Evaluation Of The Communication Range Of Smart City IoT Sensor In Rainy Sky Condition Using Lambert W Function

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***Abstract*— In this work, evaluation of the communication range of smart city IoT sensor in rainy sky condition using Lambert W function is presented. The CCIR (Comite' Consultatif International des Radio Communication) model for propagation loss is used to model the path loss in the IoT sensor coverage area. In addition, the rain attenuation is determined using the International Telecommunication Union (ITU) power-law rain attenuation model for terrestrial wireless link. The resultant expression for the communication range was solved using the Lambert W function. The simulations considered microwave frequencies (f) of 2.5 GHz, 5.5 GhHz and 10 GHz and at rain rate for network percentage outage (p) of 0.1 %, 0.01 % and 0.001 %. The rain zone considered has rain rate of 35 mm/hr at p =0.1 %, 95 mm/hr at p =0.01 %, and 180 mm/hr at p =0.001 %. The results show that the communication range for p = 0.1 % is 232.6 m at 10 GHz but increased to 683.0 m at 2.5 GHz. For f = 5.5 HGz, the communication range decreased from 372.4 m at p= 0.1 to 355.6 m at p= 0.001. Again, for p = 0.001 % the rain attenuation increased for 0.030 db for f = 2.5 GHz to 1.7492 for f = 10 GHz. Essentially, the results show that for the same set of input parameters, the communication range of the IoT sensor decreases with increase in frequency, increases with increase in allowable network outage and decreases with increase in rain rate. Also, the communication range for PB of 3 % is 680.4 m at 10 GHz but increased to 2325.2 m at 2.5 GHz. For f = 5.5 HGz, the communication range decreased from 1203.9 m at PB of 3 % to 367.1 m at PB of 16 %. Essentially, the results show that for the same set of input parameters, the communication range of the IoT sensor decreases with increase in degree of urbanization represented by PB.**

Keywords*— *Communication Range, Smart City, IoT Sensor, Lambert W Function, CCIR Path Loss Model

1.0 INTRODUCTION

Today, Internet-based wireless sensor networks, also known as IoT sensor networks are widely used for many applications. Notable applications of IoT sensor networks include smart city, smart agriculture, smart health and smart transport applications [3,4,5]. Irrespective of the application, the fundamental issues of propagation loss and rain fading associated with wireless communication links must be appropriately accounted for in the design of such IoT sensor networks [6,7,8].

Generally, empirical propagation loss models are used for wireless link design [9,10]. In respect of smart city application considered in this work, the CCIR (Comite' Consultatif International des Radio Communication) model for propagation loss is used [11,12]. Also, in this work, for the rainy sky, the rain attenuation is determined using the International Telecommunication Union (ITU) power-law rain attenuation model for terrestrial wireless link [13,14]. Then, the resultant expression for the communication range was solved using the Lambert W function [15,16]. Hence, with the Lambert W function-based solution, the impact of the degree of urbanization, the base station antenna height, the signal frequency, the rain rate and the allowable percentage outage of the network on the communication range are studied using simulations conducted on a number of IoT sensor operating in the microwave frequency range.

2. METHODOLOGY

In this study, the CCIR (Comite' Consultatif International des Radio Communication) model for propagation loss is used to model the path loss in the IoT sensor coverage area. The CCIR model is adopted as it provides parameters that capture the effect of the degree of urbanization and also the effect of the antenna height of the propagation loss. The two parameters also affect the coverage range when a given path loss value is expected in the wireless link.

In addition to the CCIR model –based path loss, the rainy sky condition also includes the rain attenuation which in this work is determined using the International Telecommunication Union (ITU) power-law rain attenuation model for terrestrial wireless link. Each of the two losses are detailed and then the expressions for determination of the attainable communication range of the IoT sensor in clear sky and rainy sky conditions are presented using the Lambert W function.

2.1 The IoT sensor propagation loss

In clear sky, the IoT sensor deployed for smart city application is subjected to propagation loss which is dependent on the degree of urbanization based on the CCIR propagation loss model. The expression for path loss based on the CCIR model is as follows [11,12]:

$$L_{CCIR} = A + B * \log_{10}(d) - E \quad (1)$$

$$A = 69.55 + 26.16 * \log_{10}(f) - 13.82 * \log_{10}(h_b) - a(h_m) \quad (2)$$

$$a(h_m) = [1.1 * \log_{10}(f) - 0.7] * h_m - [1.56 * \log_{10}(f) - 0.8] \quad (3)$$

$$B = 44.9 - 6.55 * \log_{10}(h_b) \quad (4)$$

$$\mathrm{E} = 30 - 25(\log_{10}(PB)) \quad (5)$$

Where E denoted the degree of urbanization which is a function of PB, which is the percentage of the area that is covered with building. The base station antenna height is denoted as hb while the sensor antenna height is denoted as hm. Finally, f is the signal frequency in MHz while d is the communication distance in km.

