

Channel Measurements and Characterizations for Automobile Factory Environments

Liu Liu*, Ke Zhang*, Cheng Tao*, Kun Zhang*, Ze Yuan*, Jianhua Zhang**

* School of Electronic and Information Engineering, Beijing Jiatong University, Beijing, China

** Beijing University of Posts and Telecommunications, Beijing, China

liuliu@bjtu.edu.cn, 16125064@bjtu.edu.cn, chtao@bjtu.edu.cn, 16120166@bjtu.edu.cn,

16120159@bjtu.edu.cn, jhzhang@bupt.edu.cn

Abstract—There is tremendous hype around the Internet of Things, and particularly in the industrial realm (the industrial Internet of Things, IIoT), where many expect to find the biggest opportunity in the near term. The IIoT is also an important application in the fifth generation of wireless communications. In this paper, the channel propagations are investigated based on the realistic measurement data in an automobile factory. The path loss model is extracted using Least Square (LS) method, and the K factor is also parameterized. Meanwhile, the time delay (root mean squared delay) and the amount of multipath component (MPC)s are investigated and compared with typical propagation results. These results are beneficial and informative when designing wireless networks for IIoT.

Keywords— IIoT, wireless channel, path loss, K factor, time delay

I. INTRODUCTION

There is tremendous hype around the Internet of Things, and particularly in the industrial realm (the industrial Internet of Things, IIoT), where many expect to find the biggest opportunity in the near term. The IIoT is particularly important in the application of the fifth generation of wireless communications. In this application scenario, there exists a considerable quantity of wireless sensors working at wide band (WB), such as surveillance video, or narrow band (NB), such as working condition (temperature, humidity) transmission. These frequency bands may be located at different positions of the spectrum. The transmission requirements of these various sensors are different.

At the transmission layer of the IIoT, most sensors connect the access point with wireless technologies. In the propagation environments, wireless links may be obstructed or shadowed by mechanical arms and considerable metal machines. These objects could play as the reflecting bodies generating strong echoes. However, wireless transmission technology has not been thoroughly investigated in the special propagation scenarios so far. Fundamental features of the IIoT channels deviate significantly from those in cell communication systems. The major prerequisite condition of any wideband mobile radio system is a thorough knowledge of the propagation characteristics. A reliable and realistic channel

model serves as the enabling foundation for practical design and testing of communication systems.

There has been recent interest in characterizing different types of propagation scenarios, industrial environments has not discussed in recent years. Reference [1] presented statistical radio channel impulse response models for the analysis and design of wireless factory and open plan office communication systems. In [2], researchers characterized the path loss model and channel coefficient envelope based on measurement data in factories. Reference [3] characterized the multipath propagation medium in typical manufacturing environments, and the dynamic behaviour of the medium was described. Reference [4] described the time delay spread based on measurement data in five factory buildings. Reference [5] discussed narrow-band propagation at 900 MHz, 2400 MHz, and 5200 MHz. Reference [6] reviewed of the special characteristics of the radio channel in industrial environments. The existing channel models, both narrow- and wideband versions that account for the significant noise, interferences, and multipath, were reported. In [7], researchers evaluated the channel characteristics and calculate relevant delay statistics, in which the moving robots were considered. In [8], the attenuation, root-mean squared (RMS) delay spread and coherence bandwidth were analysed based on measurement data in industrial environments. Authors in [9] characterized the industrial channels using Saleh-Valenzuela models.

The main contribution of this paper is to employ a vector signal generator and spectrum analyser as a channel sounding system to probe realistic automobile factory environments. Four frequency bands, 1.1 GHz, 1.6 GHz, 3.5 GHz and 5.8 GHz are considered in this paper. The channel parameters of time dispersion including root mean square (RMS) delay spread, number of MPCs, power difference and the K factor in different scenarios are extracted from the measurement data.

The paper is organized as follows. In Section II, the measurement system and environment are described. Section III analyses the raw data, shows the results of measurement and gives the corresponding explanation. At last, the conclusion is drawn in Section IV.

II. MEASUREMENT DESCRIPTIONS

Abandoning using a dedicated channel sounding system, we employed a vector signal generator and spectrum analyser as a channel sounder, as shown in Figure 1. The synchronization between the Tx and Rx employs a local rubidium clock, which ensures the measurement efficiency and accuracy. The channel measurement parameters are listed as in Table.1.

TABLE 1. MEASUREMENT PARAMETERS.

