

### 1.2. Research gap

Very less work has been done on consideration of humidity based mediums for measurement of either signal strength or power of the signals. The humid weather deteriorates the signal transmission and reception from the transmitter to the receiver, but quantitatively there was no mathematical model for computation of power of signals and error in the power of signals when the weather is rainy or foggy. I proposed the Taylor's Series for computing error, when weather is humid and Friis Free Space Propagation model is used, and signals are transferred through wireless communication systems.

## 2. Literature review

### 2.1. Humidity factor

Humidity factor affects the Wireless Communication System more affectively as compared to the other parameters. The Wireless Communication System is not only a single system consisting of interconnecting devices, switches, routers and transceivers but it has more components joining the Wireless Communication System to the Internet of Things. In order to study the Humidity factor effects on signal strength it has been become necessary for us to relate the parameters associated with the humidity in the system as medium of signal propagation (Franek, 2017).

There are two parameters on which humidity depends. The first parameter is temperature of the system and the second parameter is the pressure of the system. The relative humidity will have different values when the temperature of the system varies. In the cool system the relative humidity will be high and in the warm system the relative humidity will be low (Boukalov & Haggman, 2002). The relative humidity raises in the cold weather and decreases in the warm weather. The temperature of the system and the environment affects more on relative humidity, as the temperature raises the water vapors vaporizes more speedily but does not reach the saturation point, relative humidity of the system and the environment raises in values. The saturation point is reached when we have decrement in temperature and there will be no loss or gain in the mass of air (Cho *et al*., 2019).

There are three types of humidity. These types are Absolute Humidity, Relative Humidity and Specific Humidity. The Absolute Humidity is defined as the amount of water vapors per unit volume of air. The volume of air is measured in grams per cubic meter. The Relative Humidity is measured in terms of percentage. It measures the humidity in comparison with the maximum humidity. The Specific Humidity is the ratio of water vapors weight with the total moisten air weight (Fang *et al*., 2021). When we study radio propagation systems and include the humidity parameter in our updated model we can consider all the three parameters but in this research paper we have been considering only "Relative Humidity" as the new inclusion parameter (Li *et al*., 2019).

The indoor relative humidity values is from 30 to 50 percent, and sometimes it is from 30 to 60 percent. The outdoor relative humidity values is greater than 50 percent or greater than 60 percent depending upon the indoor relative humidity range either limiting to 50 or 60 percent as referred in (Mohamed *et al*., 2021).

### 2.2. Previous research work

The Friis Free Space Propagation model is a mathematical model which builds the mathematical foundation for digital signals transmission through wireless communication systems as referred in (Shaw, 2013). The Free Space Propagation model, when considered with humidity factor, updated by inclusion of relative permittivity of humidity based medium (Faraz et *al.*, 2024). This model needed further improvement in signal strength, therefore computation of error using Free Space Propagation model was required. The computation of errors is important because the errors removal from the received signals will be improved in the future.

### 2.3. Updated free space propagation model and Taylor's series

By the inclusion of Humidity Factor in the Free Space Propagation Model we will have a new model for radio wave signals for transmission from one point to another point this new model will be following:

$$\boldsymbol{Pr(d)} = \frac{\boldsymbol{Pt\ Gt\ Gr\ \lambda^2}}{\boldsymbol{€r(4\pi)^2 d^2 L}} \tag{1}$$

The Humidity Factor inclusion in the Free Space Propagation Model is the relative permittivity of the medium of communication '€r'. The mathematical visualization of the given model can be described with data and simulation of the acquire data in the coming session.