2.2 The IoT sensor losses in rainy sky

In rainy sky condition, the IoT sensor is also affected by the rain attenuation in addition to the propagation loss. The expression for rain attenuation, A_{R_p} with respect to rain rate, R_p at P percentage of time exceeded and at path length of d is given based on ITU model as follows [13,14];

$$\gamma_p = \left(maximum \left(\left[k_v (R_p)^{\alpha_v} \right], \left[\left(k_h (R_p)^{\alpha_h} \right) \right] \right) \right) \quad (6)$$

$$A_{R_p} = (\gamma_p)\,(\mathrm{d}) \quad (7)$$

Where $\mathrm{k_h}$, α_h k_v and α_v, are constants that depend on the signal frequency considered while h and v indicate horizontal and vertical polarisation respectively.

2.3 Lambert W function-based IoT sensor communication range in rainy sky

Notably, the total loss in the signal path due to path loss and rain fade in the rainy sky condition is the summation of the propagation loss and the rain attenuation. Then, the link budget expression is used to determine the total losses the IoT sensor can accommodate for any given set of data for the transmitter power ($\mathrm{P_{trans}}$), the receiver sensitivity ($\mathrm{S_{rec}}$), the transmitter antenna gain ($\mathrm{G_{trans}}$) and receiver antenna gain ($\mathrm{G_{rec}}$), where;

$$L_{CCIR} + A_{R_p} = \mathrm{P_{trans}} + \mathrm{G_{trans}} + \mathrm{G_{rec}} - \mathrm{S_{rec}} \quad (8)$$

$$A + B * \log_{10}(d) - E + \gamma_p\,(\mathrm{d}) = \mathrm{P_{trans}} + \mathrm{G_{trans}} + \mathrm{G_{rec}} - \mathrm{S_{rec}} \quad (9)$$

$$\gamma_p\,(\mathrm{d}) + B * \log_{10}(d) + A - E - \mathrm{P_{trans}} - \mathrm{G_{trans}} - \mathrm{G_{rec}} + \mathrm{S_{rec}} = 0 \quad (10)$$

The $Log(d)$ in base 10 is expressed in natural log (or LN) as;

$$Log(d) = \frac{LN(d)}{LN(10)} = \frac{LN(d)}{2.302585093} = 0.434294482\, LN(d) \quad (11)$$

Hence;

$$\gamma_p\,(\mathrm{d}) + B(0.434294482)\big(LN(d)\big) + A - E - \mathrm{P_{trans}} - \mathrm{G_{trans}} - \mathrm{G_{rec}} + \mathrm{S_{rec}} = 0 \quad (12)$$

$$K_1\,(\mathrm{d}) + K_2\, LN(d) + K_3 = 0 \quad (13)$$

Where;

$$K_1 = \gamma_p \quad (14)$$

$$K_2 = B(0.434294482) \quad (15)$$

$$K_3 = A - E - \mathrm{P_{trans}} - \mathrm{G_{trans}} - \mathrm{G_{rec}} + \mathrm{S_{rec}} \quad (16)$$

Generally, Lambert W function is expressed as;

$$W(x) = x(e^x) \quad (17)$$

The expression for communication range, d given in Equation 13 is expressed in the general Lambert W function format as follows;

$$\frac{\left(\frac{K_1}{K_2}\right)d}{\left(\frac{K_1}{K_2}\right)} = \mathrm{d} \quad (18)$$

Then,

$$LN\left(\frac{\left(\frac{K_1}{K_2}\right)d}{\left(\frac{K_1}{K_2}\right)}\right) = LN\left(\left(\frac{K_1}{K_2}\right)d\right) - LN\left(\frac{K_1}{K_2}\right) = \mathrm{LN}(d) \quad (19)$$

Hence, by substituting Equation 16 and Equation 17 into Equation 13 gives;

$$K_1(\mathrm{d}) + K_2\,\mathrm{LN}\left(\left(\frac{K_1}{K_2}\right)d\right) + K_3 - \mathrm{LN}\left(\left(\frac{K_1}{K_2}\right)\right) = 0 \quad (20)$$

When both sides are divided by K_2 it gives;

$$\left(\frac{K_1}{K_2}\right)\mathrm{d} + \mathrm{LN}\left(\left(\frac{K_1}{K_2}\right)d\right) + \left(\frac{K_3}{K_2}\right) - \mathrm{LN}\left(\frac{K_1}{K_2}\right) = 0 \quad (21)$$

$$\left(\frac{K_1}{K_2}\right)\mathrm{d} + \mathrm{LN}\left(\left(\frac{K_1}{K_2}\right)d\right) = \left(\frac{K_3}{K_2}\right) - \mathrm{LN}\left(\frac{K_1}{K_2}\right) = 0 \quad (22)$$

