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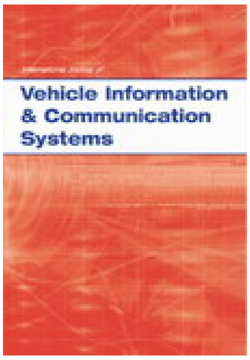

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Experimental study of the weather effects on LoRa-based vehicular communications

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Abstract: Long-range (LoRa) nodes, which work in the sub-GHz frequency bands, are used in IoT applications and in vehicular environments. Deployment of these low-power long-range sensor nodes requires better analysis of the link quality and weather and environmental conditions. In literature very little information is available about the impact of weather conditions on the performance of LoRa-based applications. The impact of the height and the shaded region will also impact the link quality. The suburban and urban environment is considered in this paper to evaluate the performance of the several link qualities under the weather conditions such as fog, humidity, temperature, shaded region and the impact of height. Regular pattern of RSSI is analysed and PDR values are presented to understand the impact of the weather conditions and other effects on the link quality. Real outdoor test bed experimentation was performed to validate the results. We have observed that increase in temperature degrades the RSSI value which further lowers the PDR. These two parameters can be improved by increasing SF value. Humidity and height of node also affect the RSSI value. The given work can help in outdoor LoRa node deployment for various modes of vehicular communications.

Keywords: humidity; temperature; weather condition; long-range technology; PHY settings.

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Biographical notes: Jetendra Joshi received his BE degree in Electronics and Communication Engineering and subsequently obtained his MS degree in Software Systems from BITS Pilani India.

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1 Introduction

The future smart autonomous vehicles and smart cities deploy V2X communication as one of the modes for fast and reliable data transmission between nodes (Wang et al. 2019). Yang et al. (2020) stated that the autonomous driving reduces travel time and avoids collision which are the major benefits of V2V communication. In the given mode the data is shared between the vehicles in a cooperative manner. Collision avoidance, congestion avoidance and traffic signal control can be done by the help of V2I mode of communication in which the vehicles on the road communicate with the roadside infrastructure. Pasha et al. (2020) described that accident prevention can be done by easily identifying the pedestrian with the help of V2P mode of communication.

Elagin et al. (2020) also stated that the smart phone can act as the data forwarder to the other network and helps in connecting the agents of vehicular network to another one and is termed as V2N. The V2N is the least explored mode in the V2X communication. Xu et al. (2018) analysed the different parameters of the vehicle such as acceleration, speed and geographic location coordinates (latitude and longitude) which are shared with the roadside infrastructure, latency, security, long distance transmission and time criticality are some of the few challenges faced by V2X communication as discussed by Alnaeli et al. (2017), Maitra and Yelamarthi (2019) and Chandra Shit (2020).

Vehicle mobility and the dynamic environment are one of the important challenges faced in the V2X communication in the vehicular environment. The data handover must take place between the two vehicles and between the RSU based on the appropriate routing protocols. Smooth handover can be hampered by poor link quality, mobility and the changing environment. Real time data dissemination is also one of the important challenges in V2X communication to provide support to the Intelligent Transportation Services (ITS) application including autonomous driving and accident avoidance. The reliable and robust V2X communication architecture is the common need for today's vehicular ecosystem. The need for the future is to propose a scheme in V2X communication that provides fast and reliable transmission to overcome the above-mentioned challenges.

Different wireless technologies are studied by various researchers to find the most suitable one that can be applied to the V2X environment. Ortiz et al. (2020); Cheung et al. (2019) and Shao and Luo (2015) analysed the technologies such as Wi-Fi, (LoRa) communication; BLE and Zigbee. Amadeo et al. (2019) and Duan et al. (2020) described some important wireless technologies in their work such as the third Generation Wi-Max, IEEE 802.11p, LTE and 5G. Haque et al. (2020) described some of the important challenges such as transmission range, communication latency, power consumption and transmission throughput that are to be considered while using these wireless technologies in the vehicular ecosystem. Abdulshaheed et al. (2020) found that the long-range transmission can be obtained easily by incorporating 4G and Wi-Max. Some of the technologies mentioned above are utilising large amounts of power for their operation and they are energy hungry. Also, the transmission frequency band on which they are working is not aligned to the dedicated frequency band of V2X communication. The mobility and the time varying environment increase the need of a greater number of routers to transfer the data from one location to another which also increases the number of hop counts that overburden the network and cause higher latency.

The low-power consumption and optimised mesh networking are the benefits of Zigbee which finds more popularity in both outdoor and indoor applications. The optimised routing can also be performed based on the multihop strategy. The communication range obtained with Zigbee technologies is very small (up to 100 m) which can be enhanced by using other technologies such as LoRa and Wi-Max. The use of multi hop strategies, which cause multiple handovers in the Zigbee wireless technology, increases the latency therefore it is required to use other technology for device-to-device communication which helps to enhance the coverage range and reduce the latency.

Lavric and Popa (2018) found that the long range of few kilometres and the balance between the data transmission rate and transmission range can be obtained by inclusion of LoRa technology in the V2X communication. Mahmud et al. (2017) used IEEE 802.15.4 low-power communication standard in the LoRa transmission. The wide area network can be easily deployable using the LoRa module which is not possible with the Zigbee. The wide area network based on the LoRa nodes is called the Long-Range wireless area network (LoRaWAN).

The transmission range of 2 to 4 km can be obtained in the urban area with line-of-sight condition and the range can be extended to 10 km in the suburban environment. Petäjäjärvi et al. (2017), Catherwood et al. (2018), Jawad et al. (2017), Benaissa et al. (2017), Ilie-Ablachim et al. (2016), and Bakkali et al. (2017) described various long-range applications like healthcare monitoring, agriculture and environmental monitoring. Podevijn et al. (2018) and Sharma et al. (2018) discussed the traffic monitoring in their work. Various smart city applications were described by Pasolini et al. (2018) whereas Wang and Fapojuwo (2018) analysed the different frequency range (of 868 MHz (Europe), 915 MHz (Australia and America) and 433 MHz) over which the LoRa module works. Adelantado et al. (2017) found that the maximum data rate of 27 kbps can be obtained in both indoor and outdoor LoRa-based applications. Vehicular communication in various environments uses dedicated short-range communications (DSRC) as the name suggests. Lee and Lim (2013) stated that DSRC is based on IEEE 802.11.

The novelty of the present work is in depth analysis of the LoRa device to device approach is formulated and tested in different modes of V2V, V2I conditions. Tables 2 and 3 show that most of the researchers have done the demonstration using real prototypes but the effect of environment and weather conditions as well as physical settings were not considered previously for outdoor scenario. The impact on RSSI was also not considered in the urban and suburban environment along with weather conditions. The abbreviations used in the given article is expressed in Table 1.

The rest of this paper is organised as follows: Section 2 presents the related work and comparison of the literature work. After that, Section 3 presents the systematic background description about the routing protocol whereas Section 4 presents the insight of the simulation environment. Section 5 discusses findings and results and Section 6 concludes the work.

Table 1 Abbreviations

S. No	*Abbreviation*	*Explanation*
1	LoRa	Long Range
2	RSSI	Received Signal Strength Indicator
3	PDR	Packet Delivery Ratio
4	SF	Spreading Factor
5	PHY	Physical
6	IoT	Internet of Things
7	V2X	Vehicle to Everything
8	V2I	Vehicle to Infrastructure
9	V2V	Vehicle to Vehicle
10	V2P	Vehicle to Pedestrian
11	ITS	Intelligent transportation system
12	LTE	Long Term Evolution

2 Related work

Nowadays, interest is shown by academicians and researchers to use LoRa in various applications. Liando et al. (2019), Petajajarvi et al. (2017) and Wang et al. (2017) stated that LoRa can be used in various setting and under the mobility scenario. Andrei et al. (2017), Liando et al. (2019) and Petajajarvi et al. (2015) stated that these devices show efficient and reliable communications till the speed of the nodes are moderate. Fargas and Petersen (2017) described that the LoRa can be used in the geolocation services and the studies analysed the performance of LoRa in mountain, forest and continental environment. Iova et al. (2017) described that the effect of temperature and vegetation generally impact the quality of signal, but the in-depth analysis of the performance is missing and the effect of change in physical parameters of the LoRa modules are also not studied in detail.

Various use cases of Internet of Things (IoT) such as health, mobility, agriculture, smart city incorporate LoRa technology for long distance communication. Sidorov et al. (2019) and Sheng et al. (2020) described in their study the impact of weather conditions on the link quality. Boano et al. (2018) and Cattani et al. (2017) analysed various weather conditions such as humidity and temperature. Ameloot et al. (2019) performed the experiment to check the relation between RSSI and the temperature. These controlled experiments do not give information about the impact of weather conditions in the open environment. Souza Bezerra et al. (2019), Ameloot et al. (2019) and Elijah et al. (2021) studied in detail to get the in-depth performance analysis of LoRa application in diverse weather conditions. Jeftenić et al. (2020) studied the extreme weather conditions around the world but failed to provide much information about the LoRa communication link. In our experiment of LoRa-based device to device communication in different vehicular modes we also observed that there is considerable packet loss in the daytime when the temperature is high and above the selected baseline temperature. The effects of weather parameters such as temperature, humidity and foggy conditions are analysed in further investigation. To the best of our knowledge the effect of the physical setting of LoRa was not considered previously in any of the literature that will help to improve the PDR and link quality of the channel. To bridge this gap both the environment location of urban and sub-urban are taken into consideration to study the effect of weather conditions. The impact of height and shaded region is also taken into consideration on the link in different vehicular environment.

In the present work we have performed in depth performance analysis of the effect of changing the physical setting on the PDR and the RSSI value that help to quantify the link quality better in vehicular scenario. The effect of weather conditions in different environmental scenarios of urban and sub-urban areas are also studied. The study of the effect of the height of node and the shaded condition are helpful in better node placement for the fast data dissemination in LoRa-based communication. First time in our study we included speed as well as environmental and weather conditions on LORA-based vehicular environment and LORA-based applications as shown in Tables 2 and 3, respectively.