Item		Value	
Excitation Signal		Multi-carrier signal	
Frequency	Bandwidth	Power	An Gain
1.1GHz	0.8 MHz NB	33 dBm	0dBi
1.6GHz	0.8 MHz NB	33 dBm	0dBi
3.5GHz	0.8 MHz NB	33 dBm	3 dBi
5.8 GHz	8MHz WB	33 dBm	16 dBi

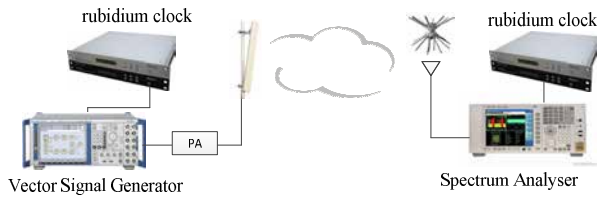


Figure 1. Block diagram of the channel sounding system

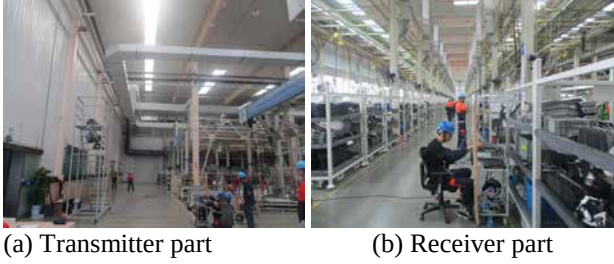


Figure 2. Measurement setup

Two types of industrial environments are considered in this measurement, LoS (100 measurement spots) and NLoS (33 measurement spots). In NLoS scenarios, the propagation links are semi-blocked (shadowed) by metal machines and robots. The dimension of the measured workshop is 130 m×59 m×8 m, the Tx antenna is elevated with the height of 5 m.

In our measurement, we use frequency-domain method (Multi-tone signal or OFDM signal) to get the raw channel impulse response (CIRs). Assume that there is one OFDM symbol with N subcarriers transmitted. $X[m]$ denotes the excitation signal on the m -th subcarrier. After N -point IFFT, the discrete-time transmit signal $x(n)$ can be written as

$$x(n) = \frac{1}{N} \sum_{m=0}^{N-1} X[m] \exp\left(j2\pi \frac{mn}{N}\right) \quad (1)$$

The convolved output between the excitation signal and the time-variant CIR denoted as a function of the discrete time variable (n) and the time delay (τ) can be expressed as

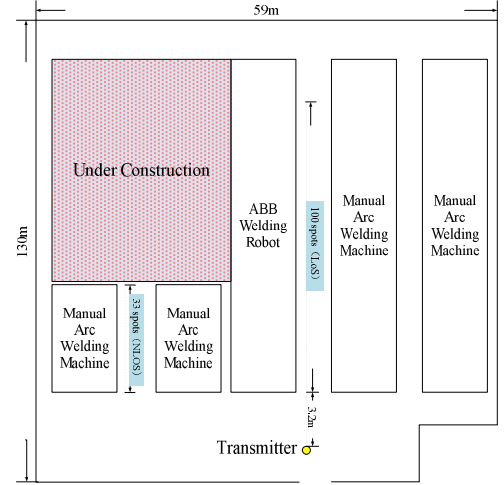


Figure 3. Environment map of the automobile factory

$$y(n) = h(n, \tau) * x(n) + w(n) \quad (2)$$

$$= \sum_{\tau=0}^{L-1} h(n, \tau) x(n - \tau) + w(n)$$

where L is the number of fading paths, $w(n)$ denotes the additive white Gaussian noise (AWGN). The channel is assumed as constant over the duration of one multi-tone signal, i.e., $h(n, \tau) = h(\tau)$. After the CP removal and FFT operation, the received signal can be given by

$$Y[m] = \left(\sum_{\tau=0}^{L-1} h(\tau) e^{-j2\pi\tau k/N} \right) X[m] + W[m] \quad (3)$$

$$= H[m] X[m] + W[m]$$

Then the frequency domain correlation processing is performed as

$$\tilde{H}[m] = \frac{Y[m] X^*[m]}{|X[m]|^2} = H[m] + W'[m] \quad (4)$$

Finally, the extracted CIR can be obtained from (4) via the Fourier series as

$$\tilde{h}(\tau) = \sum_{m=0}^{N-1} \tilde{H}[m] e^{j2\pi\tau m/N} \quad (5)$$

After that, we can extract the real MPCs from $\tilde{h}(\tau)$. The noise threshold determination and path searching method were detailed in [10], and will not be described further due to the space limitation.