Notably, $e^{(M+N)} = \left(\mathrm{e}^{(\mathrm{M})}\right)\mathrm{e}^{(\mathrm{N})}$ and also $\mathrm{e}^{(\mathrm{LN}(x))} = x$ then when the antilog is taken on both sides of Equation 22 it gives;

$$\left(\left(\frac{K_1}{K_2}\right)\mathrm{d}\right)\left(e^{\left(\left(\frac{K_1}{K_2}\right)\mathrm{d}\right)}\right) = \left(\frac{K_1}{K_2}\right)\left(e^{\left(\frac{-K_3}{K_2}\right)}\right) \quad (23)$$

Now, since $\left(\left(\frac{K_1}{K_2}\right)\mathrm{d}\right)\left(e^{\left(\left(\frac{K_1}{K_2}\right)\mathrm{d}\right)}\right)$ has the form $x(e^x)$, then, the Lambert W function solution for d is given as;

$$\left(\frac{K_1}{K_2}\right)\mathrm{d} = W\left(\left(\frac{K_1}{K_2}\right)\left(e^{\left(\frac{-K_3}{K_2}\right)}\right)\right) \quad (24)$$

$$\mathrm{d} = \left(\frac{K_1}{K_2}\right)\left[W\left(\left(\frac{K_1}{K_2}\right)\left(e^{\left(\frac{-K_3}{K_2}\right)}\right)\right)\right] \quad (25)$$

The solution to the resultant Lambert W function in d is obtained from web-based Lambert W function calculator which is accessed at: https://www.had2know.org/academics/lambert-w-function-calculator.html.

3. RESULTS AND DISCUSSION

The case study IoT sensors used in the simulations communicate via wireless links operating at microwave frequencies (f) of 2.5 GHz, 5.5 GhHz and 10 GHz and at rain rate for network percentage outage (p) of 0.1 %, 0.01 % and 0.001 %. The rain zone considered has rain rate of 35 mm/hr at p =0.1 %, 95 mm/hr at p =0.01 %, and 180 mm/hr at p =0.001 %. The rain attenuation constants for the horizontal and vertical polarization are obtained for the different frequencies from [17]. The simulation was also conducted for different base station antenna heights of 15 m, 30 m and 45 m.

The result of the Lambert W function output and communication range for the three frequencies, 2.5 GHz, 5.5 GHz and 10 GHz and different network percentage outage of 0.1 %, 0.01 % and 0.001 % are presented in Table 1. Also, the results for the path loss and rain attenuation for the three frequencies, 2.5 GHz, 5.5 GHz and 10 GHz and different network percentage outage of 0.1 %, 0.01 % and 0.001 % are presented in Table 2.

The graph of communication range, d versus frequency, f is shown in Figure 1, the graph of communication range, d versus network percentage outage, P is shown in Figure 2 while the graph of communication range, d versus Rain rate, Rp is shown in Figure 3. Specifically, the communication range for p = 0.1 % is 232.6 m at 10 GHz but increased to 683.0 m at 2.5 GHz. For f = 5.5 HGz, the communication range decreased from 372.4 m at p= 0.1 to 355.6 m at p= 0.001. Again, for p = 0.001 % the rain attenuation increased for 0.030 db for f = 2.5 GHz to 1.7492 for f = 10 GHz. Essentially, the results show that for the same set of input parameters, the communication range of the IoT sensor decreases with increase in frequency, increases with increase in allowable network outage and decreases with increase in rain rate.

The result of the communication range for the three frequencies, 2.5 GHz, 5.5 GHz and 10 GHz and the three different base station antenna height, hb of 15 m, 30 m and 45 m are presented in Table 3. Also, the results for the path loss and rain attenuation for the three frequencies, 2.5 GHz, 5.5 GHz and 10 GHz and the three different base station antenna height, hb of 15 m, 30 m and 45 m are presented in Table 4.

The graph of communication range, d versus frequency for the three different base station antenna height, hb are shown in Figure 4 while the graph of communication range, d versus base station antenna height, hb is shown in Figure 5. Specifically, the communication range for hb = 15 m 170.6 m at 10 GHz but increased to 468.4 m at 2.5 GHz. For f = 5.5 HGz, the communication range increased from 266.7m at hb = 15 m to 367.1m at hb = 45 m. Essentially, the results show that for the same set of input parameters, the communication range of the IoT sensor increases with increase in antenna height.