Table 2 Comparative study of LoRa-based application in V2X environment

Literature	*Prototype*	*Speed*	*Evaluation under different environment condition*	*Evaluation under different weather conditions*	*Reliability*
Cheung et al. (2019)	yes	no	no	no	yes
Li et al. (2018a)	yes	no	no	no	yes
Li et al. (2018b)	yes	yes	no	no	no
Sanchez-Iborra et al. (2017)	yes	no	no	no	no
Santa et al. (2019)	yes	yes	no	no	no
Janani et al. (2018)	yes	no	no	no	yes
Haque et al. (2020)	yes	yes	no	no	yes
Our Proposed scheme	yes	yes	yes	yes	yes

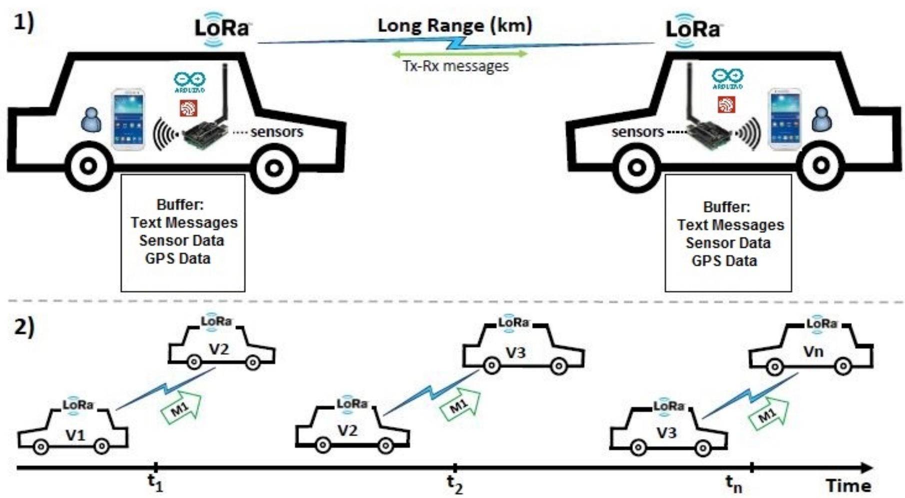
Table 3 Comparative study of the effect of weather conditions on LoRa-based application

Literature	*Effect of temperature and humidity*	*Real practical scenario*	*Other effects and fog conditions*	*Effect of physical setting on transmission*	*Effect of environmental scenario*
Ortiz et al. (2020)	No	yes	no	no	Yes
Ameloot et al. (2019)	yes	yes	yes	no	no
Boano et al. (2018)	Yes	No	No	Yes	No
Elijah et al. (2021)	yes	yes	No	No	No
Our Proposed scheme	Yes	Yes	Yes	Yes	yes

3 Background

Long range, low power, less complex networking protocols are some of the advantages of the use of LoRa technologies in the vehicular environment. The best selection of sub-GHz frequency band and low-transmission power will make the LoRa technologies suitable for different IoT applications. Figure 1 depicts LoRa-based testbed equipped vehicles which perform different modes of communication. The LoRa-based communication works better in V2V and V2I environments.

Figure 1 LoRa-based vehicular communication



3.1 Hardware implementation

The block diagram of the experimental setup to analyse the effect of temperature and humidity is shown in Figure 2. The experimental test device consists of Pycom-Lopy LoRa module. The NEO 6M GPS module is attached to the LoRa module to get the information about the location of the node. The test device consists of LoRa module along with temperature sensor DHT11 or sensor BME280.

All nodes measure the temperature and humidity using a DHT 11 sensor it also measures the location of static and mobile node in different environmental condition of urban and suburban scenario.

The received location information gets recorded along with the PDR and RSSI value on the computing device. The actual experimental setup is shown in Figure 3.

Figure 2 Block diagram of LoRa setup

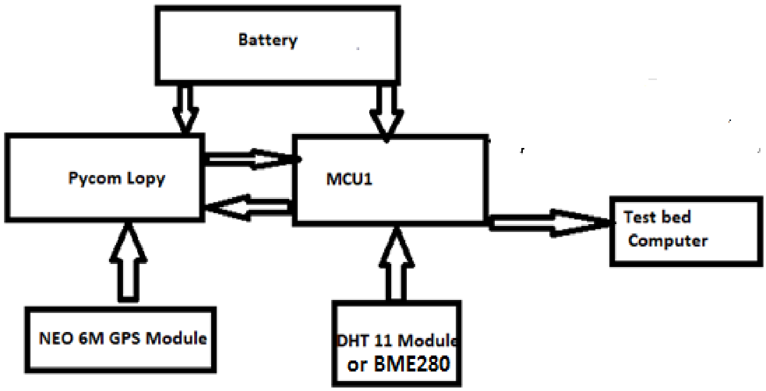
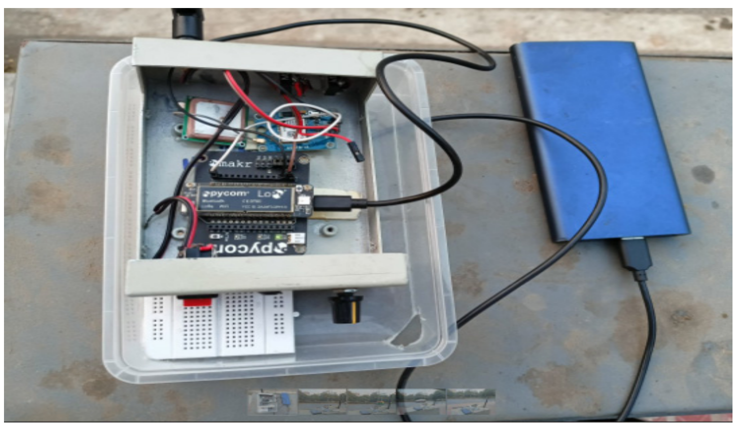


Figure 3 LoPy module with sensors



4 Experimental steps and methodology

The considered five scenarios for the suburban environment are as follows:

1 Considering the scenario of temperature variation along the two consecutive days. The variation of temperature on RSSI and PDR is examined for the given experimental days.

2 Considering the scenario of humidity variation along the two consecutive days. The variation of humidity on RSSI and PDR is examined for the given experimental days.

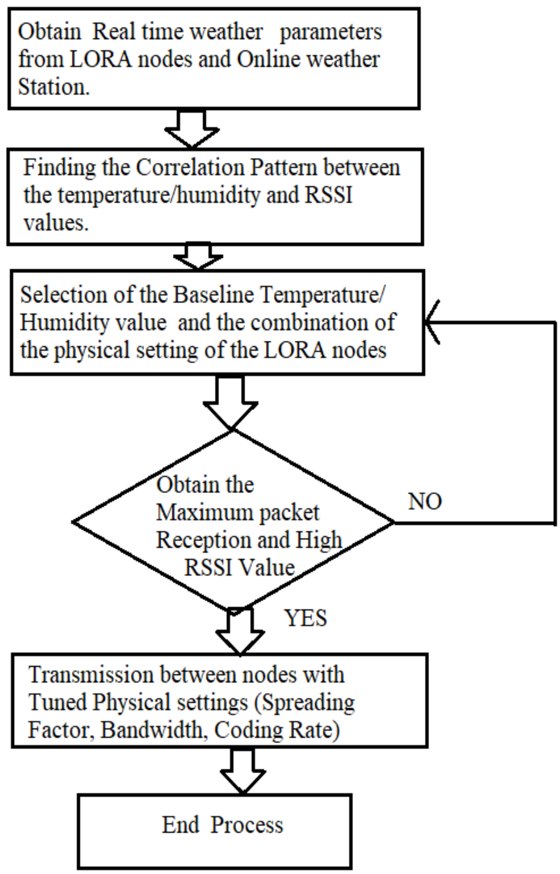
3 Considering the scenario of foggy condition variation along the two consecutive days. The variation of fog intensity on RSSI and PDR is examined for the given experimental days.

4 Considering the scenario of impact of height and the node placement for both urban and suburban environment on the link quality. The variation of height on RSSI and PDR is examined for the given environmental condition.

5 Considering the scenario of impact of shading on the link quality. The variation of shading and open (unshaded) region on RSSI and PDR is examined for the given environmental condition.

The effect of different weather and environmental parameters on vehicular communication has been done using the pseudocode given below and the flow chart is given in Figure 4.

Figure 4 Flowchart to examine the Effect of weather condition



Attribute of vehicle → priority flag, id, RSSI value, GPS location.

Attributes of the Environmental and weather parameter → temperature, humidity, rainfall intensity and Duration, Environmental condition (Urban and Sub-urban).

{

Match = detect (RSSI value & Environmental parameter)

if (Match > = Threshold value of the channel link RSSI) {

Normal Vehicular communication (with initial PHY setting of LORA module).

} **else**

{

Adaptive vehicular communication (with a switching scheme over the time for the PHY settings as shown in Table 4)

Store the best possible PHY setting for the given Environmental conditions.

}

End

Table 4 Physical setting of LoRa combination

Setting ID	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*
SF	7	7	7	7	9	9	9	9	12	12	12	12
Coding Rate	4/5	4/5	4/8	4/8	4/5	4/5	4/8	4/8	4/5	4/5	4/8	4/8
BW (KHz)	125	250	125	250	125	250	125	250	125	250	125	250

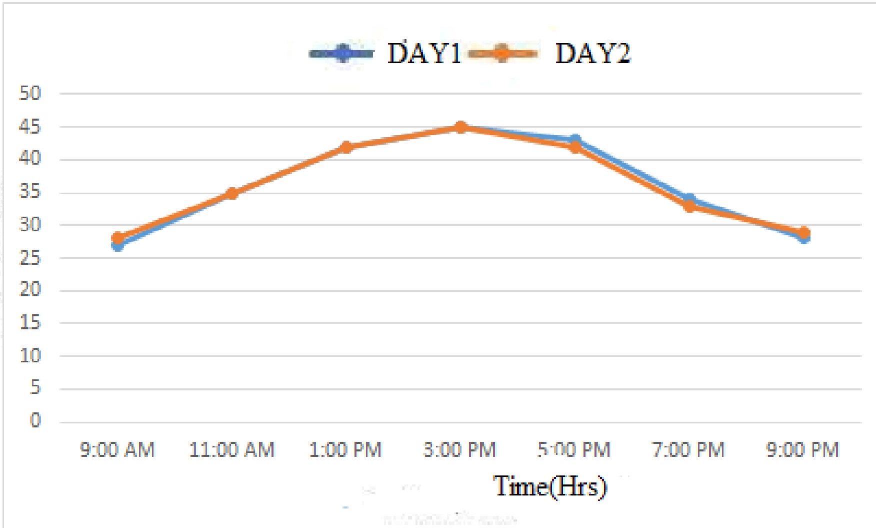
5 Results and discussion

5.1 Effect of weather condition (temperature) in the suburban environment

Using the sensors BMP680 or DHT 11 sensor module the value of temperature and humidity are obtained. The daily atmospheric temperature is recorded by the sensor module DHT11 which is attached with LoPy-based test bed on the vehicle as movable and as static node. The daily atmospheric temperature values were gathered from the online weather station. The suburban environment of Neemrana, Rajasthan, was taken as the experimental test bed scenario.