The new Humidity based model can be simplified by separating constants from variable.

$$\boldsymbol{Pr(d)} = \frac{\boldsymbol{Pt\ Gt\ Gr\ \lambda^2}}{\boldsymbol{€r(4\pi)^2 L}} * \frac{\boldsymbol{1}}{\boldsymbol{d^2}} \tag{2}$$

Here K is a new constant

$$\boldsymbol{K} = \frac{\boldsymbol{Pt\ Gt\ Gr\ \lambda^2}}{\boldsymbol{€r(4\pi)^2 L}} \tag{3}$$

$$\boldsymbol{Pr(d)} = \boldsymbol{K}.\frac{\boldsymbol{1}}{\boldsymbol{d^2}} \tag{4}$$

The Taylor's Series can be mathematically represented as follows:

$$\boldsymbol{y(x)} = \boldsymbol{y(0)} + \boldsymbol{(x - x0)y(0)'} + \frac{\boldsymbol{(x-x0)^2}}{\boldsymbol{2!}}\boldsymbol{y(0)''} + \frac{\boldsymbol{(x-x0)^3}}{\boldsymbol{3!}}\boldsymbol{y(0)'''} + \cdots \tag{5}$$

The Taylor's Series expansion and application of Taylor's series to Free Space Propagation Model for Humidity based mediums will be elaborated in the next section.

## 3. Research methodology

The Taylor's Series expansion can be applied to any mathematical function which exists as a function of a constant and a variable. In this research paper I will calculate the Taylor's Series based errors estimated through calculation of terms of the Taylor's Series. The Taylor's Series is a traditional method widely used for calculation of errors found in any experimental result or theoretical propositions. In order to calculate the errors we have collected data from (Mohamed *et al.*, 2021) shown in the given tables 1-5. Mathematically describing the Taylor's Series as a series which consists of derivatives of the given function divided by the factorial of the power of the term. The derivatives and their power increase term by term.
The Relative Humidity is an important factor for determining the quality of signals, signal strength and the effect of humidity on signal strength. The mathematical models which are

designed for radio wave signals which are either short distance models or far distance models assume air as the medium of pass through and do not include the effects of humidity or water. It is very clear from different data acquisition resources (Abdorahimi, & Sadeghioon, 2019) that when there is a rainy weather or fog in the atmosphere the signal strength and quality of the signal does not remains same as it is in the atmosphere where air is the medium. In this research paper my objective is to consider fog, water based mediums for signal transfer and include the relative humidity parameter for water based atmosphere, and calculate the errors using the Taylors Series in the received signal strength.

The formula for Complex Permittivity of particles as referred in (Mohamed *et al.*, 2021) can be expressed as

$$\in = \in' + j \in'' \quad (6)$$

In the equation 8, the term € denotes the permittivity. The permittivity of the medium consists of real part and the imaginary part. The real permittivity and imaginary permittivity are based upon the dielectric constant as we know that the dielectric constant has to be considered as it is included when we calculate capacitance of parallel plate capacitors and it is shown with the variable Epsilon–d.

The real permittivity and imaginary permittivity including Humidity factor can be represented as follows:

$$\in_h' = \in' + \mathbf{0.04}\boldsymbol{H} - \mathbf{7.78} * \mathbf{10^{-4}}\boldsymbol{H^2} + \mathbf{5.56} * \mathbf{10^{-6}}\boldsymbol{H^3} \quad (7)$$

$$\in_h'' = \in'' + \mathbf{0.02}\boldsymbol{H} - \mathbf{3.71} * \mathbf{10^{-4}}\boldsymbol{H^2} + \mathbf{2.76} * \mathbf{10^{-6}}\boldsymbol{H^3} \quad (8)$$

In the above equations 'H' denotes the relative humidity. For the purpose of error calculation we assume that ∈^'=4.43 and ∈^"=0.04.

### 3.1. Experimental design

In order to perform this research work, the independent variable is Power received "Pr" and the dependent variables are the distance between the transmitter and receiver "d", the initial distance between the transmitter and receiver "d0". In order to perform experimental design, I have to perform substitutions to get the results.