The simulation was also conducted for three different degree of urbanization represented by PB which is the percentage area of the city that is covered with building. Notably, PB of 3 % is for rural area, PB of 8 % is for sub-urban area and PB of 16 % is for urban area. The results for the communication range, d versus frequency for different degree of urbanization represented by PB are shown in Table 5, Figure 6 and Figure 7.

Specifically, the communication range for PB of 3 % is 680.4 m at 10 GHz but increased to 2325.2 m at 2.5 GHz. For f = 5.5 HGz, the communication range decreased from 1203.9 m at PB of 3 % to 367.1 m at PB of 16 %. Essentially, the results show that for the same set of input parameters, the communication range of the IoT sensor decreases with increase in frequency but decreases with increase in degree of urbanization represented by PB.

Table 1 The Lambert W function output and communication range for the three frequencies, 2.5 GHz, 5.5 GHz and 10 GHz and different network percentage outage of 0.1 %, 0.01 % and 0.001 %

	P =0.1 % Rain rate, Rp=35 mm/hr and hb =45 m			P =0.01 % Rain rate, Rp=95 mm/hr and hb =45 m			P =0.001 % Rain rate, Rp=180 mm/hr and hb =45 m		
f (MHz)	x(e^x)	x from Lambert W function calculator	Range, d (m)	x(e^x)	x from Lambert W function calculator	Range, d (m)	x(e^x)	x from Lambert W function calculator	Range, d (m)
10,000	**0.016981**	**0.0167**	**232.6**	**0.059581**	**0.056319**	**223.5**	**0.133051**	**0.118216**	**210.1**
5,500	**0.003483**	**0.003471**	**372.4**	**0.018088**	**0.01777**	**367.1**	**0.051919**	**0.049416**	**355.6**
2,500	**0.000328**	**0.000328**	**683.0**	**0.001005**	**0.001003**	**681.9**	**0.002057**	**0.002052**	**681.6**

Table 2 The path loss and rain attenuation for the three frequencies, 2.5 GHz, 5.5 GHz and 10 GHz and different network percentage outage of 0.1 %, 0.01 % and 0.001 %

	P =0.1 % Rain rate, Rp=35 mm/hr and hb =45 m			P =0.01 % Rain rate, Rp=95 mm/hr and hb =45 m			P =0.001 % Rain rate, Rp=180 mm/hr and hb =45 m		
f (MHz)	Rang, d (m)	Rain fade, A_{R_p} (dB)	CCIR path loss , L_{CCIR} (dB)	Rang, d (m)	Rain fade, A_{R_p} (dB)	CCIR path loss, L_{CCIR} (dB)	Rang, d (m)	Rain fade, A_{R_p} (dB)	CCIR path loss , L_{CCIR} (dB)
10,000	232.6	0.2471	129.8	223.5	0.8334	129.2	210.1	1.7492	128.3
5,500	372.4	0.0514	130.0	367.1	0.2629	129.7	355.6	0.7312	129.3
2,500	683.0	0.0049	130.0	681.9	0.0148	130.0	681.6	0.0304	130.0