The atmospheric temperature data were plotted for the consecutive two days as shown in Figure 5. The two consecutive days taken are 28 to 29 May 2022 and both days are clear sunny days with humidity level less than 15%. The data is collected from the time 9 am to 9 pm daily.

Figure 5 Atmospheric temperature data for both the experimental days (see online version for colours)



The onboard and atmospheric temperatures are plotted as seen from Figure 6 for two consecutive days. Equation (1) (Forster and Lopez, 2007) gives the relation between the onboard temperature and the ambient atmospheric temperature.

$$T_j = T_a + \left(P_d \times R_{ja}\right) \quad (1)$$

where

T_j the onboard junction temperature of the semiconductors.

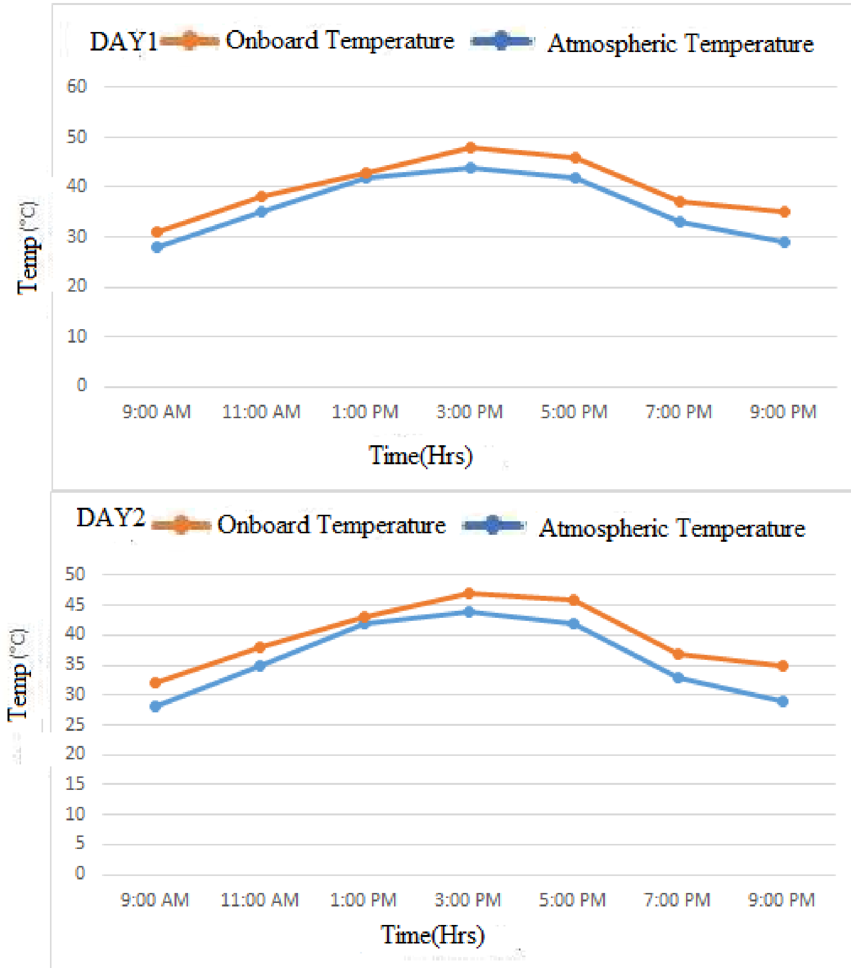
T_a the air temperature.

T_a is the junction to ambient thermal resistance.

P_d is the dissipated power.

From Figure 6, we concluded that for both consecutive days the atmospheric temperature increases, and it has direct impact on onboard temperature which also rises to higher value during the given time. The experimental test bed consists of semiconductor devices which are influenced by atmospheric temperature and have an impact on the LoRa radio.

Figure 6 Onboard temperature and atmospheric temperature for the Day 1 and Day 2 (see online version for colours)



The amount of solar radiation directly impacts the atmospheric temperature, and this leads to the direct relation between the RSSI values of the link to the atmospheric temperature.

The correlation can be determined using expressed by Zhou et al. (2016) as follows:

$$\begin{aligned} Cov(D1, D2) &= \left(\sum \left(D1 - \mu(D1)\right) \times D2 - \mu(D2)\right) \div (n-1) \\ Cov(D1, D2) &= \left(Cov(D1, D2) \div \left(std(D1)\ X\ std(D2)\right)\right) \end{aligned} \tag{2}$$

where *cov*, μ and *std* and *cov* are the covariance, mean and standard deviation, respectively. D1 presents the value of the calculated RSSI while D2 represents the temperature value. After using equation (2) and finding the parameters of the correlation value the data is tabulated for the two given consecutive days in Table 5.

Table 5 Correlation test: temperature vs. RSSI for suburban location

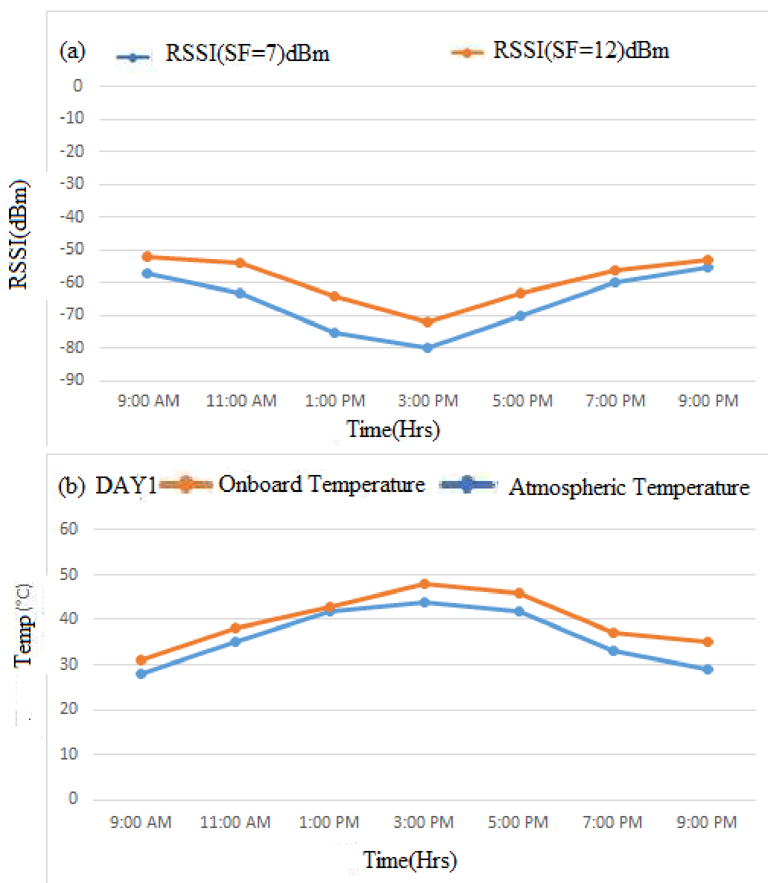
Days	*Pearson Correlation*
28th may	.78
30th may	.85

Using equations (2) and (3) with the atmospheric temperature obtained from the collected data for the two days. Luomala et al. (2016) stated the mean values of the RSSI.

$$Mean(RSSI) = \left(\sum(RSSI\right) / n \tag{3}$$

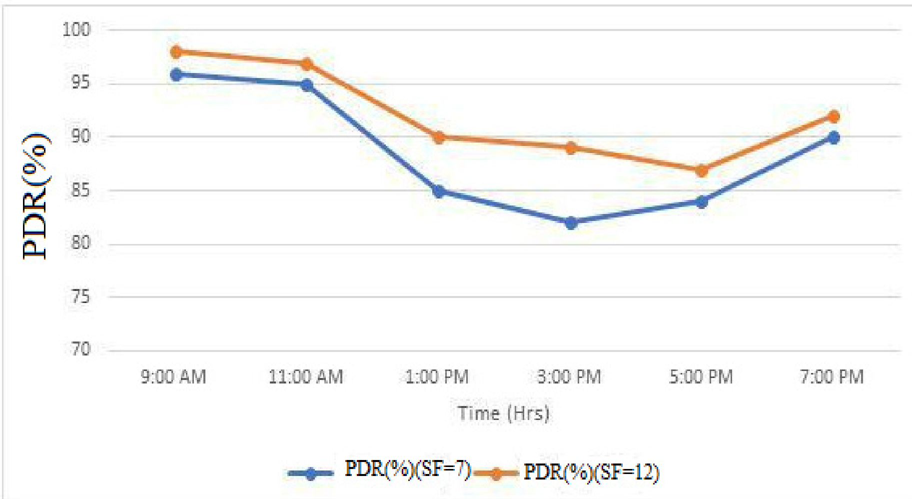
Figures 7(a) and 7(b) show the temperature chart of 28th and 30th May 2022. The positive correlation between RSSI value with the temperature is also shown in Figures 7(a) and 7(b) for the day1. During the day the RSSI value increases with the increase in temperature. These figures reflect the peak values of about 38 to 44°C were observed. Larger value of RSSI is obtained during the given time. The onboard temperature lies between 40°C and 50°C.

Figure 7 (a) RSSI vs. time graph for the Day1 (b) Temperature (onboard and atmospheric) with time (see online version for colours)



The same pattern between the amount of RSSI and atmospheric temperature can be observed on day 2. Both days are clear and sunny with very low humidity value that leads to the same observation from the day 1 chart of the atmospheric and onboard temperature data as above in Figure 8. The phenomena of packet delivery loss are observed due to the degradation in the RSSI values during high-atmospheric temperature. The graph between the packet delivery ratio with RSSI for the given time of the experimental days is shown in Figure 8.

