IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received 11 September 2023, accepted 26 September 2023, date of publication 3 October 2023,
date of current version 16 October 2023.

Digital Object Identifier 10.1109/ACCESS.2023.3320584

RESEARCH ARTICLE

Research on the Influence of Mechanical Vibration on Radio Wave Propagation

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This work was supported in part by the National Key Research and Development Program of China under Grant 2021YFF0600303.

ABSTRACT The mechanical vibration of antenna might cause vibration of the path loss of the electric wave propagation, especially under high electric wave frequencies. In this paper, the impact of mechanical vibration on wireless communication path loss in 5G communication is analyzed, including sub 6-GHz and mmWave frequencies. An experimental method is proposed including suggested antenna types, positions and frequencies and a series of experiments were conducted. Two types of antennas and one vibrating table are used to set different mechanical vibration and antenna situations. Three hundred received voltages are collected through self-control system to calculate range, standard deviation and median as path loss statistical identity. It is concluded that the amplitude and direction of mechanical vibration will largely affect the range and standard deviation of path loss. But other parameters like frequency will not, especially median. Higher frequency of radio signal will cause more sensitive path loss to mechanical vibration. And by analysis, multipath characteristc is the reason that path loss of omnidirectional antenna is more volatile than directional antenna. With the application of 5G, the path loss fluctuation caused by mechanical vibration is a negative factor, and it is necessary to mitigate its negative impact.

INDEX TERMS Mechanical vibration, electric wave propagation, millimeter wave, path loss, 5G, industrial internet.

I. INTRODUCTION

Mechanical vibration is ubiquitous in people's daily life. Nature vibration such as wind, rain, waves and artificial vibration such as cars, machines and human voice are all included in mechanical vibrations. Such vibrations are common under the conditions of manufacturing and power industry especially. Generally speaking, the impact of mechanical vibration on wireless communication is concentrated in two scenarios. The first scene is the windy outdoor condition. The wind under this condition would affect the antenna to vibrate. The second scene is wireless-manufacturing condition. As the development of 5G technology and the wireless manufacturing internet, the wireless transceiver components and antennas would be installed on machines massively. And the mechanical vibration due to production process would influence the antenna. The attainability of wireless communication channels under industrial scenarios had been widely studied. Several researchers have focused their research interests on the influence of such vibrations to antenna and communication. [1], [2], [3], [4] Bahattin et al. [5] analyzed effects of the platform vibration on the cylindrical array IFF antennas to improve the accuracy of radar. Emily et al. [6] and Ian et al. [7] studied the chaotic vibration caused by aircraft and managed to reduce the effect by applying monopole antennas or Chebyshev or minimum-variance distortionless response (MVDR) beamformers. Though several researches had held to precisely described or comprehensively reduced the mechanical vibration, a specific method to reduce influence of mechanical vibration on wireless communication under different conditions had not yet been studied.

With the development of the Industrial Internet of Things, 5G wireless fully connected factories have emerged [8], [9], [10]. Wireless connectivity has greatly

The associate editor coordinating the review of this manuscript and approving it for publication was Agustin Leobardo Herrera-May.

improved the automation and intelligence levels of industrial production. In these factories, a large number of 5G wireless modules are installed on vibrating machines. The reliability of wireless access in industrial environments is critical to ensuring safe and orderly production. To ensure this, reliable data on path loss and its variations due to random mechanical vibrations are needed in the design of industrial wireless systems. Therefore, it is necessary to conduct research on radio wave propagation in industrial vibration environments, including FR1 (Frequency range 1) and FR2 (Frequency range 2). As mentioned earlier, comprehensive research in this field is lacking, especially regarding path loss, which is a core parameter of radio wave propagation. Specifically, there is no systematic study on the relationship between path loss at different frequencies and mechanical vibration parameters such as frequency, amplitude, and direction. Therefore, we designed a detailed measurement experiment to conduct research in this area.

II. EXPERIMENTAL SETUP

As the purpose of comprehensively study the influence of mechanical vibration to electric wave propagation, we measured the path loss under different frequencies and vibrations at mechanical vibration laboratory of CAICT in Baoding, Hebei, China. The experiment layout is shown in Figure 1.