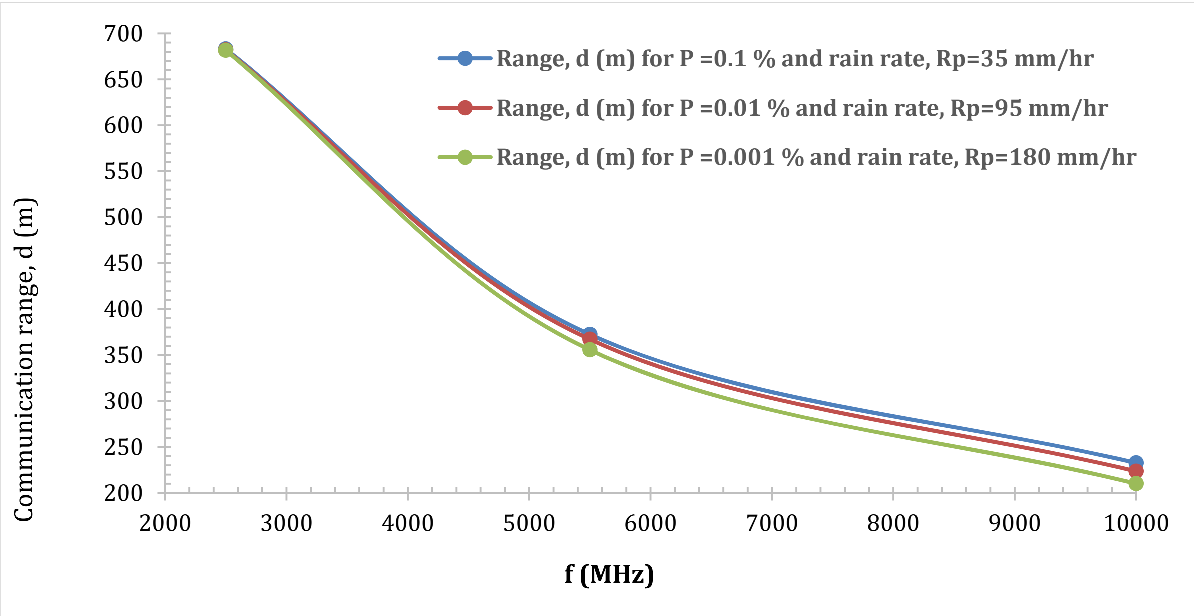

Figure 1 The communication range, d versus frequency, f is shown in Figure 1

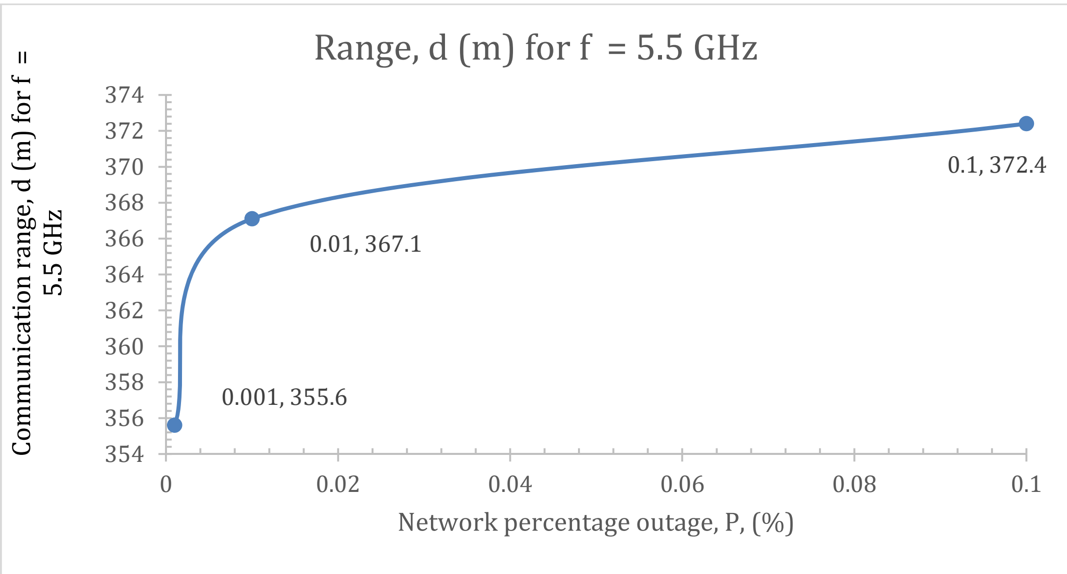

Figure 2 The communication range, d versus network percentage outage, P

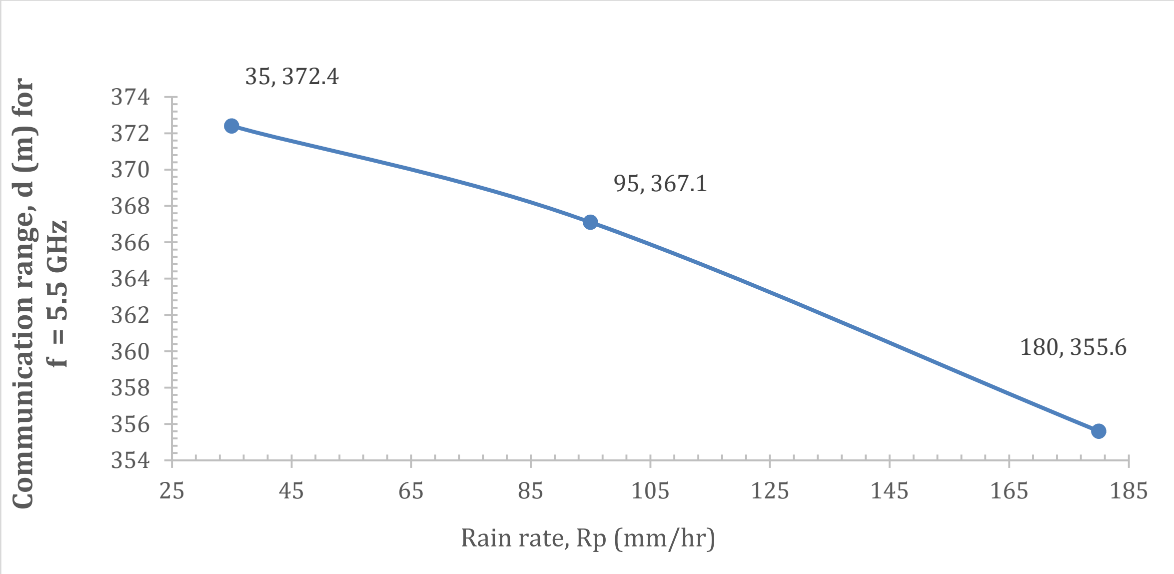

Figure 3 The communication range, d versus Rain rate, Rp

Table 3 The Lambert W function and communication range for the three frequencies, 2.5 GHz, 5.5 GHz and 10 GHz and different antenna height(hb) 15 m, 30 m and 45 m