III. PATH LOSS CHARACTERISTICS

Commonly, previous measurement results show that the received power attenuation mainly depends on the distance between the transmitter and the receiver. After obtaining the received power against the distance between the transmitter and the receiver, the empirical path loss model in decibels can be used for the power attenuation prediction as

$$PL(d) = A + 10 \cdot n \cdot \log_{10}(d) + X_{\sigma} \quad (6)$$

where d is the distance of the transceiver in meters, n is the path loss coefficient, A is the intercept, and X_σ represents the shadowing term. In the measurement data processing, the linear regression based on LS method is employed to estimate A and n . The extracted results are listed in TABLE 2.

TABLE 2. PATH LOSS PARAMETERS

	Frequency Band	n	A
1	1.1GHz	2.50	14.11
2	1.6GHz	2.61	16.39
3	3.5GHz	2.67	24.01
4	5.8 GHz	2.65	46.10

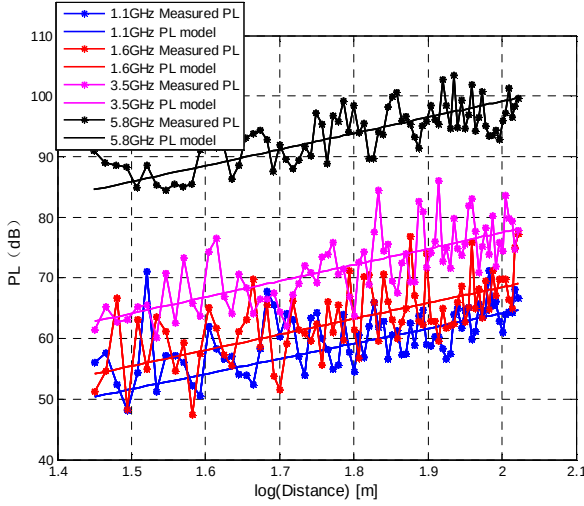


Figure 4. Path loss against the distance

We measured the same route (LoS and NLoS) at different central frequencies. The estimated path loss exponent is around 2.6, as showed in Figure. 4, which exhibits a higher value than the value ($n=2.0$) in the free space model. Furthermore, it can be found that the extracted path loss exponent is independent of the frequency band. This similar phenomenon is also stated in [11], i.e., there is no clear relationship between path-loss exponent and frequency. Meanwhile, our extracted results vary significantly with the path-loss parameters obtained from various industrial measurement campaigns summarized in [11] (Table I). It could be guessed that the path loss exponent changes with the environment (the size, the height, the density of machines in the working space), frequency, and link configuration. Hence, it is suggested using larger path loss exponent when planning the wireless link in industrial environments.

IV. K FACTOR

In our measured industrial environments, we considered LoS and NLoS scenarios. The received signal envelop can be characterized as a Ricean distribution variable with the corresponding probability density function given by

$$P(r) = \frac{r}{\sigma^2} \cdot \exp\left(-\frac{r^2 + s^2}{2\sigma^2}\right) \cdot I_0\left(-\frac{rs}{\sigma^2}\right) \quad (7)$$

where $I_0(\cdot)$ is the n th-order modified Bessel function of the first kind, σ^2 is the variance of the diffuse components, and s^2 is the power of the LoS path. A moment based K-factor estimator is used to extract the K-factor [12]

$$\hat{K}_{2,4} = \frac{-2\hat{\mu}_2^2 + \hat{\mu}_4 - \hat{\mu}_2\sqrt{\hat{\mu}_2^2 - \hat{\mu}_4}}{\hat{\mu}_2^2 - \hat{\mu}_4} \quad (8)$$

where the closed forms of the even moment are $\hat{\mu}_2 = E[r^2]$ and $\hat{\mu}_4 = E[r^4]$, respectively.

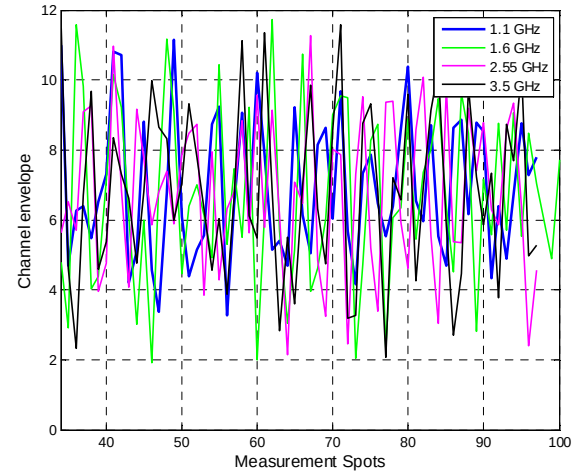


Figure 5. Channel envelope values against the measurement spots

TABLE 3. K-FACTOR

	Frequency	LoS (dB)	NLoS(dB)
1	1.1GHz	6.38	3.79
2	1.6GHz	4.60	4.22
3	3.5GHz	5.05	3.99
4	5.8 GHz	7.26	4.29