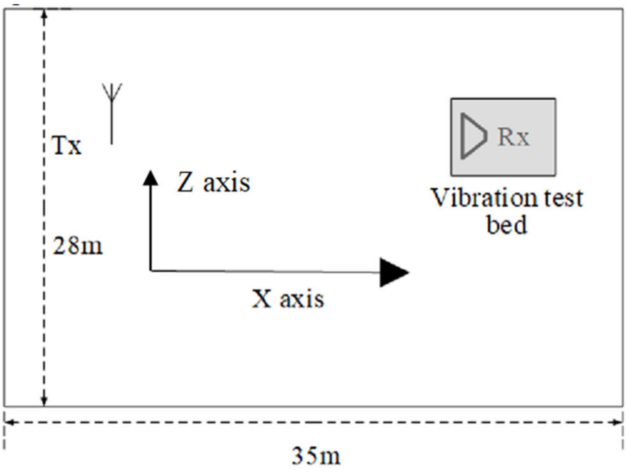


FIGURE 1. Experiment layout top view.

The transmit antenna was fixed on tripod and connected with input signal. Connected with a receiver using coaxial cable, Rx antenna was fixed on vibrating table. The receiver is not placed on the vibration table to avoid damage. Two typical frequency bands were tested in this experiment:

For FR1, we chose 2.7 GHz and 4.8 GHz as the test frequencies. The output voltage of signal generator was set to 10 dBm. And two series of antennas' combination were tested under the test of this frequency band. 1. Both Tx and Rx antennas were horn antennas. The height of both antennas was 1.63 m with the distance of 12.5 m. 2. Tx antenna used omnidirectional antenna and on receiver side still used horn antenna. Both transmitter and receiver had the height of 2.1 m and the distance is 14.5 m. The related directions of antenna under FR1 are shown in Figure 2.

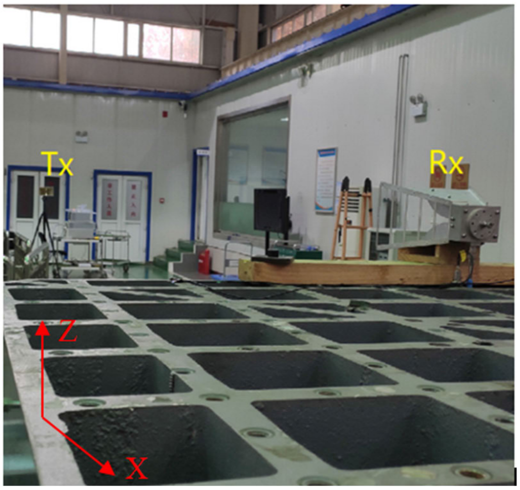


FIGURE 2. Antenna arrangement on FR1 wave band.

FR2 frequency band (millimeter wave). Under the millimeter wave frequency band, we chose the testing frequency as 27.5 GHz, 37 GHz and 40 GHz. On the Tx side we used omnidirectional antenna; on the Rx side we used horn antenna. Both heights were set to 1.54 m with distance of 12.5 m. Due to the great path loss of the millimeter wave, we connected a power amplifier to the signal generator and then output the wave to antenna to increase the dynamic range of measurement. The antenna arrangement on FR2 wave band is shown in Figure 3.

FIGURE 3. Antenna arrangement on FR2 wave band.

The above-mentioned omnidirectional antenna was a dual-cone antenna with a white nylon shell. The Standing wave ratio within the frequency range between 1.7 GHz and 50 GHz was smaller than 2, which means such omnidirectional antenna was well functioning under FR1 and FR2 frequency bands. For FR1, the horn antenna used for transmission was a dual-ridge horn antenna with a gain of 2.1dB to 12.5dB over a frequency range of 0.7GHz to 6GHz. The horn antenna used for reception was a dual-ridge horn antenna with metal grid sidewalls, with a gain of 2.1dB to 12.5dB over a frequency range of 0.7GHz to 6GHz.

For FR2, the horn antenna used for both transmission and reception was a small dual-ridge horn antenna, with a gain of 11.2dB to 17.5dB over a frequency range of 18GHz to 40GHz.

Using vibrating table in the testing process could generate controllable trigonometric wave. The horizontal dimension of the vibrating table is 1.5m × 1.5m, and the vertical expansion table size is 2.0m × 2.0m. The rated sine thrust is 98KN. The maximum displacement are 76mm (vertically) and 52mm (horizontally), respectively. The rated impact thrust is 196KN, the maximum speed is 2.0m/s, and the maximum acceleration is 100g.