	hb =15 m **Rain rate, Rp=95 mm/hr at p =0.01 %**			**hb =30 m** **Rain rate, Rp=95 mm/hr at p =0.01 %**			**hb =45 m** **Rain rate, Rp=95 mm/hr at p =0.01 %**		
f (MHz)	**x(e^x)**	**x from Lambert W function calculator**	**Range, d (m)**	**x(e^x)**	**x from Lambert W function calculator**	**Range, d (m)**	**x(e^x)**	**x from Lambert W function calculator**	**Range, d (m)**
10,000	0.040958	0.039377	170.6	0.051531	0.049064	201.3	0.059581	0.056319	223.5
5,500	0.011966	0.011825	266.7	0.015412	0.015412	329.1	0.018088	0.01777	367.1
2,500	0.000632	0.000631	468.4	0.000839	0.000839	589.7	0.001005	0.001003	681.9

Table 4 The Lambert W function and communication range for the three frequencies, 2.5 GHz, 5.5 GHz and 10 GHz and different antenna height(hb) 15 m, 30 m and 45 m

	hb =15 m **Rain rate, Rp=95 mm/hr at p =0.01 %**			**hb =30 m** **Rain rate, Rp=95 mm/hr at p =0.01 %**			**hb =45 m** **Rain rate, Rp=95 mm/hr at p =0.01 %**		
f (MHz)	**Rang, d (m)**	**Rain fade, A_{R_p} (dB)**	**CCIR path loss , L_{CCIR} (dB)**	**Rang, d (m)**	**Rain fade, A_{R_p} (dB)**	**CCIR path loss, L_{CCIR} (dB)**	**Rang, d (m)**	**Rain fade, A_{R_p} (dB)**	**CCIR path loss , L_{CCIR} (dB)**
10,000	170.6	0.6361	129.4	201.3	0.7506	129.2	223.5	0.8334	129.2
5,500	266.7	0.1910	129.8	329.1	0.2358	130.0	367.1	0.2629	129.7
2,500	468.4	0.0102	130.0	589.7	0.0128	130.0	681.9	0.0148	130.0