Figure 8 Effect of SF on the PDR for the given experimental day (see online version for colours)



The graph also shows the effect of changing value of the SF as stated above from the SF=7 to SF=12 in the LoRa module test node. The value of PDR increases by 8 to 10% within the range of 35 to 45°C as the maximum RSSI degradation was observed during the given time of the day because of increase in the temperature. The increase in SF leads to the improvement in the link quality and hence the RSSI and the PDR also increases.

5.2 Experimental results of the performance of the effect of weather condition (temperature) in the urban environment

RSSI level-based heat map is generated through the experiment when both the nodes are static and placed at different locations Figure 9 shows the RSSI heatmap for the given road segment A-B-C and in between this road segment we have intersection junction at T1, T2 and T3 where traffic lights are already present in the real scenario. The two heatmaps are plotted which are taken between 1am to 3 pm with the two different physical settings of the LoRa module. Two cases are considered, case 1: where BW=125, C/r=4/5 and SF=7 and case 2: where BW=125, C/r=4/5 and SF=12.

Figure 9 RSSI heatmap for the given road segment (A-B-C) (see online version for colours)

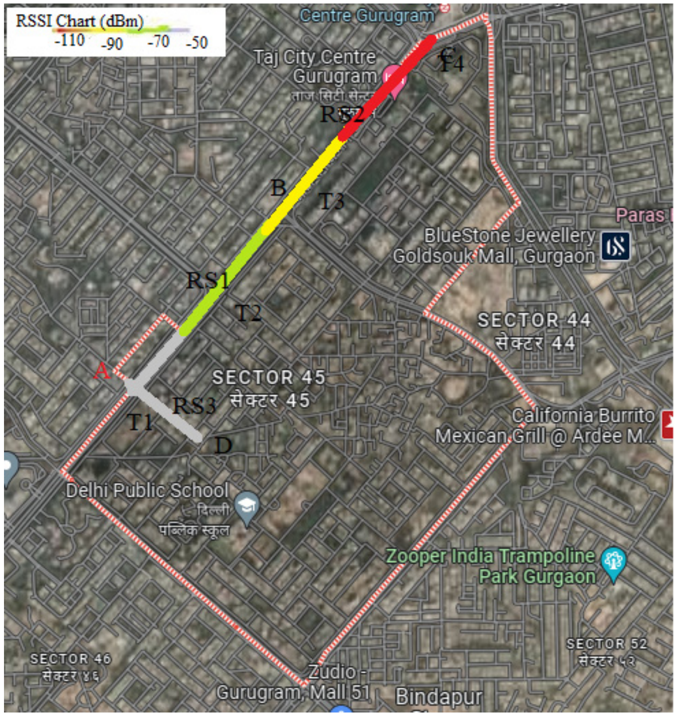


Table 6 gives the distance chart of the different points on the road segments which are calculated using a speedometer.

Table 6 Distance chart of the different road segments

Segment	*Distance (Metres)*
A-B	800
A-T1	600
T1-T2	600
T2-T3	200
A-D	400
A-C	1200

The daily atmospheric temperature values were gathered from the test bed sensor module and from the online weather station. The location of Huda City, Gurgaon, was selected as the experimental test bed. The atmospheric temperature data were plotted for the consecutive two days as shown in Figure 10. The two consecutive days taken are 12th and 13th June 2022 and both days are clear sunny days with humidity level less than 10%. The data is collected between 9 am and 9 pm daily for two consecutive days.

After analysing Figure 11 it is observed that onboard temperature increases as atmospheric temperature increases. The experimental test bed consists of semiconductor devices which are influenced by atmospheric temperature and have a direct effect on LoRa radio.

Figure 10 Atmospheric temperature chart of two consecutive days (see online version for colours)

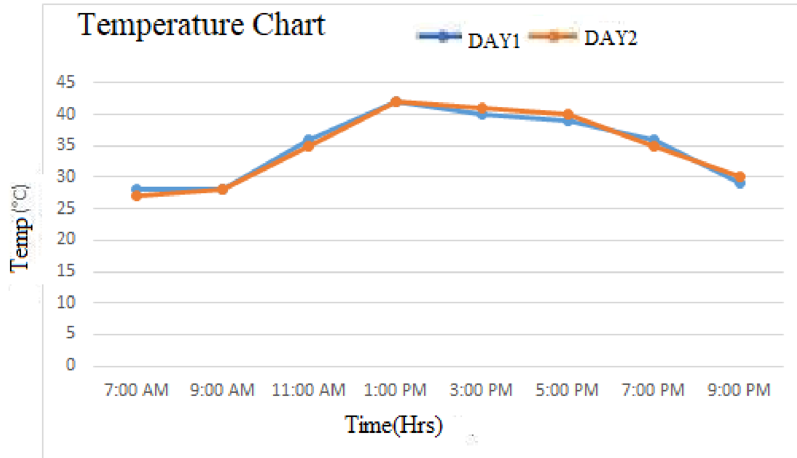
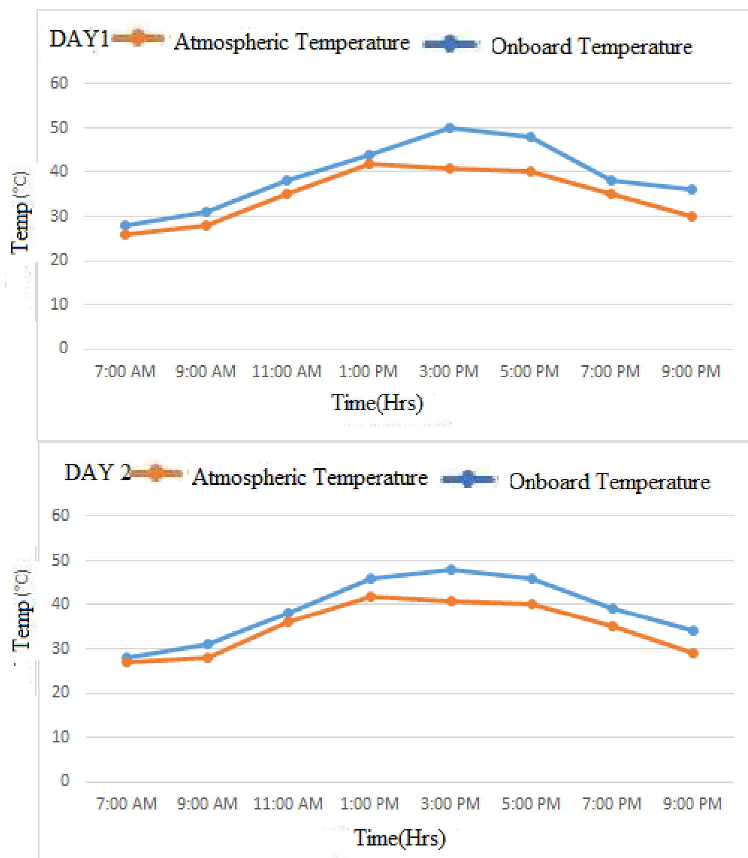


Figure 11 Onboard temperature and atmospheric temperature for two consecutive days (see online version for colours)



The amount of solar radiation directly impacts the atmospheric temperature, and this leads to the further change in the value of RSSI. After using the above equation (2) and finding the parameters of the correlation value the data is tabulated for the two given consecutive days in Table 7.

Table 7 Correlation test: temperature vs. RSSI for urban location

Days	*Pearson Correlation*
12th June	.78
13th June	.82

From the visual inspection of Figure 11, a positive correlation of the SSI value with the temperature for both the days is observed. During the day the RSSI value increases with the increase in temperature. Figures 12(a) and 12(b) show the temperature chart of both the days of 12th and 13th June 2022. Peak values of about 43 to 45°C were observed. Stronger value of RSSI obtained during the given time. The onboard temperature is in the range of 45 to 55°C and the atmospheric temperature lies between 35°C and 45°C.

Figure 12 (a) RSSI vs. time graph and temperature graph (onboard and atmospheric) with time for Day 1 (b) RSSI vs. time graph for the Day 2 and temperature (onboard and atmospheric) with time for Day 2 (see online version for colours)

