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# Empirical study on directional millimeter-wave propagation in vehicle-to-infrastructure communications between road and roadside



**Key words:** Millimeter-wave; Two-path model; Root-mean-square delay spread; Power delay profile; CI-TRH path-loss model

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# Motivation

1. The design of millimeter-wave (mmWave) communication systems is highly dependent on the wireless channel characteristics under various environments; therefore, it is necessary for researchers to study mmWave channels in different scenarios.

2. The long-distance propagation characteristics at mmWave frequencies are neglected by most studies.

3. We carry out a large number of channel measurements in mmWave vehicle-to-infrastructure (V2I) long-distance (1900 m) communication scenarios in the 41 GHz band.

# Main idea

1. The vibration features of the received signal strength (RSS) can be best modeled by the modified two-path model considering road roughness.

2. A novel close-in (CI) model considering the effect of the transmitter (TX) and receiver (RX) antenna heights (CI-TRH model) is developed.

3. The variation in both root-mean-square (RMS) delay spread and power delay profile (PDP) shape parameters with TX-RX distance is analyzed.

4. The two-section exponential PDP model is extended to a more general form.

# Method

1. The widely adopted strategy to handle reflections from rough surfaces is to multiply the reflection coefficient by a scattering coefficient.

2. The influence of the heights of both TX and RX on path-loss exponent (PLE) is considered.

3. By dividing the raw data obtained along the TX-RX track into a number of bins, the channel impulse responses (CIRs) in each bin can be regarded as stationary.

# Major results

1. Considering road roughness, the deep fading of received signal strength indicator (RSSI) is significantly reduced compared to the case of the specular reflective surface.

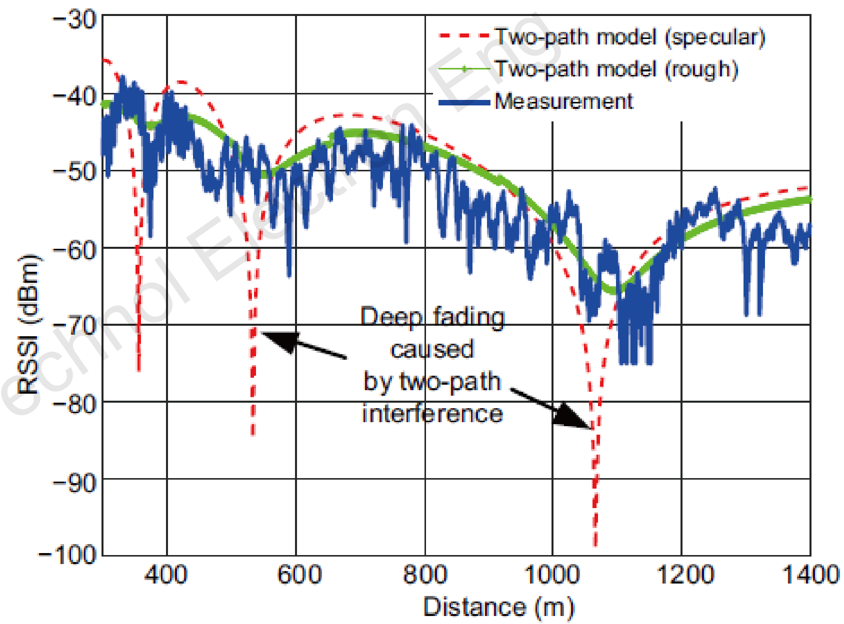


**Fig. 6 Comparison of RSSI simulation results, including the specular and rough surface scenarios and the actual tests when the TX moves from 1900 m to the RX**

RSSI: received signal strength indicator; RX: receiver; TX: transmitter. References to color refer to the online version of this figure

# Major results (Cont'd)

2. CI-TRH model and its parameters can be expressed as

$$\begin{aligned}&\mathrm{PL}^{\text{CI-TRH}}(f,d,h_{\mathrm{TX}},h_{\mathrm{RX}})\,(\mathrm{dB})\\&=\mathrm{FSPL}(f_{\mathrm{c}},1\ \mathrm{m})\,(\mathrm{dB})+10n\lg d\\&\quad\cdot\left(1+b_{\mathrm{TX}}\frac{h_{\mathrm{TX}}-h_{\mathrm{B_0}}}{h_{\mathrm{B_0}}}+b_{\mathrm{RX}}\frac{h_{\mathrm{RX}}-h_{\mathrm{B_0}}}{h_{\mathrm{B_0}}}\right)\\&\quad+\chi_{\sigma}^{\text{CI-TRH}},\quad d\geq 1\ \mathrm{m},\end{aligned}\tag{16}$$