Substituting the following in equation (5),

$$\boldsymbol{Pr(d)} = \boldsymbol{y(x)}$$

$$\boldsymbol{Pr(0)} = \boldsymbol{y(0)}$$

The Taylor's Series expansion of Free Space Propagation model for Humidity based mediums will become

$$\boldsymbol{Pr(d)} = \boldsymbol{Pr(0)} + (\boldsymbol{d} - \boldsymbol{d0})\boldsymbol{Pr(0)}' + \frac{(\boldsymbol{d}-\boldsymbol{d0})^2}{\mathbf{2!}}\boldsymbol{Pr(0)}'' + \frac{(\boldsymbol{d}-\boldsymbol{d0})^3}{\mathbf{3!}}\boldsymbol{Pr(0)}''' + \cdots \quad (9)$$

### 3.2. Data collection process

For this research work the data is collected from the World Wide Web source (Mohamed *et al*., 2021). Secondly the Pakistan Meteorological Department (PMD) website is the source of data for the proposed research work.

### 3.3. Specific calculations undertaken

The specific calculations undertaken for calculating Power received in decibels and Power received in decibels mill watt are given below.

By assuming the following initial conditions we have

$$\boldsymbol{d0 = 100\ km}$$

$$\boldsymbol{d = 10\ km}$$

The first term of the Taylor's Series will be

$$\boldsymbol{Pr(d0) = Pr(100) = -24.5\ dBm}$$

$$\boldsymbol{Pr(d) = -64.5\ dBm}$$

$$\boldsymbol{K = \frac{50(1)(1)(1/3)^2}{(4\pi^2)(100^2)(1)} = 0.03511}$$

Now determining the second term of Taylor's Series, we get

$$\boldsymbol{Pr(d)' = -\frac{K}{d^2}}$$

$$\boldsymbol{Pr(d0)' = -\frac{K}{d0^2}}$$

$$\boldsymbol{Pr(d0)' = -\frac{0.03511}{100^2}}$$

$$\boldsymbol{Pr(d0)' = -0.000003511 = -3.5 * 10^{-6}}$$

$$\boldsymbol{Pr(d0)'in\ dBm = 10log(-0.000003511) = 10log(-3.5 * 10^{-6}) = -54.5593}$$

Then determining the third term of Taylor's Series, we get

$$\boldsymbol{Pr(d)'' = \frac{2K}{d^3}}$$

$$\boldsymbol{Pr(d0)'' = \frac{2K}{d0^3}}$$

$$Pr(d0)'' = \frac{2(0.03511)}{(100)^3}$$

$$Pr(d0)'' = 0.0000070 = 7.0 * 10^{-6}$$

$$Pr(d0)''in\ dBm = 10log(0.0000070) = 10log(7.0 * 10^{-6}) = -51.5490$$

Then determining the fourth term of Taylor's Series, we get

$$Pr(d)''' = -\frac{6K}{d^4}$$

$$Pr(d0)''' = -\frac{6K}{d0^4}$$

$$Pr(d0)''' = -\frac{6(0.03511)}{(100)^4}$$

$$Pr(d0)''' = -0.0000000021 = -2.1 * 10^{-9}$$

$$Pr(d0)'''in\ dBm = 10log(-0.0000000021) = 10log(-2.1 * 10^{-9}) = -86.7778$$

Then substituting the first term, second term and the third term in equation (9), we get

$$Pr(10) = -24.5 + (10 - 100)Pr(0)' + \frac{(10 - 100)^2}{2!}Pr(0)'' + \frac{(10 - 100)^3}{3!}Pr(0)''' + \cdots$$

$$Pr(10) = -24.5 + (10 - 100)(-54.5593) + \frac{(10 - 100)^2}{2!}(-51.5490) + \frac{(10 - 100)^3}{3!}(-86.7778) + \cdots$$

$$Pr(10) = -24.5 + (-90)(-54.5593) + \frac{(-90)^2}{2.1}(-51.5490) + \frac{(-90)^3}{3.2}(-86.7778) + \cdots$$

$$Pr(10) = -24.5 + 4910.337 + 208773.45 + 10543502.7 \ldots$$

$$Pr(10) = 10757161.99\ Watts = 10.757161 * 10^6\ Watts$$

Now considering d = 20 in equation (9), we get

$$Pr(20) = -24.5 + (20 - 100)Pr(0)' + \frac{(20 - 100)^2}{2!}Pr(0)'' + \frac{(20 - 100)^3}{3!}Pr(0)''' + \cdots$$