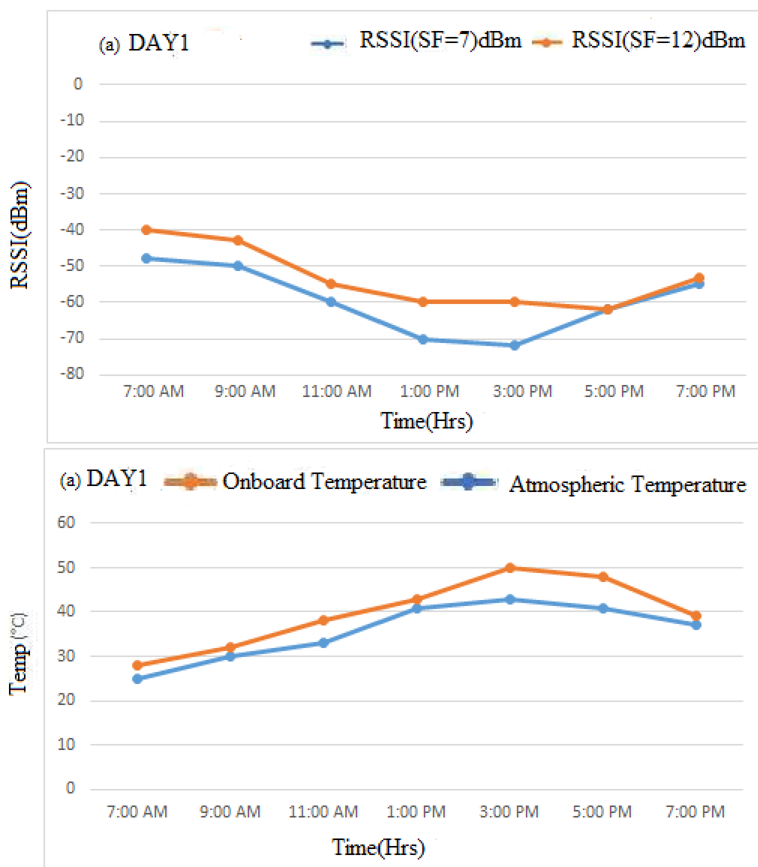
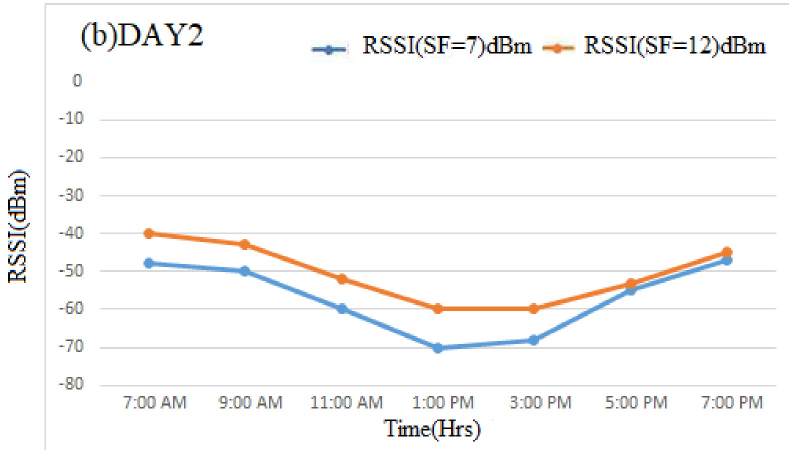
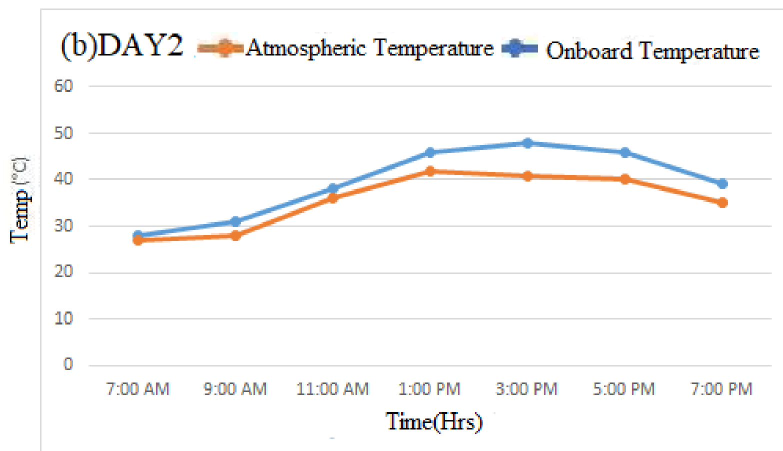


Figure 12 (a) RSSI vs. time graph and temperature graph (onboard and atmospheric) with time for Day 1 (b) RSSI vs. time graph for the Day 2 and temperature (onboard and atmospheric) with time for Day 2 (see online version for colours) (continued)



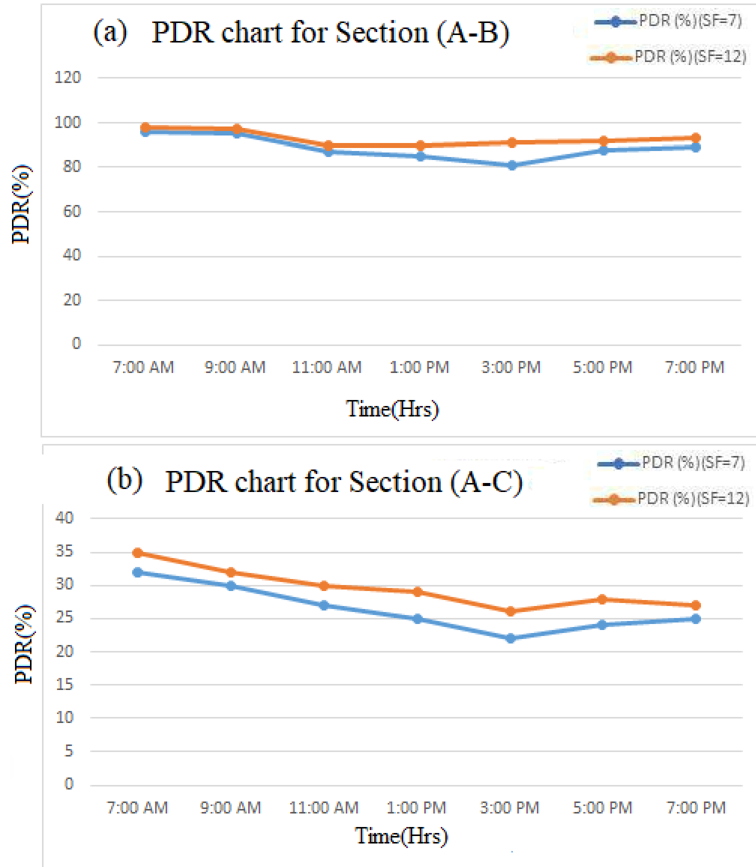


The graph between the PDR with RSSI for the given time of the experimental days are shown in Figures 13(a) and (b). The PDR graph is taken for the two-road section.

The first graph (see Figure 13(a)) is for the road section A-B and the second graph (see Figure 13(b)) is for the road segment A-C. Both the graphs show the effect of changing value of the SF as stated above from the SF=7 to SF=12 is done in the LoRa module test node has the impact on the PDR.

The value of PDR increased by 8% within the range of 35 to 45°C as given in Figure 13(a) but in the second graph as shown in Figure 13(b) the improvement is 15 to 20% as the maximum RSSI degradation was observed during the given time of the day because of increase in the temperature and also due to the environmental surrounding which causes fading and other multipath interference due to the location of high-rise buildings at the location point C labelled in the map as given in Figure 8.

Figure 13 (a) Effect of SF on the PDR for the given experimental day for section (A-B) (b) Section (A-C) (see online version for colours)



5.3 Experimental results of performance of the effect of weather condition (humidity) in the suburban environment

The daily atmospheric temperature values and the relative humidity were recorded from the test bed module and from the online weather station. The location between the road sections Rx-B of distance 1 km at Neemrana, Rajasthan, was chosen for the experimental bed. The atmospheric temperature data were plotted for one day as shown in Figure 14. The day 23rd September 2022 is densely cloudy and there is drizzle in the morning till 11 am and moderate rain in the afternoon time for the given day with the humidity level between 80% and 95%. The data is collected from the time 9 am to 5 pm daily for the given day.

Figure 15 shows the relative humidity data gathered for one day. After analysing the results shown in Figure 15, the value of relative humidity is observed to be between 85 to 95%.

Figure 14 Temperature chart for the given experimental day for humidity measurement

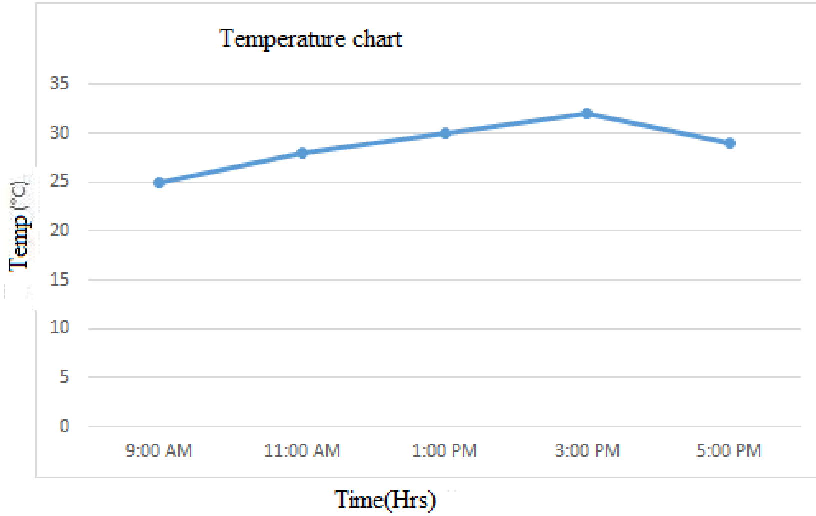
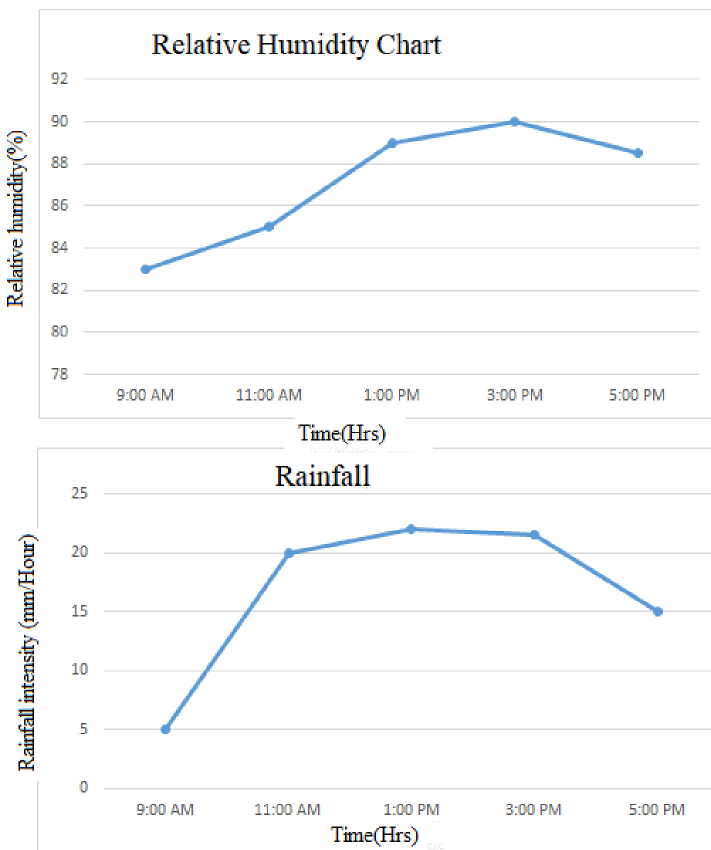


Figure 15 Relative humidity and rainfall intensity chart for the given experimental day



During the given time slot of 11 am to 3 pm for the given day the amount of rainfall is also observed. For instance, in Figure 15, on the 23rd of September 2022 peak values ranging from 84 to 90% were observed. The intensity of rainfall varies from 15 to 23 mm/h.