**Table 2 CI-TRH model parameters**

| Parameter | Value |
|---|---|
| $f_{\mathrm{c}}$ (GHz) | 41 |
| $h_{\mathrm{B_0}}$ (m) | 2 |
| TX height range (m) | 1–6 |
| RX height range (m) | 1–4 |
| $n$ | 0.9947 |
| $b_{\mathrm{TX}}$ | 0.0157 |
| $b_{\mathrm{RX}}$ | 0.0172 |
| $\chi_{\sigma}^{\text{CI-TRH}}$ (dB) | 4.726 |
| PLE | 2.0054 |

CI-TRH: close-in model considering TX and RX heights; $f_{\mathrm{c}}$: mmWave frequency; $h_{\mathrm{B0}}$: average height of TX and RX vehicles; PLE: path-loss exponent; RX: receiver; TX: transmitter

# Major results (Cont'd)

3. The measured RMS delay data matches well with the log-normal prediction $N_{\log}(1.78,\ 0.58^2)$ . With an increase in the distance, the value of RMS delay spread decreases.



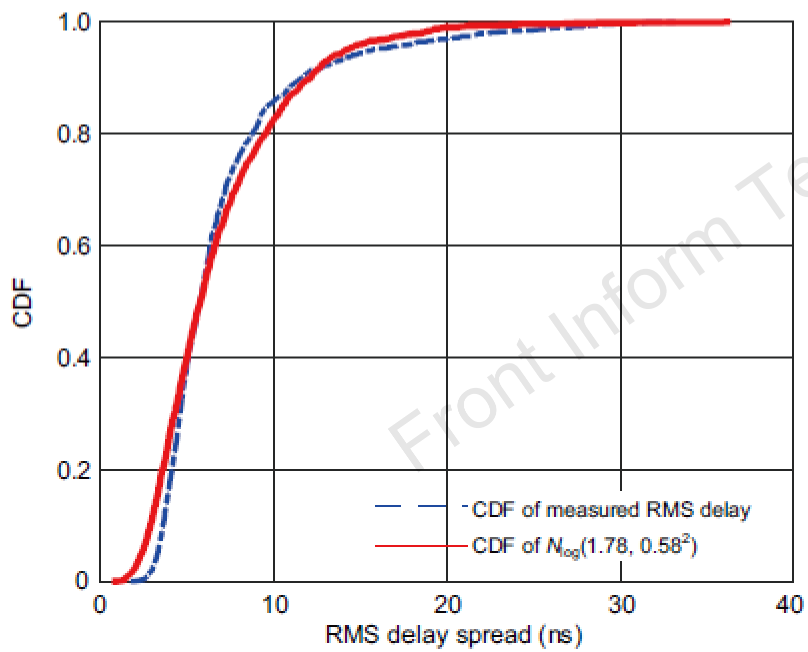


**Fig. 9 CDF of the actually measured RMS delay spread and the fitted log-normal distribution**
CDF: cumulative distribution function; RMS: root-mean-square