To describe the mechanical wave, we defined the connection line between Tx and Rx as x axis. Limited by the capability of vibrating table, we set limit to the vibration amplitude. When the vibrating frequency is 5 Hz, the set vibration amplitude (peak-peak) was between 0 mm to 40 mm; When the vibrating frequency is 10 Hz, the set vibration amplitude was between 0 mm to 20 mm. Under the same amplitude condition, higher frequency meant larger acceleration. As a result, it would be hard for the vibration table we used in this measurement to reach 20 mm amplitude under 10 Hz.

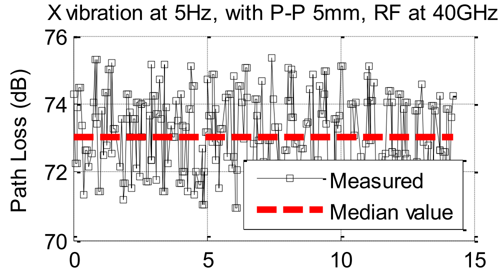
We also defined the direction of gravity as Z axis. When the vibration frequency on Z axis is 5 Hz, we set the amplitude of the wave between 0.5 mm to 40 mm.

Specifically, in the FR1 frequency band testing, the maximum mechanical vibration displacement settings were 0.5mm, 3mm, 10mm, and 40mm.

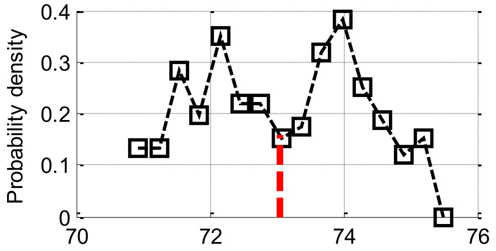
In the FR2 frequency band test, the maximum displacements were set to 0.5mm, 1mm, 2mm, 3mm, 5mm, 7mm, 10mm, 20mm, 30mm, and 40mm for vibration frequency of 5Hz. For a vibration frequency of 10Hz, the maximum displacements were set to 0.5mm, 1mm, 2mm, 3mm, 5mm, 7mm, 10mm, 15mm, and 20mm.

During the test, we used computer to control the vibration table. Input the experimental parameters into the computer controller, which outputs analog signals. Drive the vibration table to work through a power amplifier, install sensors on the vibration table, and feedback the signals collected by the sensors to the controller. Compare them with the output signals of the controller to perform automatic tuning. Also, we developed a control program for automatic testing. The program used ethernet and computer to control the signal generator as well as receiver remotely, automatically set the instrument status and read and saved the received voltage level value.

For each condition with fixed parameters of electric frequency and mechanical vibration, the program continuously read 300 received voltage level value to calculate the change under time domain of path loss. In this research, the major focus was about the change of path loss corresponds to random mechanical vibration. Also, all the listed path loss data were kept the gain of antenna. A typical path loss curve under time domain and probability distribution is shown in Figure 4. With the limitation of the reaction of the receiver to program command, the time spent to read 300 received voltage level value would be varied slightly between 14 seconds and 16 seconds.



(a) Time (s)



(b) Path loss distribution scale (dB)

FIGURE 4. Typical path loss curve under time domain and possibility distribution analysis.

Analysis of multiple path loss sample sequences similar to Figure 4 shows that some sequences are distributed close to a normal distribution while others are not normally distributed.

III. RESULTS AND ANALYSIS

Under each parameter condition, a correlated path loss curve like Figure 4 would be generated. From the curves we could receive three statistical characteristics: median, standard deviation and range. We further analyzed and compared these characteristics by using a sample size of 300 path loss measurements for each test.

A. INFLUENCE OF MECHANICAL VIBRATION ON MEDIAN OF PATH LOSS

The statistical analysis of the experiment results shows that the infection of mechanical vibration on median of path loss is ignorable. The test results under the electric wave frequency of 2.7 GHz and 37 GHz are shown in Figure 6. The change of median with mechanical vibration amplitude under the condition of 2.7 GHz is less than 1 dB and 4 dB under 37 GHz.