From the visual inspection of Figure 16, a relation of the relative humidity with the RSSI for day 1 is observed. The observed data shows that the value of RSSI from the time slot of 11 am to 3 pm is almost the same for the given day. The RSSI of the link reduced due to fall in the temperature caused by downpour of rain. The signal degradation can happen due to the attenuation and scattering of the EM waves especially for the frequency above 10 GHz. The DSD value is much smaller than the operating frequency of the LoRa module with a wavelength of 0.32 m, hence the RSSI value and the link get less affected in this situation.

Figure 16 Effect of SF on the RSSI value during humidity measurement (see online version for colours)

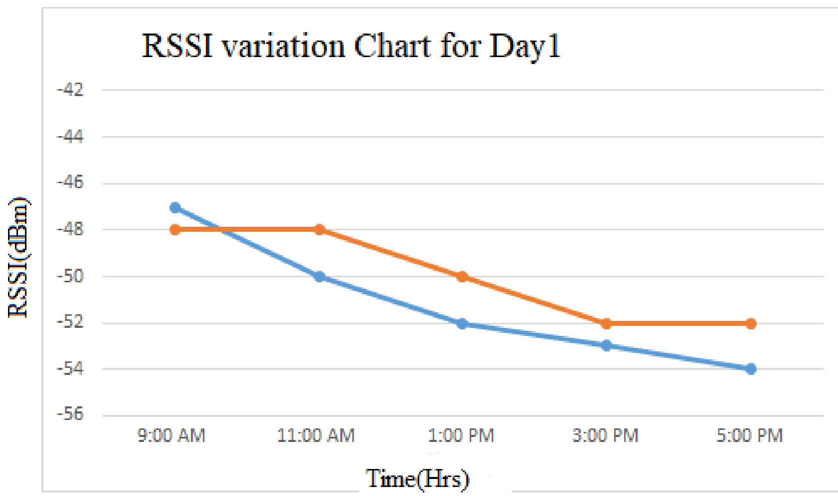


Figure 17 shows the road section A-B. The graph shows the effect of changing value of the SF from the SF=7 to SF=12 in the LoRa module test node has the impact on the PDR. The value of PDR increased by 4 to 5% within the range of humidity above 85 to 95% in the graph.

5.4 *Experimental results of performance of the effect of weather condition (humidity) in urban environment*

The daily atmospheric temperature values and the relative humidity were gathered from the test bed module and from the online weather station. The location between the road section A-B of distance 800 m at Huda City Gurgaon, was chosen for the experimentation. The atmospheric temperature data were plotted as shown in Figure 18, for two consecutive days 24th and 25th September 2022. These two days are densely cloudy and there is rain in the afternoon times with the humidity level between 80% and 95%. The data is collected from 9 am to 5 pm daily for two consecutive days.

Figure 17 Effect of SF on PDR during humidity measurement (see online version for colours)

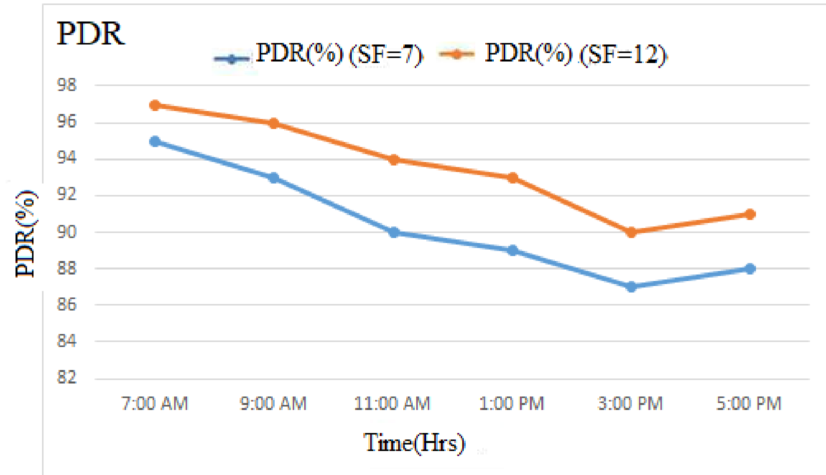


Figure 18 Temperature chart for the experimental days during humidity measurement in urban scenario (see online version for colours)

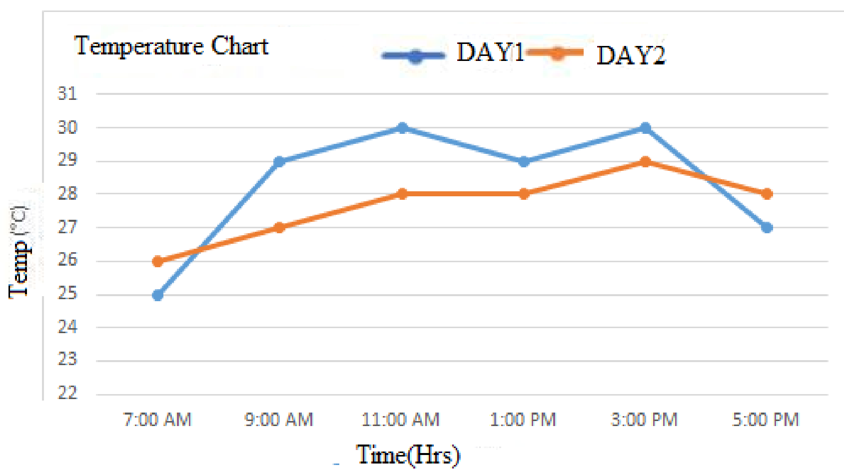


Figure 19 shows the relative humidity data collected for both consecutive days. After analysing Figure 19 the value of relative humidity is found in the range of 85% to 95% from 11 am to 3 pm. We have also observed the amount of rainfall as 32% during the same time for both the days.

Figure 19 Relative humidity chart for the experimental days during humidity measurement in urban scenario (see online version for colours)

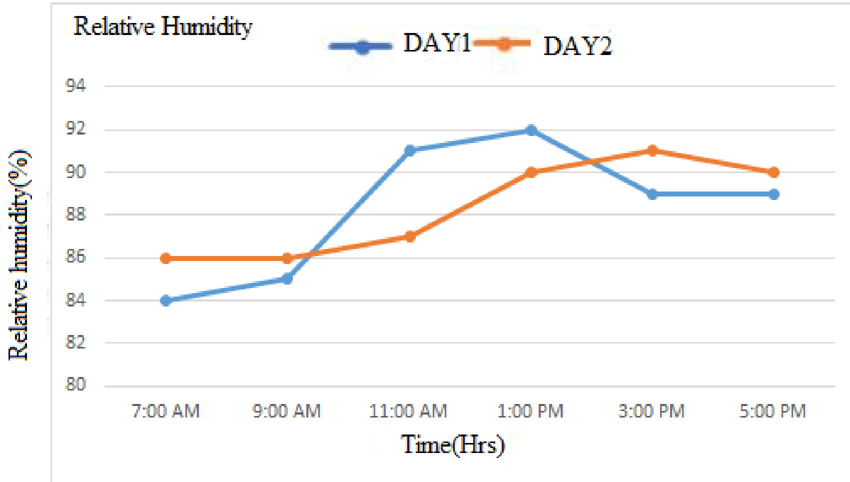


Figure 20 shows the effect of rainfall on RSSI for Day1 and Day2. The value of RSSI increases with the high value of humidity. On 24th and 25th September 2022, high values of the relative humidity were observed with peak values ranging from 88 to 92%. Figure 20 shows the intensity of rainfall varies from 10 to 30 mm/h. The observed data shows that the value of RSSI from the time slot of 11 am till 3 pm is almost the same for both the days. From the given data we observed that the rain has a small effect on the RSSI as shown in Figure 21. The RSSI of the link reduced due to fall in the temperature caused by downpour of rain.

Figure 20 Rainfall intensity graph for two consecutive days (see online version for colours)

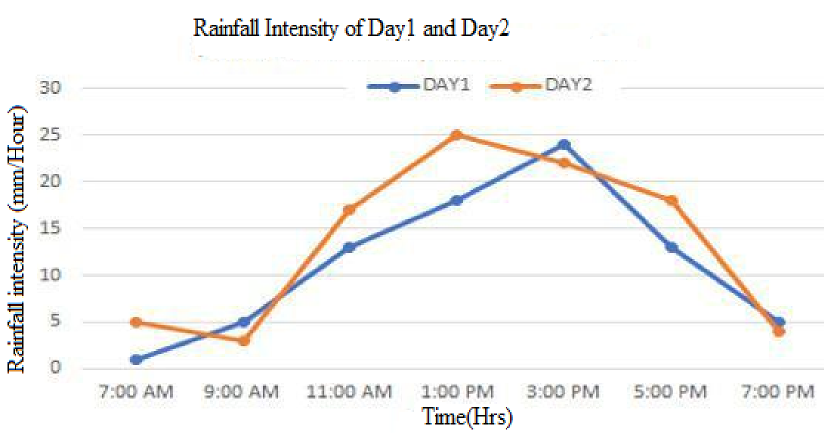
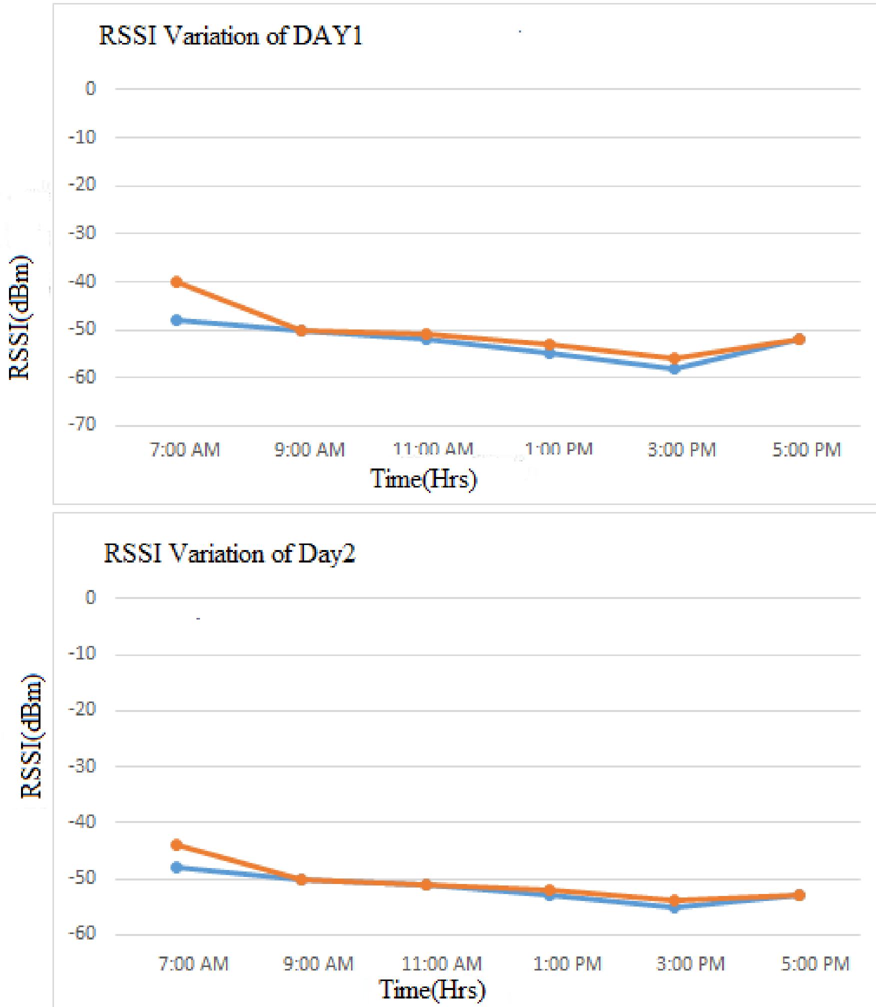