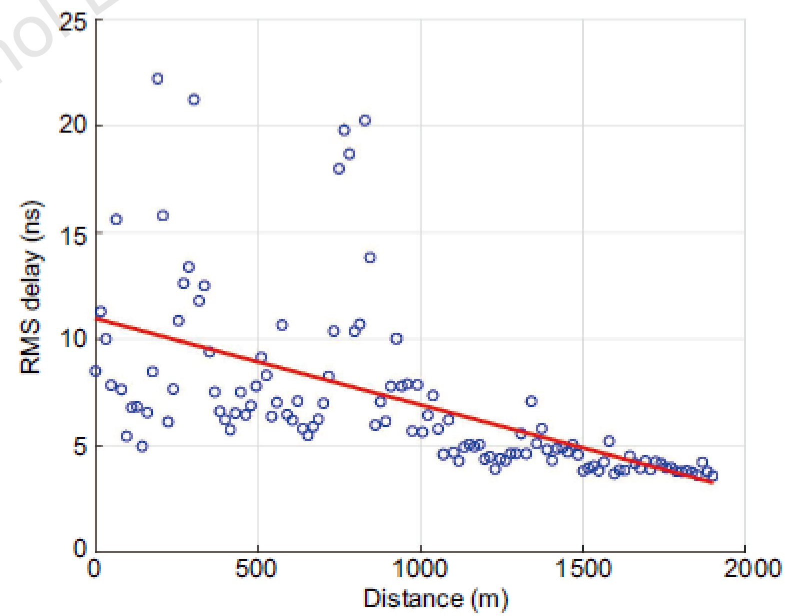


**Fig. 11 RMS delay distribution versus distance**
RMS: root-mean-square. References to color refer to the online version of this figure

# Major results (Cont'd)

4. The new two-section exponential PDP model and measured power delay profile over the distance can be expressed as

$$P(\tau)=\begin{cases}0, & \tau<0,\\ 1, & \tau=0,\\ a_1\mathrm{e}^{-b_1\tau}, & 0<\tau<\tau_c,\\ a_2\mathrm{e}^{-b_2\tau}, & \tau\geq\tau_c,\end{cases} \tag{23}$$



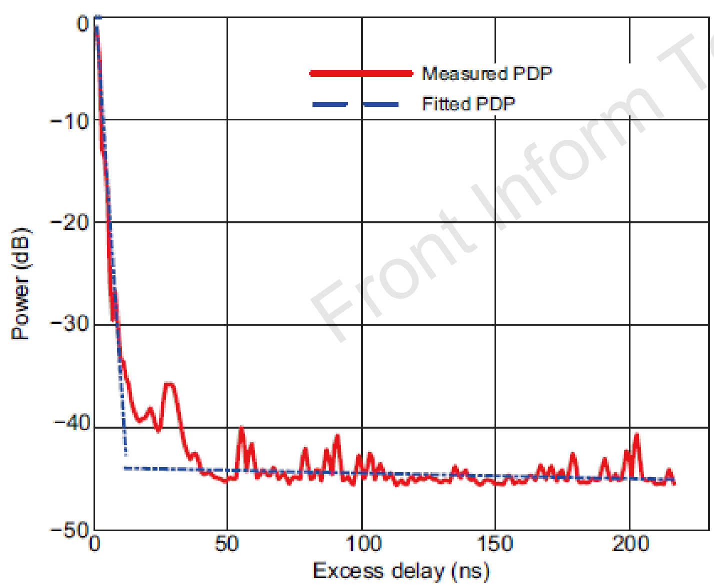


**Fig. 12** Measured power delay profile (PDP) and the corresponding best fit with the improved two-section exponential model