We can perform this type of analysis: Vibration is a periodic mechanical movement that returns to its origin. Therefore, the variation of path loss within one cycle of mechanical vibration should also be periodic. The median value of path loss is likely to appear near the origin of mechanical vibration, so it is less sensitive to changes in vibration amplitude. At the same time, we also observed that the median value of path loss at 37GHz is more sensitive to

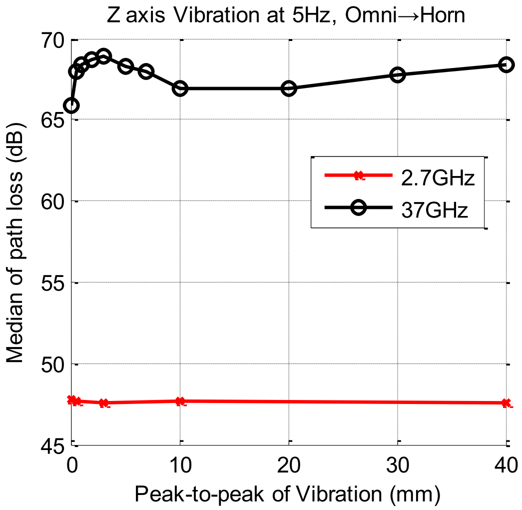


FIGURE 5. Change of path loss median with mechanical vibration amplitude under 2.7GHz and 37GHz.

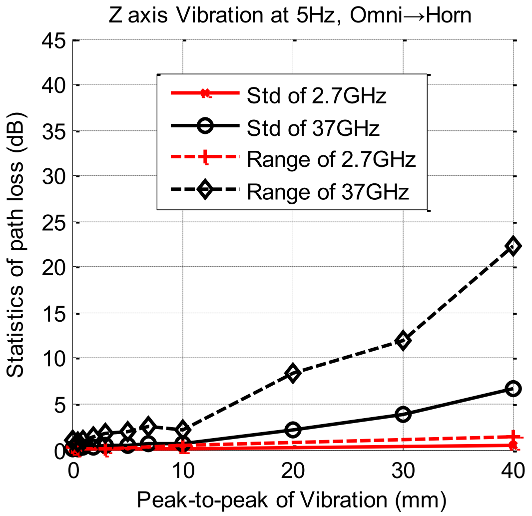


FIGURE 6. Standard deviation and range of path loss sequence under time domain with 2.7GHz and 37GHz electric wave frequency.

changes in mechanical vibration amplitude because its wavelength is shorter, which leads to more significant changes in multipath phase due to the change in position caused by mechanical vibration.

B. INFLUENCE OF RADIO FREQUENCY UNDER MECHANICAL VIBRATION ON PATH LOSS FLUCTUATION

The statistical analysis of standard deviation and range of the path loss under time domain shows that the range of change of signal with higher frequency is more sensitive to mechanical vibration. Figure 6 shows the standard deviation and range of path loss sequency of electric propagation under time domain with 2.7GHz and 37GHz electric wave frequency. Obviously, standard deviation of 2.7GHz is smaller than that of 37GHz and the range have the same relationship. Due to the analysis, we consider that such difference is mainly caused by the contrast between the frequency of radio electric wave and the mechanical wave. Higher radio wave frequency would cause shorter wavelength. When the displacement of mechanical vibration is the same, the impact on the phase of high-frequency multipath propagation is more significant, which leads to a larger range and standard deviation of the path loss variation.

C. INFLUENCE OF MECHANICAL VIBRATION DIRECTIONS ON PATH LOSS FLUCTUATION

Measurement shows that the mechanical vibrations on different directions would differently infect the path loss variation. Figure 7 shows standard variation and range of the path loss under time domain with electric wave propagation and frequency of 27.5GHz in X axis direction and Z axis direction. Figure 8 shows the same results with the frequency of 37 GHz. With other parameters kept unchanged, the difference of the two direction of the mechanical vibration would cause the obvious difference of the corresponding path loss statistic indicator.

The possible reasons are: Mechanical vibration can cause changes in multipath phase, and multipath is distributed in the spatial angular domain, which should be different along the X, Y, and Z axes because the distribution of reflecting objects in the propagation environments along these three axes is also different.