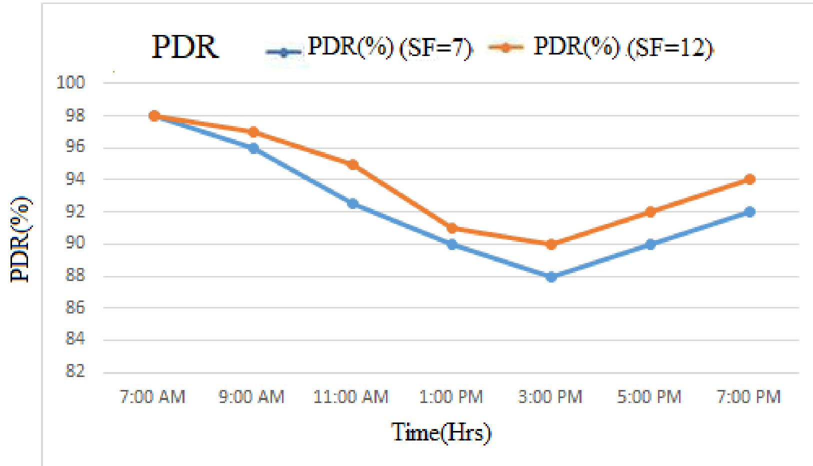
Figure 21 Effect of SF on RSSI for both experimental days during humidity measurement in urban scenario (see online version for colours)



The graph, as shown in Figure 22, is for the road section A-B. The graph shows the effect of changing value of the SF (SF=7 to SF=12) in the LoRa module test node which has the impact on the PDR. The value of PDR increased by 2% when humidity is above 85% to 95%.

During the rain the effect on the RSSI link was much less significant and successful packet delivery can take place. The wavelength of the LoRa transmission is very large as compared to the DSD value so there is very less effect on LoRa-based transmission due to multipath effect.

Figure 22 The effect of SF on PDR during humidity measurement in urban scenario (see online version for colours)



5.5 *Effect of height or node placement in the suburban and urban environment*

The LoRa test bed module must be placed at the appropriate height so that the best link quality can be obtained. The node deployment must be done in such a manner that appropriate height is chosen for the best result. In the given case the experiment is performed to see the impact of node height on the received RSSI strength at the receiver node. The transmitter node is placed at different heights of 1 m, 3 m and 6 m height and the environmental testing of the vehicular environment is done. The experiment was performed for the location between the road section A-B of distance 800 m at Huda City Gurgaon, and the road segment of Rx-B of 1.5 km at Neemrana location. Figures 23 and 24 show the impact of height on the RSSI strength in urban and suburban environment which helps to provide information about the link.

Figure 23 The impact of height on RSSI for urban environment (see online version for colours)

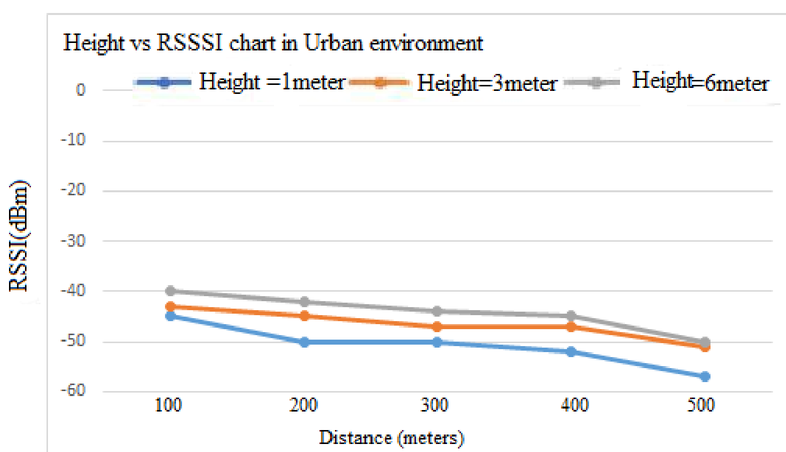
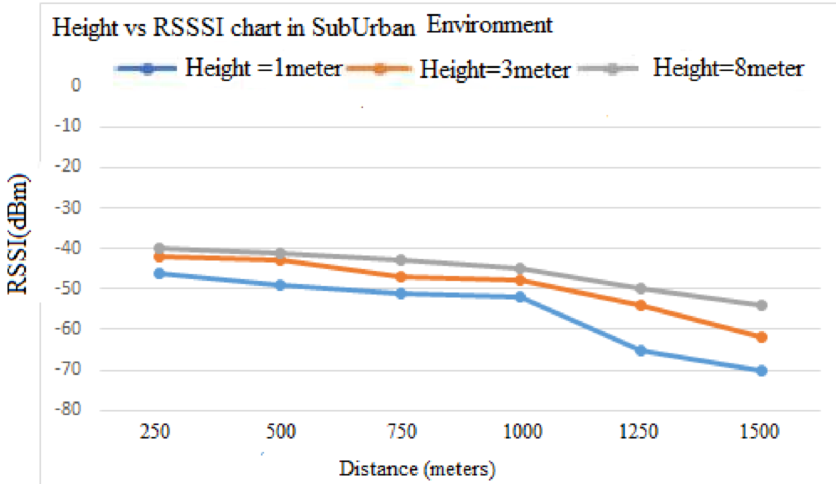


Figure 24 The impact of height on RSSI for sub-urban environment (see online version for colours)



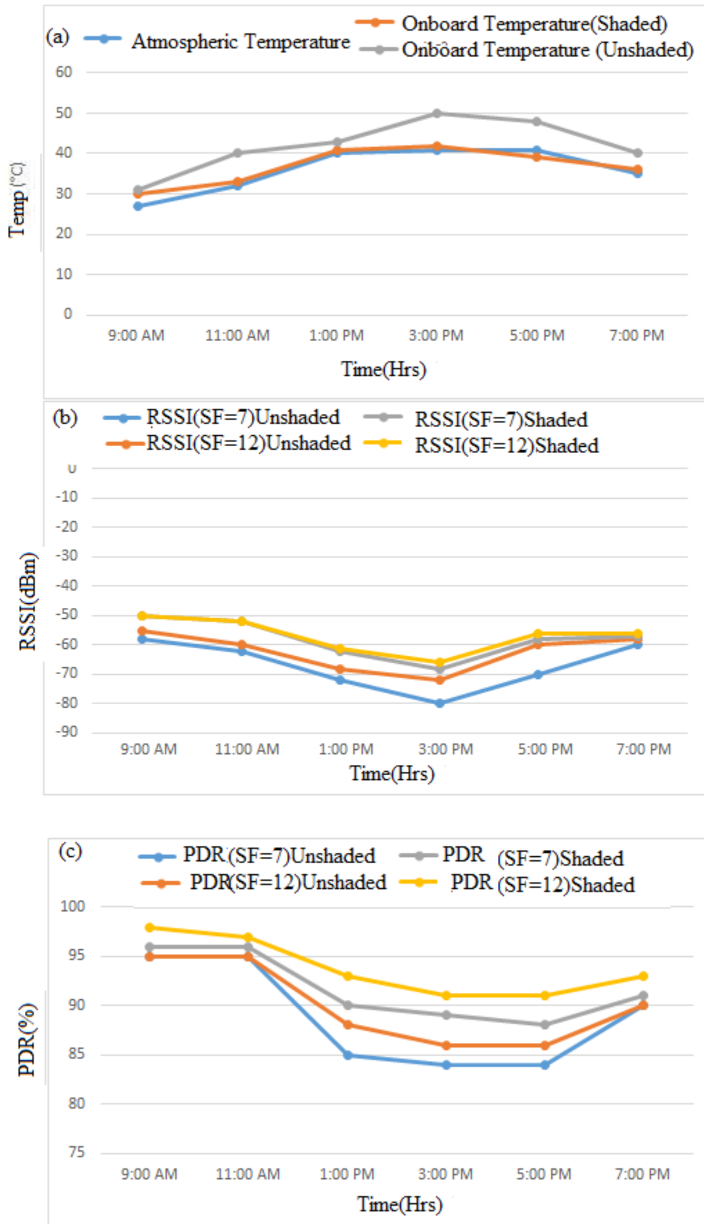
5.6 *Effect of shading condition in the suburban environment*

The LoRa test bed module must be placed at the appropriate height of 6metres so that the best link quality can be obtained. The node deployment must be done in such a manner that both the nodes are placed in the shaded region and the result is compared with the results obtained above when the nodes are placed directly under the sun or unshaded region. In the given case the experiment is performed to see the impact of shaded region on the received RSSI strength at the receiver node. The transmitter and receiver node are placed in a shaded region between the road segments of Rx-B of 1.5 km at Neemrana location. Figure 25(a) shows the atmospheric temperature of the experimental day and the impact of temperature on onboard device when it is kept in shaded and unshaded area in the suburban environment.