The extracted K factor values of LoS and NLoS are listed in Table 3. In LoS scenarios, K factor values are around 5 dB. In addition, it is expected that as the frequency increases, the wavelength decreases and more objects act as reflectors, causing the value of the K factor to decrease. Our measurement results mainly verified this statement except the LoS K factor at 1.1 GHz. This may be caused by some faults from the measurement. We will measure this value in our future measurement. K factor values are little smaller than that in LoS environments. Figure 5 plots the channel envelope values against the measurement spots. It shows that the fluctuation degree of the channel envelope at different frequency bands is nearly the same, which verifies the extracted K factor.

V. TIME DELAY CHARACTERISTICS

The time delay spread is important to any digital communication system. It quantifies the echo delay between the first arriving signal and the last ones. The statistical data is mainly about the multipath delay spread to evaluate the small-scale fading of wireless channel. In this section, the amount of MPCs in LoS and NLoS scenarios, and the RMS delay spread values with bandwidth of 8MHz are investigated. In this following section, we will find there is only one resolvable receiving component in time delay domain when the bandwidth of the excitation signal (NB) is 0.8 MHz.

Figure 6 and Figure 7 plot the amount of resolvable MPCs in LoS and NLoS scenarios. It can be found that the amount of resolvable MPCs is mainly dependent on the bandwidth, but not LoS or NLoS environments. When the bandwidth of 0.8 MHz, in most cases, no MPCs but only one incident wave can be extracted from the received signal. When the bandwidth is 8 MHz, more echo waves could be extracted. The resolvable distance of the excitation signal with the bandwidth of 0.8 MHz is 375 m, whereas, this distance value is 37.5 m when the bandwidth is 8 MHz. Wider bandwidth makes detecting MPCs much easier. For this reason, when characterizing the channel with the bandwidth order of MHz, the primary parameter is the channel envelope (not resolvable MPC), but not the time delay spread. Meanwhile, Table 4 lists the RMS results when the bandwidth of the excitation signal is 8 MHz.

TABLE 4. RMS DELAY SPREAD

Frequency	LoS	NLoS
5.8 GHz	9.37 us	15.3 us

VI. CONCLUSIONS

This paper has presented the measurement and analysis of the propagation fading behaviour in automobile factory environments, focusing on the LoS and NLoS terrains. The results of the path loss exponent values have been reported. The estimated values ($n=2.6$) are relatively larger than that of the free space model. In the measured environments, the LoS component is dominant, and thus we use K factor to specify the power ratio between the direct ray and the sum of the powers of all other rays. Based on the measurement data, we find the K factor values are around 6 dB in LoS scenarios and 4 dB in NLoS environments, respectively. Furthermore, the characteristics of the time delay and the amount of multipath components are investigated in this paper. We find there is only one resolvable signal when the bandwidth is 0.8 MHz, both the LoS and NLoS scenarios. When the bandwidth is 8 MHz, more resolvable multipath components can be extracted. The investigation results are applicable to the design of IIoT.

ACKNOWLEDGMENT

The research was supported in part by the Beijing Nova Programme (Grant No. Z161100004916068), the NSFC project under grant No. 61471027, the Research Fund of National Mobile Communications Research Laboratory ,

Southeast University (No. 2017D01), and Beijing Science and Technology Talents Program (2016023).