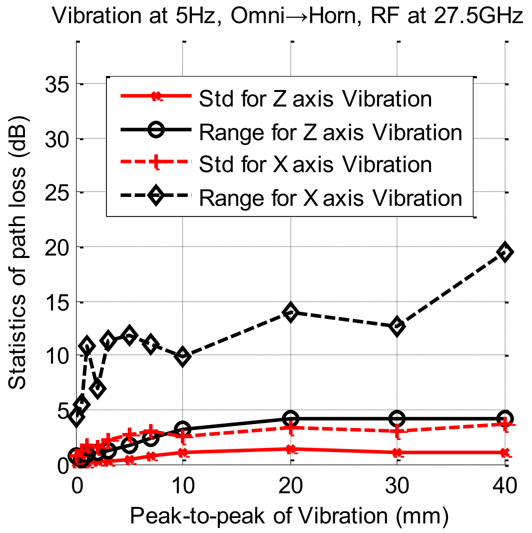


FIGURE 7. Standard deviation and range of path loss sequence under time domain with 27.5GHz electric wave frequency and mechanical vibration in X-axis and Z-axis directions.

D. INFLUENCE OF MECHANICAL VIBRATION FREQUENCY ON PATH LOSS FLUCTUATION

Measurement shows that with all the conditions remain the same but mechanical vibration frequency, the frequency has a limited influence on path loss variation. Figure 9 shows the standard variation and range of path loss sequence under time domain with 27.5 GHz electric wave frequency

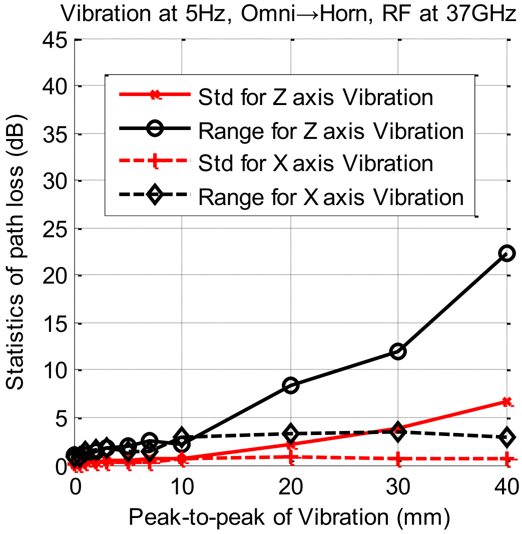


FIGURE 8. Standard deviation and range of path loss sequence under time domain with 37GHz electric wave frequency on mechanical vibration direction of X axis and Z axis.

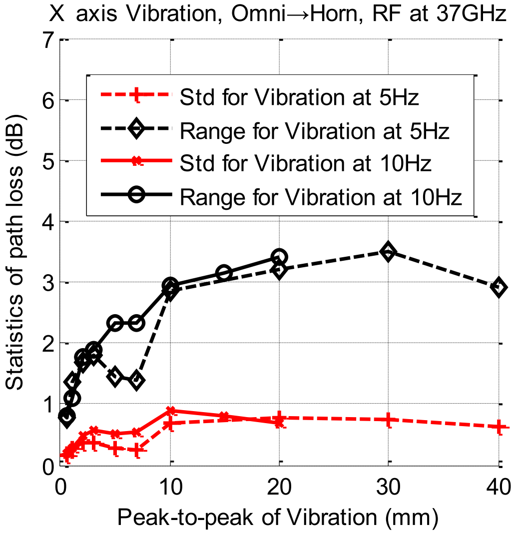


FIGURE 10. Standard deviation and range of path loss sequence under time domain with 37GHz electric wave frequency and 5Hz and 10Hz mechanical vibration frequency respectively.

and 5 Hz and 10 Hz mechanical wave frequency respectively. Figure 10 shows the similar result under the electric wave frequency of 37 GHz. From the two figures, it is easy to recognize that the same statistical value under 5 Hz and 10 Hz mechanical vibration are nearly coincident. Such result shows that mechanical vibration frequency has a limited influence on path loss variation. The conceptual analysis would be as follow: the position displacement of Rx antenna caused by mechanical vibration would be periodic. As a result, the influence of mechanical vibration on the path loss would also be periodic which is same with the antenna displacement. But when only consider the range of variance of path loss, it would be less sensitive to mechanical vibration.