$$\boldsymbol{Pr(20) = -24.5 + (20-100)(-54.5593) + \frac{(20-100)^2}{2!}(-51.5490) + \frac{(20-100)^3}{3!}(-86.7778) + \cdots}$$

$$\boldsymbol{Pr(20) = -24.5 + (-80)(-54.5593) + \frac{(-80)^2}{2.1}(-51.5490) + \frac{(-80)^3}{3.2}(-86.7778) + \cdots}$$

$$\boldsymbol{Pr(20) = -24.5 + 4364.744 + 164956.8 + 7405038.933}$$

$$\boldsymbol{Pr(20) = 7574335.977\, Watts = 75.74335 * 10^5 Watts}$$

Taking the difference

$$\boldsymbol{Pr(20) - Pr(10) = 7574335.977 - 10757161.99 = -3182826.013\, Watts}$$

$$\%\boldsymbol{Error\ or\ Decrease\ in\ Power} = \frac{\boldsymbol{Pr(20) - Pr(10)}}{\boldsymbol{Pr(20)}} = \frac{\boldsymbol{7574335.977 - 10757161.99}}{\boldsymbol{7574335.977}} = \boldsymbol{-42.02118\, percent}$$

Thus the error estimate in received power signals have been calculated to be -42.02118 percent when the far distance changes from 10 km to 20 km.

## 4. Results and discussion

The implications of this research work are broader in the sense that in order to maintain the quality of signal when signals are propagated through humidity based medium, the signal strength and power of the signal measured in decibels or decibels mill watt parameters are important and these should be controlled by using Free Space Propagation model for humidity based mediums.

For the purpose of simulation we have considered the parameters for simulating our model as following: We have an antenna with frequency of 900 MHZ, dimension of 1 meter, transmitter produces 50 watts of power, 50 watts of power is applied to unity gain antenna with 900 MHZ carrier frequency, a free space distance of 100 meter from antenna, the received power in dBm has been calculated here for real relative permittivity data and imaginary relative permittivity data. The derived results are as follows:

The Table I elaborates the numerical values of Relative Humidity with real permittivity and imaginary permittivity. When weather is free from moisture, the real permittivity is 4.271 and the imaginary permittivity is 0.109. The Relative Humidity ranges from 20 to 100 with difference of 25, the real permittivity ranges from 4.804 to 6.051 and the imaginary permittivity ranges from 0.109 to 1.150.

TABLE I. THE RELATIONSHIP BETWEEN RELATIVE PERMITTIVITY VERSUS HUMIDITY

| Index | Relative Permittivity Versus Humidity | | |
|---|---|---|---|
| | *Relative Humidity* | *E'h* | *E''h* |
| 1 | Dry | 4.271 | 0.109 |
| 2 | 20 | 4.804 | 0.383 |
| 3 | 45 | 5.002 | 0.509 |
| 4 | 70 | 5.169 | 0.568 |
| 5 | 75 | 5.399 | 0.618 |
| 6 | 80 | 5.497 | 0.679 |
| 7 | 85 | 5.623 | 0.754 |
| 8 | 90 | 5.781 | 0.847 |
| 9 | 95 | 5.975 | 0.958 |
| 10 | 100 | 6.051 | 1.150 |

The Figure I elaborates graphically the relation between Relative Humidity and Real Permittivity. As Relative Humidity increases from 10 to 20 the Relative Permittivity increases from 4.2 to 4.8 abruptly then remains stable from 4.8 to 6.1.