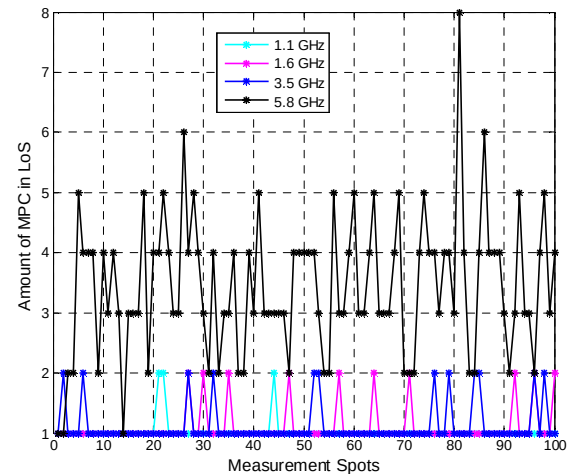


Figure 6. The amount of MPCs in LoS scenarios

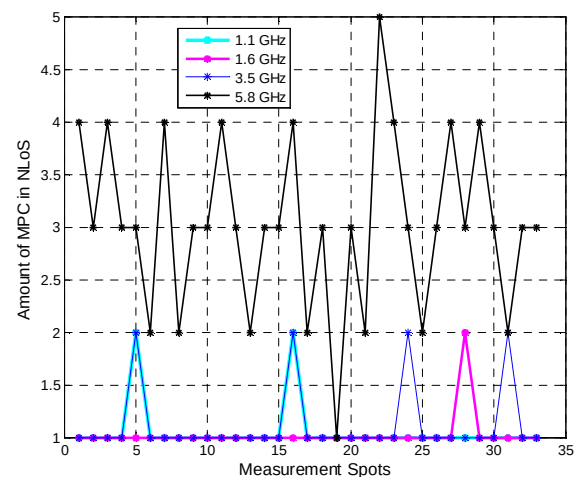


Figure 7. The amount of MPCs in NLoS scenarios

REFERENCES

- [1] Rappaport T S, Seidel S Y, Takamizawa K. Statistical channel impulse response models for factory and open plan building radio communicate system design[J]. IEEE Transactions on Communications, 1991, 39(5): 794-807.
- [2] Rappaport T S, McGillem C D. UHF fading in factories[J]. IEEE Journal on Selected Areas in Communications, 1989, 7(1): 40-48.
- [3] Yegani P, McGillem C D. A statistical model for line-of-sight (LOS) factory radio channels[C]// Vehicular Technology Conference, 1989, IEEE. IEEE Xplore, 1989: 496-503 vol.2.
- [4] Rappaport T S. Delay spread and time delay jitter for the UHF factory multipath channel[C]// Vehicular Technology Conference, 1988, IEEE. IEEE, 1988: 186-189.
- [5] Tanghe E, Joseph W, Martens L, et al. Large-scale fading in industrial environments at wireless communication frequencies[C]// Antennas and Propagation Society International Symposium. IEEE, 2007: 3001-3004.
- [6] Cheffena M. Propagation Channel Characteristics of Industrial Wireless Sensor Networks [Wireless Corner][J]. IEEE Antennas & Propagation Magazine, 2016, 58(1): 66-73.
- [7] Holfeld B, Wieruch D, Raschkowski L, et al. Radio Channel Characterization at 5.85 GHz for Wireless M2M Communication of Industrial Robots[C]// IEEE WCNC. IEEE, 2016.

- [8] Miaoudakis A, Lekkas A, Kalivas G, et al. Radio channel characterization in industrial environments and spread spectrum modem performance[C]// Emerging Technologies and Factory Automation, 2005. Etfra 2005. IEEE Conference on. IEEE, 2006: 7 pp.-93.
- [9] Karedal J, Wyne S, Almers P, et al. Statistical analysis of the UWB channel in an industrial environment[C]// Vehicular Technology Conference, 2004. Vtc2004-Fall. 2004 IEEE. IEEE, 2004: 81-85 Vol. 1.
- [10] Liu L, Tao C, Sun R, et al. Non-stationary channel characterization for high-speed railway under viaduct scenarios[J]. Chinese Science Bulletin, 2014, 59(35): 4988-4998.
- [11] Cheffena M. Propagation Channel Characteristics of Industrial Wireless Sensor Networks [Wireless Corner][J]. IEEE Antennas & Propagation Magazine, 2016, 58(1): 66-73.
- [12] Nikolic Z B. Principles of Mobile Communication: Gordon L. Stuber; Second Edition; Kluwer Academic Publishers, Boston, 2001, 752 pages, ISBN 0-7923-7998-5[J]. Microelectronics Journal, 2001, 32(12): 1050-1051.



Liu Liu received the B.E. and Ph.D. degrees from Beijing Jiaotong University, Beijing, China, in 2004 and 2010, respectively. From 2010 to 2012, he was a Post Ph.D. Researcher with the School of Electronic and Information Engineering, Institute of Broadband Wireless Mobile Communications, Beijing Jiaotong University, where he has been an Associated Professor since 2012. His general

research interests include channel measurement and modeling for different propagation environments and signal processing of wireless communication in time-varying channel.



Ke Zhang received the B.E. degree from Harbin University of Science and Technology, Harbin, China, in 2016. She is currently pursuing the M.S. degree of institute of Broadband Wireless Mobile Communications, School of Electronic and Information Engineering, Beijing Jiaotong University. Her general research interest focuses on channel measurement and characterizations.