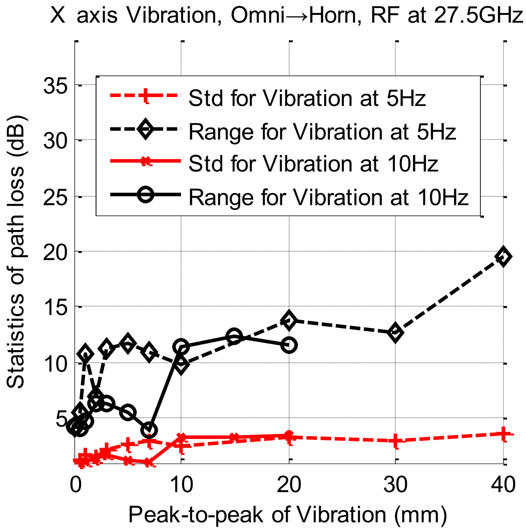


FIGURE 9. Standard deviation and range of path loss sequence under time domain with 27.5GHz electric wave frequency and 5Hz and 10Hz mechanical vibration frequency respectively.

E. INFLUENCE OF ANTENNA DIRECTIVITY ON PATH LOSS FLUCTUATION

Experiment results shows that under the same mechanical vibration condition, omnidirectional antenna would bring larger fluctuation on path attenuation than directional antenna. Figure 11 shows two groups of experiment data under 2.7 GHz electric wave frequency. One of them uses omnidirectional antenna as transmitter and horn antenna as receiver, and the other one uses two horn antennas both as Tx and Rx antenna. Figure 12 shows the correlated curve under 4.8 GHz electric wave frequency. Obviously, the first group would have larger standard deviation and range. Such experiment result shows that it is possible that the fluctuation of path attenuation induced by mechanical variation might be due to the variance of multipath signal with the change of variation. If we only consider the free-space propagation model, when the propagation distance exceeds 10m, the fluctuation of the distance caused by mechanical vibration on Z axis is less than 40 mm, which the rate of change is less than 4%, the corresponding free space path loss would be less than 0.04 dB. When the amplitude of mechanical wave on Z axis is 40mm, The change of the receiving and transmitting antenna facing angle is about 0.1 degree, which will cause slight change of the antenna direction. Under the condition of horn antennas for both Tx and Rx position, the change of the antenna direction is less than 0.2 dB. Under the condition of Omnidirectional antenna as transmitter and horn antenna as receiver, such change is less than 0.1 dB. The theoretical calculation shows that the result only considering free-space propagation is considerably smaller than the experiment results. Also, as the second situation would have more multipath components than the first situation, the path loss fluctuation caused by mechanical vibration would be more significant. Especially under the environment of wireless industrial internet, numerous metal equipment and walls are contained in the power and manufacturing plant. As a result, such environment would cause numerous multipath, thus attention should be paid to the influence of mechanical vibration on the propagation of electric waves.

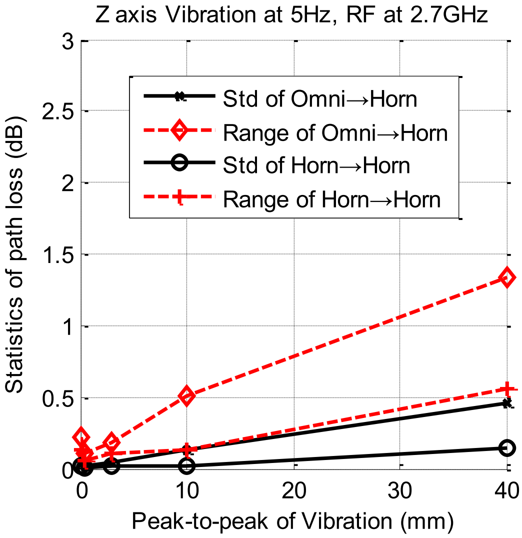


FIGURE 11. **Standard deviation and range of the path loss sequence under time domain and mechanical vibration with 2.7GHz electric wave frequency. Two antenna combinations are included.**

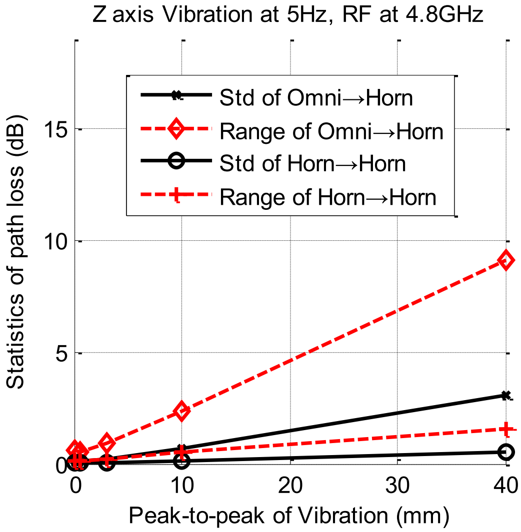


FIGURE 12. **Standard deviation and range of the path loss sequence under time domain and mechanical vibration with 4.8GHz electric wave frequency. Two antenna combinations are included.**