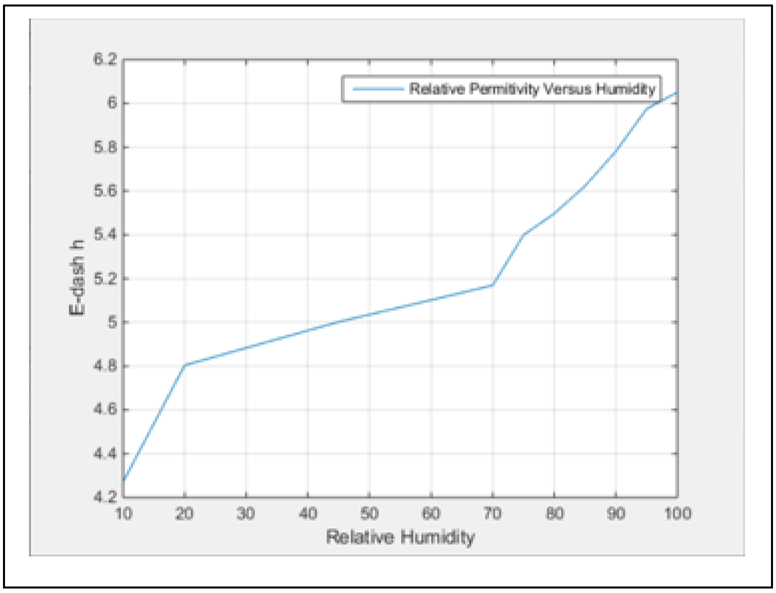


**Fig. 1.**Relative Permitivity E'h Versus Humidity

The Figure II elaborates graphically the relation between Relative Humidity and Imaginary Permittivity. As the Relative Humidity increases from 10 to 20, the Imaginary Permittivity increases from 0.1 to 0.35 sharply then remains stable from 0.39 to 1.1 when the Relative Humidity increases from 20 to 100.

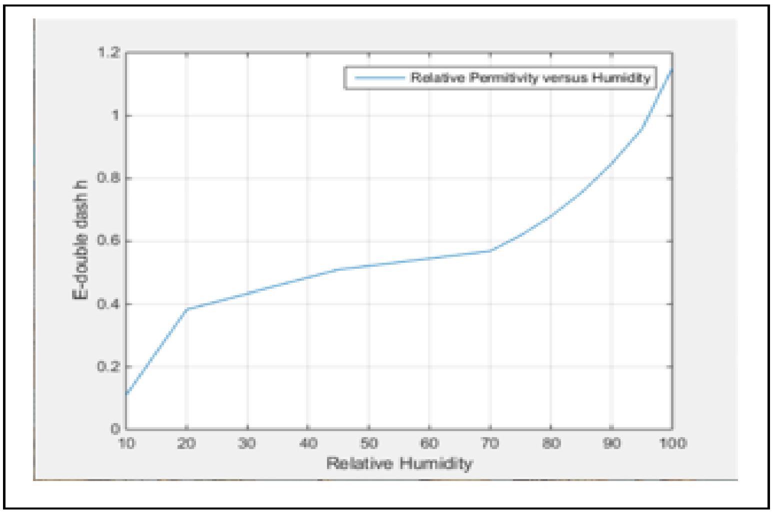


**Fig. 2.**Relative Permitivity E''h Versus Humidity

The Table II elaborates the numerical values of Relative Humidity, the ratio of Real Permittivity to Imaginary Permittivity, the ratio of Imaginary Permittivity to Real Permittivity. When Relative Humidity increases from 20 to 100, the ratio of Real Permittivity to Imaginary Permittivity decrease from 12.54308 to 5.26173 and the ratio of Imaginary Permittivity to Real Permittivity decrease from 0.797252 to 0.190051.