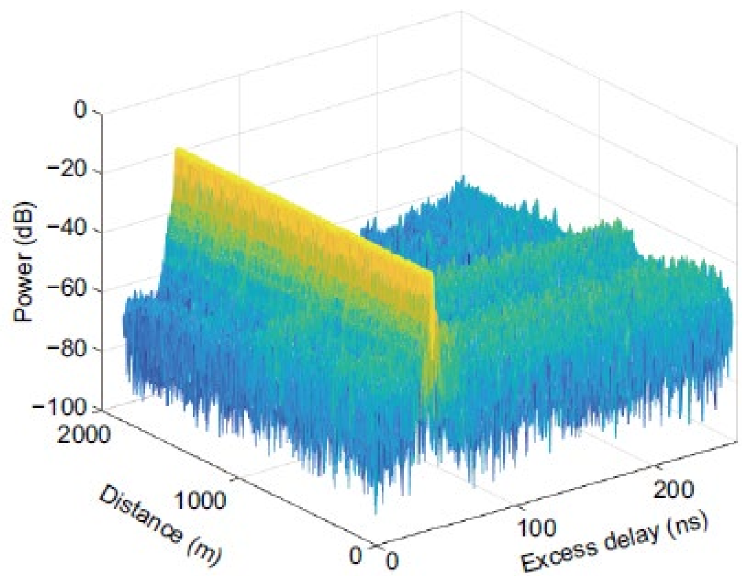


**Fig. 13** Measured power delay profile over the distance

# Major results (Cont'd)

5. Relationship between the actual measured shape parameters and the distance:

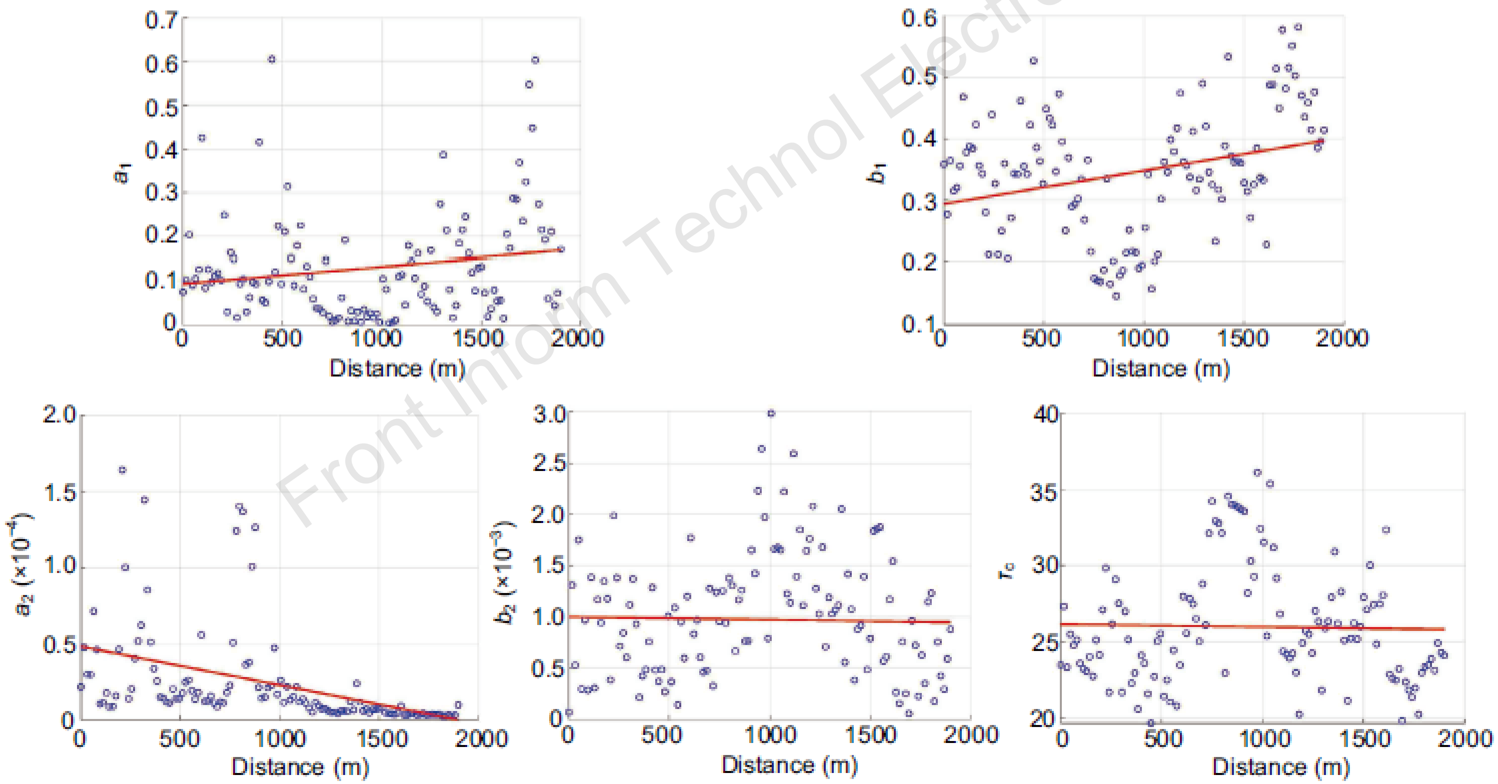




**Fig. 15** Relationship between the actual measured shape parameters $a_1$, $b_1$, $a_2$, $b_2$, $\tau_c$ and the distance (References to color refer to the online version of this figure)

# Conclusions

1. A larger discrepancy in the TX and RX antenna heights results in a larger PLE, and the overall PLE ranges from 2.0402 to 2.1049 in V2I long-distance communication scenarios.

2. The RMS delay spread decreases as the distance increases, which is caused by the faster loss in the energy of the reflected and scattered paths.

3. Some PDP parameters, such as $b_2$ and $\tau_c$, are insensitive to the distance, whereas some other parameters such as $a_1$, $a_2$, and $b_1$ change significantly with the distance.

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