F. INFLUENCE OF MECHANICAL VIBRATION AMPLITUDE ON PATH LOSS FLUCTUATION

From statistical perspectives, Figure 6 to Figure 12 shows clearly that the standard deviation and range of the corresponding path loss of electric wave propagation would increase with the increment of the amplitude of mechanical vibrations. But as such positive relation is correlated with many factors like radio frequency, the increment relation is not linear. And it is possible that there would be a limit like what is shown in Figure 11.

The analysis shows that larger amplitudes will bring greater changes in the multipath distribution, which will have a more significant impact on path loss. However, there is a certain limit to the effect of multipath on path loss. We can consider a situation where a main path and a multipath are superimposed. When the phase of the main path and the multipath at the receiver are the same, the path loss reaches the minimum value. When the phase difference between the main path and the multipath at the receiver is 180°, the path loss reaches the maximum value. The changes introduced by vibration can only be distributed between the maximum and minimum values. Of course, similar analyses can be done when there are multiple multipaths.

IV. CONCLUSION

Both the wind outdoors and machines in industrial environment can cause vibration of wireless communication antennas, which can in turn lead to fluctuation of path loss of electric wave propagation. Some of our industry partners and telecom operators have observed such phenomena. The fluctuation of path loss is undoubtedly a critical focus of any wireless communication system, but this topic has not yet been comprehensively studied. Therefore, we conducted experiment on Sub 6GHz and millimeter wave frequency band. Mechanical vibration frequency is set to 5Hz and 10Hz, amplitude is set to 0mm to 40mm, and the experiment environment is set the same as in the large manufacturing factory building. By setting each parameter, we calculate the path loss curve under time domain. And from the curve, we conclude three statistical indicators: median, standard deviation and range. By comparing and analyzing the indicators, we summarize the conclusion as follows: from statistical perspectives, with the increment of amplitude of mechanical vibration, the corresponding standard deviation and range of the path loss of electric wave propagation will also increase. But the mechanical vibration has limited influence on median of path loss. On the fluctuation of path loss perspectives, the mechanical wave frequency has ignorable influence on path loss variance when other variables are same. The vibration on different directions will cause different influence on path loss fluctuation. Path loss variation of radio frequency signals would have higher sensitivity to the mechanical wave, which means the fluctuation of path loss of millimeter wave would be affected deeper by mechanical vibration than the Sub 6GHz. Furthermore, under the same mechanical vibration conditions, the omnidirectional antenna would cause greater path loss fluctuation than the directional antenna. By analysis, we propose that as the higher radio frequency would cause shorter wave length, mechanical vibration is more likely to cause large multipath carrier phase changes and further cause large path loss fluctuation. Due to such reasons, omnidirectional antenna will bring richer multipath scattering under industrial environment. With the gradual application of the 5G+ industrial internet, industrial communication requires relatively stable path loss. Apparently, the fluctuation of path loss is one of the negative defects. Based on our experiments, we recommend: 1. Try to avoid installing the antenna in a location with accelerated vibration. 2. If vibration exists at the antenna installation location, try best to use directional antennas or beamforming antennas but avoid using omnidirectional antennas. 3. If antennas vibrate violently, give priority to choosing Sub 6GHz frequency band. 4. If the above three suggestions are not effective enough, sufficient fading margin or self-adaptive power control mechanism should be applied on design and deployment of the wireless communication system according to the results of our experiments in this study.

In actual cases, such as in industrial scenarios, there are different sources of mechanical vibrations that could influence different ranges of frequencies. But currently the test bench can only generate controllable single frequency mechanical vibration and random vibration. Considering that the amplitude and other parameters of random vibration are not easy to accurately set, but the amplitude and frequency of single frequency mechanical vibration can be accurately set, we use single frequency mechanical vibration in our experiment. This paper is a fundamental research attempt to clarify the impact of single frequency mechanical vibration on radio wave propagation.

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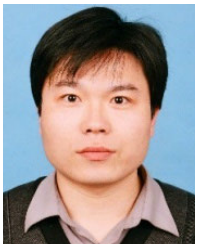

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