TABLE II. THE RELATIONSHIP BETWEEN RELATIVE PERMITTIVITY RATIOS VERSUS HUMIDITY

| **Table Head** | **Relative Permittivity Ratio Versus Humidity** | | |
|---|---|---|---|
| | ***Relative Humidity*** | ***E'h/E''h*** | ***E''h/E'h*** |
| 1 | Dry | 39.18348 | 0.025520 |
| 2 | 20 | 12.54308 | 0.797252 |
| 3 | 45 | 9.82711 | 0.101759 |
| 4 | 70 | 9.10035 | 0.109885 |
| 5 | 75 | 8.73624 | 0.114465 |
| 6 | 80 | 8.09572 | 0.123521 |
| 7 | 85 | 7.45755 | 0.133925 |
| 8 | 90 | 6.82526 | 0.146514 |
| 9 | 95 | 6.23695 | 0.160334 |
| 10 | 100 | 5.26173 | 0.190051 |

The Table III elaborates the numerical values of Relative Humidity and the Product of Real Permittivity and Imaginary Permittivity. The first column of the table describes the product results of Real Permittivity and Imaginary Permittivity whereas the second column of the table describes the approximated results. The product value is calculated to be 0.465539 and ends at 6.95865 when Relative Humidity is dry and 100.

TABLE III. THE RELATIONSHIP BETWEEN RELATIVE PERMITTIVITY PRODUCT VERSUS HUMIDITY

| Index | Relative Permittivity Versus Humidity | | |
|---|---|---|---|
| | *Relative Humidity* | *E'h*E''h* | *Approximated Product* |
| 1 | Dry | 0.465539 | 0.4655 |
| 2 | 20 | 1.839932 | 1.8399 |
| 3 | 45 | 2.546018 | 2.5460 |
| 4 | 70 | 2.935992 | 2.9360 |
| 5 | 75 | 3.336582 | 3.3366 |
| 6 | 80 | 3.732463 | 3.7325 |
| 7 | 85 | 4.239742 | 4.2397 |
| 8 | 90 | 4.896507 | 4.8965 |
| 9 | 95 | 5.72405 | 5.7240 |
| 10 | 100 | 6.95865 | 6.9587 |

The Figure 3 elaborates graphically the relation between Relative Humidity and Product of Real Permittivity and Imaginary Permittivity. When the Relative Humidity ranges from 10 to 20, the Product of Real Permittivity and Imaginary Permittivity increases from 0.5 to 2. When the Relative Humidity ranges from 20 to 100, the Product of Real Permittivity and Imaginary Permittivity increases in curve form from 2 to 7.

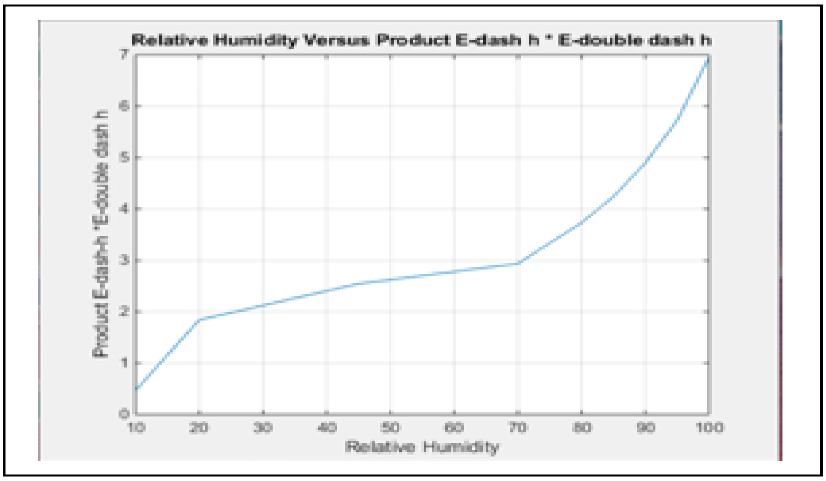


**Fig. 3.**Relative Humidity Versus Product E'h*E''h

The Figure 4 elaborates graphically the relation between Relative Humidity and division operation of Real Permittivity and Imaginary Permittivity. When the Relative Humidity ranges from 10 to 20, the Quotient of Real Permittivity and Imaginary Permittivity suddenly decreases from 40 to 12. When the Relative Humidity ranges from 20 to 100, the Quotient of Real Permittivity and Imaginary Permittivity suddenly decreases from 12 to 5 in stable from.