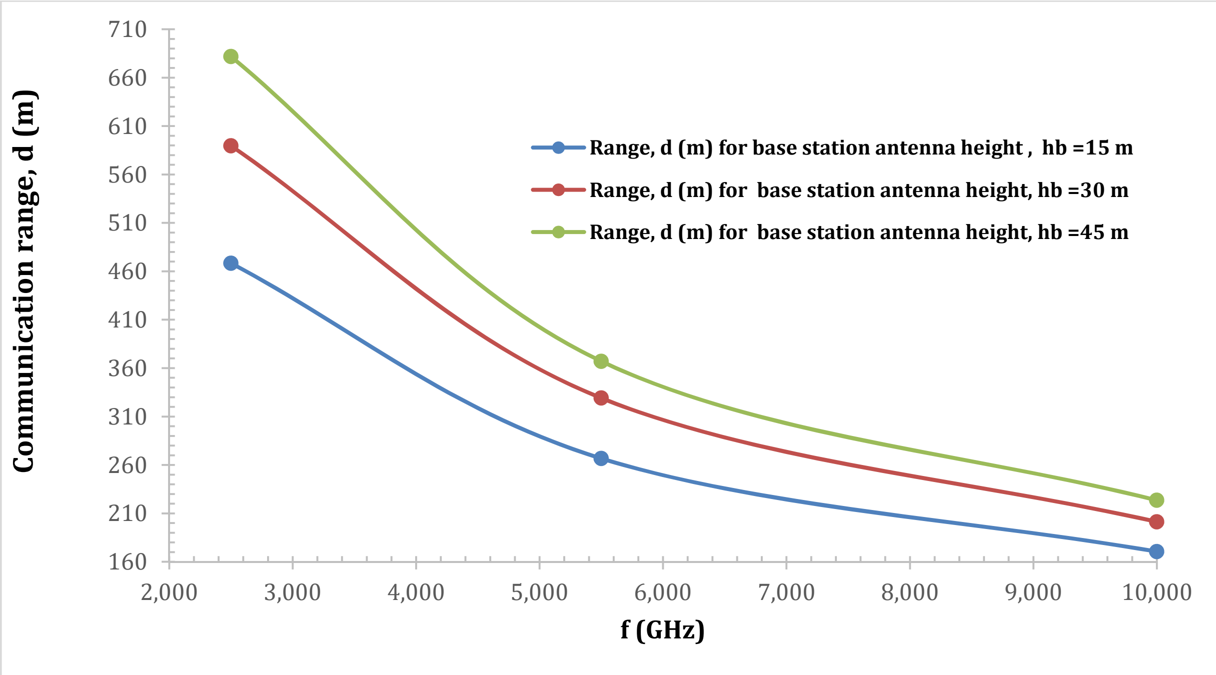

Figure 4 The graph of communication range, d versus frequency for the three different base station antenna height, hb

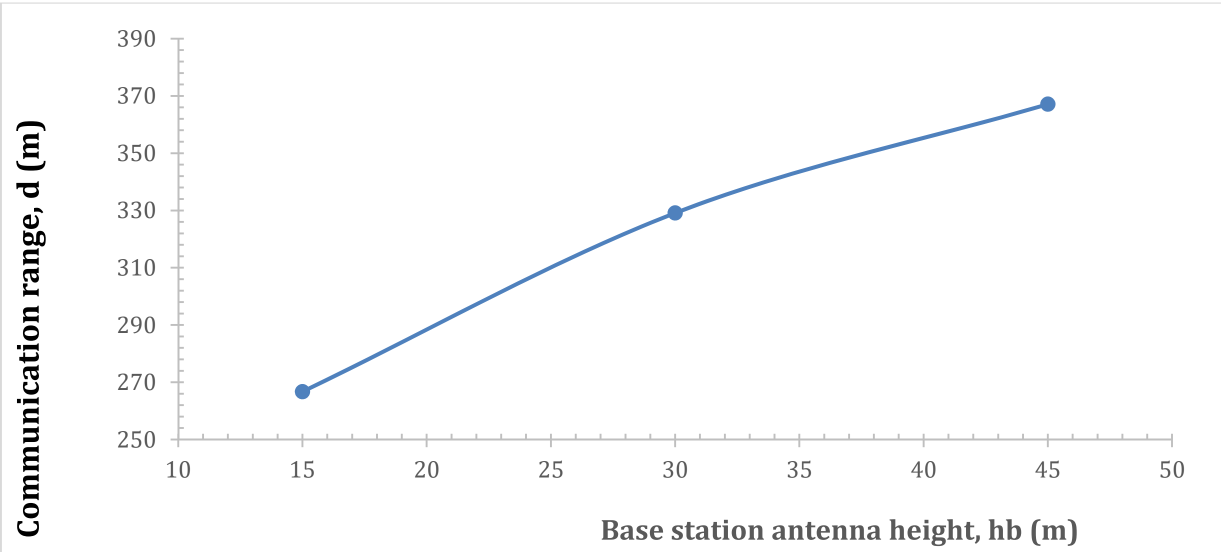

Figure 5 The graph of communication range, d versus base station antenna height, hb

Table 5 The results for the communication range, d versus frequency for different degree of urbanization represented by PB

	Percentage area covered with building, **PB = 3 %**			Percentage area covered with building, **PB = 8 %**			Percentage area covered with building, **PB = 16 %**		
f (MHz)	**x(e^x)**	**x from Lambert W function calculator**	**Range, d (m)**	**x(e^x)**	**x from Lambert W function calculator**	**Range, d (m)**	**x(e^x)**	**x from Lambert W function calculator**	**Range, d (m)**
10,000	0.203492	0.171433	680.4	0.099081	0.090508	359.2	0.059581	0.056319	223.5
5,500	0.061778	0.058281	1203.9	0.03008	0.029214	603.5	0.018088	0.01777	367.1
2,500	0.003431	0.00342	2325.2	0.001671	0.001668	1134.1	0.001005	0.001004	682.6