Figure 25(b) shows the impact of shaded region on the RSSI strength in suburban environment. From the visual inspection of Figure 25(b) a relation of the shading effect with the RSSI for Day1 and Day2 is observed. Higher RSSI values were observed during the shaded region as compared to the unshaded region.

Figure 25(c) shows the effect of changing value of the SF (SF=7 to SF=12) in the LoRa module test node which has the impact on the PDR. The value of PDR increased by 10% when the effect of temperature is prominent in shaded and unshaded region between 11 am to 5 pm.

Figures 25 (a) The atmospheric and onboard temperature of the node lying in shaded and unshaded region in the sub-urban location (b) The effect of RSSI due to shaded and unshaded region in the sub-urban location (c) The effect of changing value of the SF and its impact on the PDR due to shaded and unshaded region in the sub-urban location (see online version for colours)



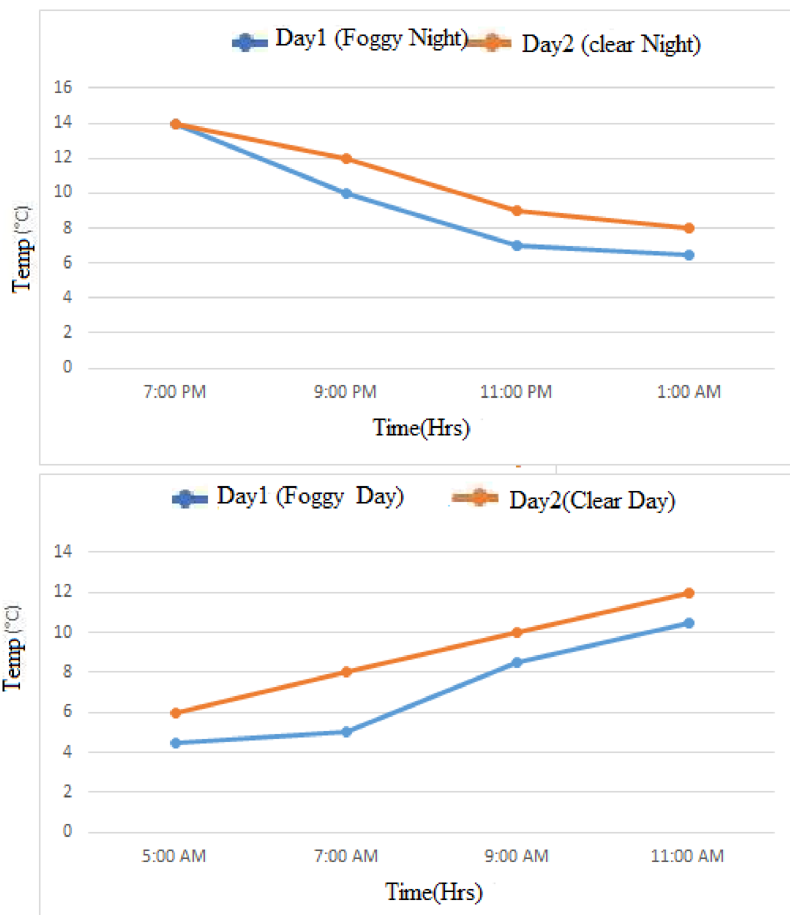
5.7 *Effect of foggy condition in the urban environment*

The daily atmospheric temperature values and the relative humidity were gathered from the test bed module and from the online weather station. The experimental testbed was taken between the road sections A-B of distance 800 m at Huda City, Gurgaon. The atmospheric temperature data are plotted in Figure 26, for two consecutive days 2nd and 3rd January 2022.

These two days were foggy day and night, and the humidity level lies between 40% and 65%. The data is collected from the time 7 pm to 1 am at night on 2nd January and from 5 to 11 am on the 3rd of January 2022 for the two consecutive days.

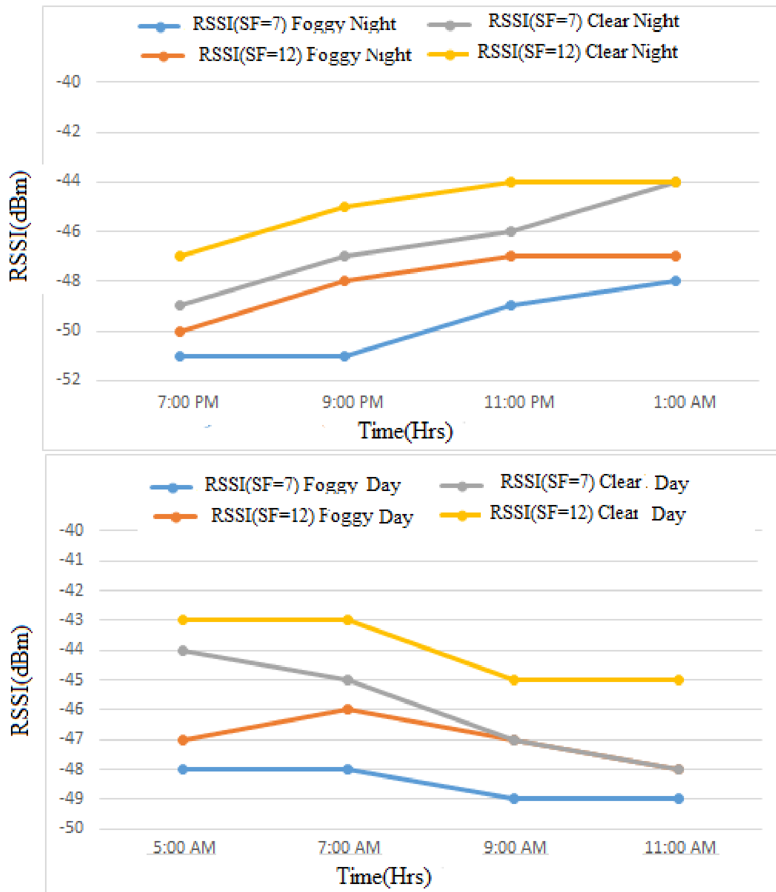
We have taken the reference for the same location and for same time 7 pm to 1 am at night on 7th January and from 5 to 11 am on the 8th of January 2022 for the two consecutive days when the temperature is same but there is no fog on both these days. Figures 26 show the atmospheric temperature of the experimental day and the impact of fog on the link quality is under examination.

Figure 26 Temperature chart for the experimental days during foggy condition (see online version for colours)



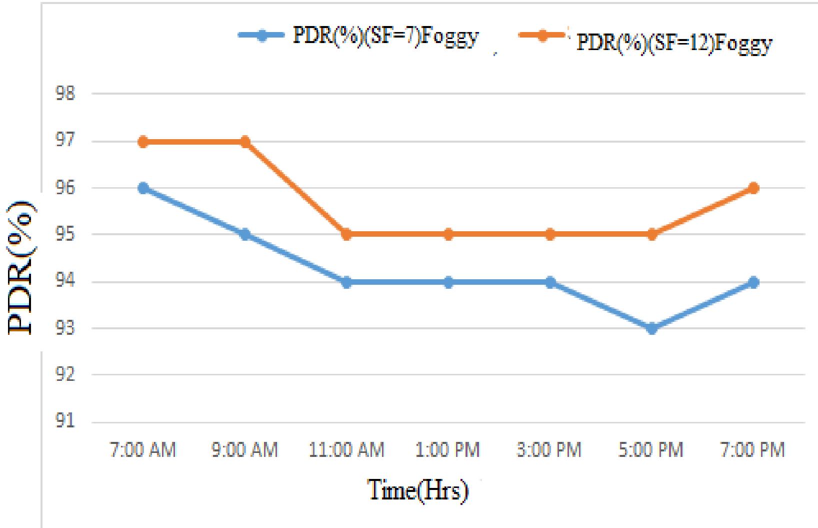
From the visual inspection of Figure 27 relation of the effect of fog with the RSSI for Day 1 and Day 2 is observed. The fog intensity rates vary from mild to very dense during the different time intervals as shown in Figure 27. It can be shown that the value of RSSI from around 1 to 9 am is almost same for both the days. This indicates that the occurrence of fog has a small effect on the RSSI.

Figure 27 The impact of fog attenuation on the RSSI strength in urban environment (see online version for colours)



The graph as shown in Figure 28 is for the road section A-B. The graph shows the effect of changing value of the SF (SF=7 to SF=12) in the LoRa module test node which has the impact on the PDR. The value of PDR increased by 2% when the fog level was very high between 1 am and 9 am.

Figure 28 Effect of SF on PDR during foggy condition (see online version for colours)



All the packets are delivered successfully during the fog situation and there is very little impact on the link quality during the time. This can be attributed to the fact that the attenuation due to fog may be considered as another form of rain. Fog in the environment can be measured by the amount of water vapour per unit volume and by the size of the droplets. The frequencies less than 2 GHz have a minor impact due to the fog attenuation. Optical bands and IR region are major impacted by the fog attenuation while millimetre waves are affected by rain.

6 Conclusion

Five scenarios of LoRa-based vehicular environment are analysed to observe the effect of weather conditions on the link quality. The first scenario involves the impact of temperature on the RSSI value, and it is observed that RSSI degrades with increase in temperature which lowers the PDR also. Both parameters can be increased by increasing SF value. We have also seen that RSSI value degrades more in unshaded regions compared to shaded regions. The second scenario involves the impact of humidity on the RSSI value. We have observed that there is correlation between the humidity and the RSSI value of the link. We have seen that RSSI value degrades with humidity, but degradation rate is lower compared to temperature. In the third scenario we have studied the impact of fog on the RSSI value which also degrades the RSSI value. The fourth scenario involves the impact of height of the node from the ground on the RSSI value. The results show that the increase in height of the node directly improves the link quality in both suburban and urban environment. The LoRa-based vehicular communication faced some limitation in transferring data at higher transmission rate and experience spectrum interference due to large number of deployments of LoRa-based vehicular and static nodes along road segments. The LoRa-based communication also experiences the problem of small payload size and has limited byte count. In future, we will perform a detailed investigation of node deployment problems and scenarios related to timely-based data dissemination which helps in handling the emergency vehicles situation.

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