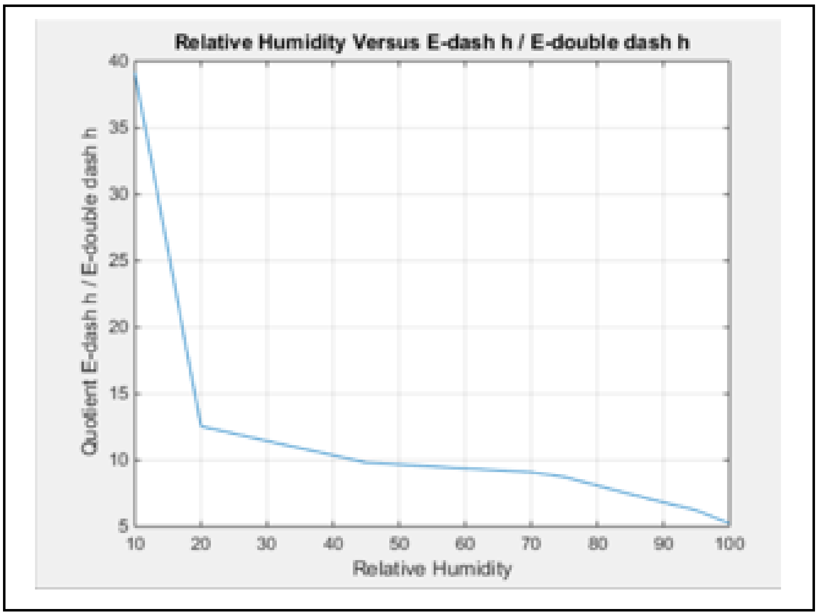


**Fig. 4.**Relative Humidity Versus Quotient E'h/E''h

The Figure 5 elaborates graphically the relation between Relative Humidity and division operation of Imaginary Permittivity and Real Permittivity. When the Relative Humidity ranges from 10 to 45, the Quotient of Imaginary Permittivity and Real Permittivity increases from 0 to 0.8 and then decreases from 0.8 to 0.1 then remains stable up to 0.9.

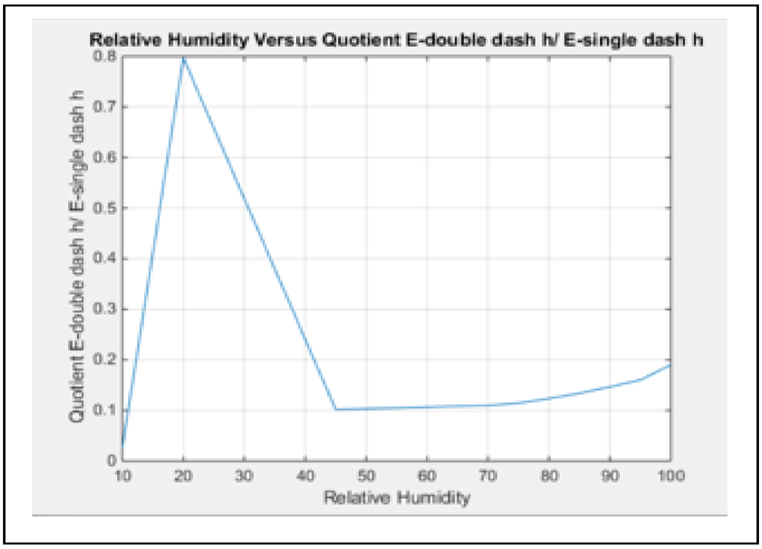


**Fig. 5.**Relative Humidity Versus Quotient E''h/E'h

## 5. Conclusion and recommendations

The Taylor's Series when applied to the Free Space Propagation Model for Humidity based mediums, provides percentage error in the received power of -42.02118 percent. The power of the signals were 10757161.99 Watts and 7574335.977 Watts at 10 km and 20 km distance and free space distance of 100 meters from antenna.

As future research work the Free Space Propagation model for humidity based mediums can be applied to work for advanced receiver designs especially for controlling and maintaining the signal strength and power of signals.

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