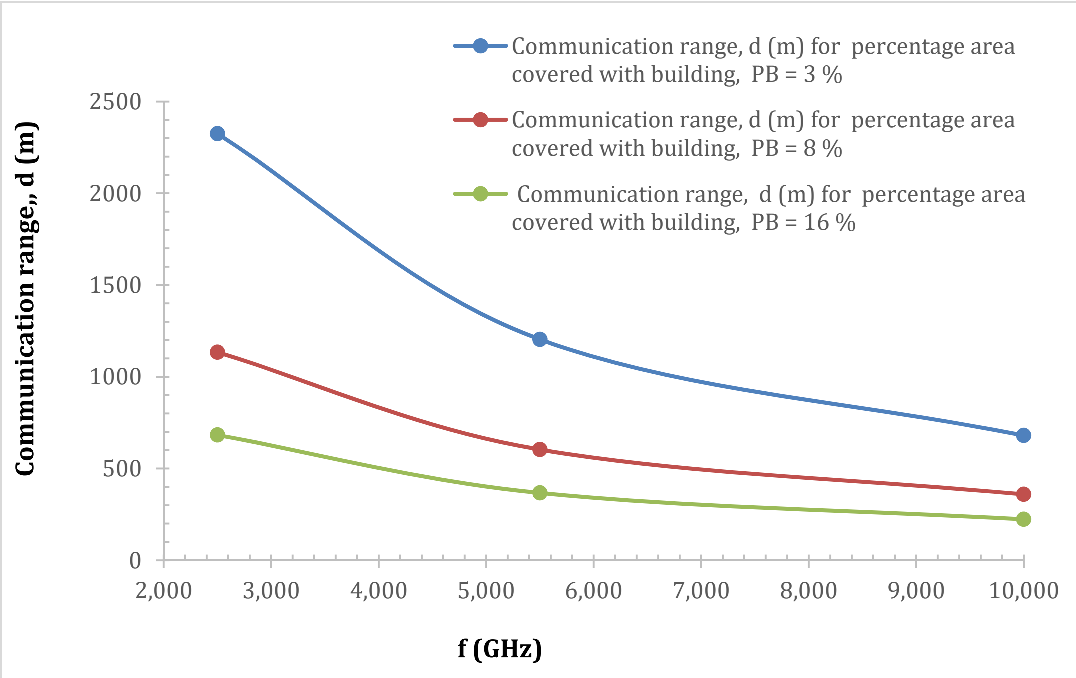

Figure 6 The graph of communication range, d versus frequency for degree of urbanization represented by PB

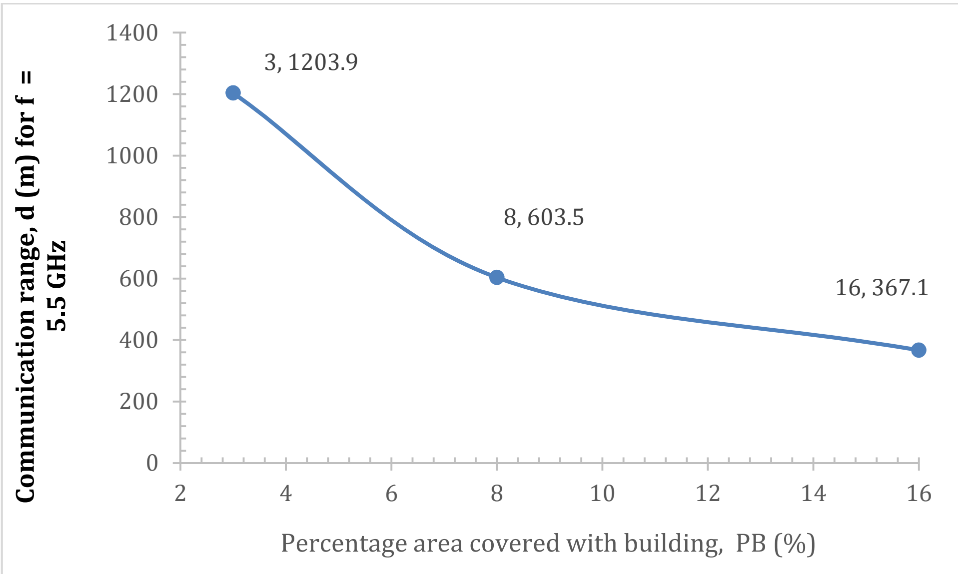

Figure 7 The graph of communication range, d versus degree of urbanization represented by PB for f = 5.5 GHz

4 CONCLUSION

The communication range of IoT sensor node operating in the microwave frequencies of 2.5 GHz to 10 GHz under rainy sky condition is presented. The sensor node is to be deployed for smart city application. Accordingly, the CCIR propagation loss model was used to estimate the loss in the signal path due to the obstructions in the city. Notable obstructions in the model are buildings which are captured by PB parameter that indicates the percentage of the area that is covered by building.

Also, the study considered rainy sky condition and hence, the power-law rain attenuation model was used. The resultant expression for the communication range required the use of Lambert W function which was then used to determine the communication range for different network parameter configurations. In all, the results clearly demonstrated the effectiveness of the Lambert W function if solving the log-product expression for the communication range. The results also showed that for the same set of input parameters, the communication range of the IoT sensor decreases with increase in frequency, increases with increase in allowable network outage and decreases with increase in rain rate. Also, the transmission range increases with decrease in the percentage area that is covered with buildings.

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