A Simple Empirical Expression for Line-of-Sight Probability in Industrial Environment

Mohammad Hossein zadeh, Marina Barbiroli, and Franco Fuschini

Abstract—**This letter presents a new formula for the line-of-sight probability in the industrial environment. In addition to link distance, the evaluation also considers the relative height of the access point and user equipment concerning the industrial clutter level. The method accuracy is checked against raw data collected through ray tracing simulations. Comparison with existing models shows satisfactory overall performance.**

Index Terms—**Line-of-sight (LoS), ray tracing (RT), wireless industrial networks.**

I. Introduction

WIRELESS technologies for industrial application have been attracting increasing attention over the years, to the extent that they are often acknowledged as key enablers for the advent of Industry 4.0 and Industrial Internet of Things [1], [2], [3]. Wireless solutions can be effectively employed for many applications in industrial contexts, such as process monitoring and control, surveillance for emergency detection, smart metering, cable replacement, remote control, and autonomous robotics [1], [4].

The performance of wireless services and applications greatly depends on whether propagation occurs in *line-of-sight* (LoS) or *non-line-of-sight* (NLoS). In the former case, the transmitter and the receiver are in clear visibility, which is instead prevented by the presence of some obstruction in the latter. In many cases, LoS propagation represents a favorable condition, corresponding to lower attenuation and weaker multipath effects. In the general framework of wireless communication systems, lower attenuation means a larger signal-to-noise ratio (SNR), i.e., better quality of service. Therefore, LoS (un)availability is likely to be particularly crucial in the industrial environment, where obstructions often coming from metal items can be quite severe, or in 5G and beyond networks, where the possible resort to communication frequencies in the millimeter waveband would correspond to heavier penetration losses.

Moreover, the LoS occurrence is also beneficial to the execution of wireless applications, such as beamforming (BF) or localization. Effective BF schemes should look for effective beam-steering strategies corresponding to the largest SNR value. Although this is not, in general, a trivial task, it can be greatly simplified in the LoS presence, where orienting the antenna radiation lobes in the link direction can often represent a (sub)optimal solution. In wireless location services based on time-of-arrival (ToA), location accuracy is in general much better in LoS conditions, as only in that case the ToA can be reliably turned into the actual transmitter–receiver distance necessary for the execution of the triangulation task [5].

Finally, the sensitivity of wireless propagation properties to the LoS/NLoS condition is also highlighted in many reports and recommendations released by technical regulatory institutions, such as ETSI or ITU, where different path loss formulas are proposed for LoS and NLoS cases [6].

Whether a wireless link works in LoS or NLoS depends on geometrical conditions, i.e., on the positions of the transmitter and of the receiver, and on the number, position, shape, and size of the items present between them. As a general trend, the LoS occurrence is expected to reduce with increasing link distance, with a rate that is case-dependent. LoS analysis and detection can be therefore carried out based on a thorough geometrical description of the environment.

Previous investigations on LoS/NLoS occurrence in wireless scenarios have resulted in LoS probability models usually consisting of simple, exponentially decreasing functions with link distance. For instance, exponential formulas are recommended in reports from ETSI [6] and ITU [7].

In this letter, a new empirical expression for the LoS probability in the industrial environment is presented and discussed. In addition to the link distance, the relative height of the access point (AP) and of the user equipment (UE) with respect to machinery heights is also considered for LoS prediction. Concerning previous models, the new formula looks like a better tradeoff between accuracy and flexibility. The model is extracted from a large dataset collected utilizing ray tracing (RT) simulations over a multitude of industrial scenarios. The rest of this letter is organized as follows. The LoS probability assessment framework is described in Section II, whereas results are included and discussed in Section III. Finally, Section IV concludes this letter.

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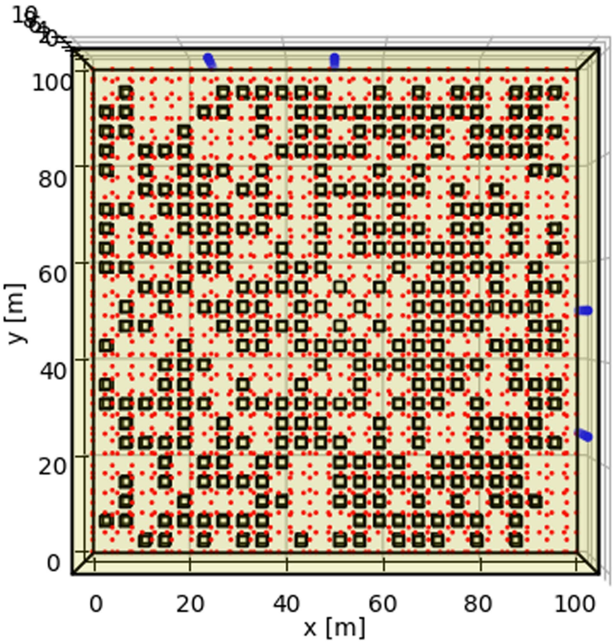

Fig. 1. Examples of irregular scenarios. Red and blue points represent the UEs and the APs, respectively.

TABLE I
VALUES OF THE FEATURES DESCRIBING THE GEOMETRICAL LAYOUT FOR LOS/NLOS DETECTION

Shed size	100 m × 100 m × 10 m
MS (m)	2, 3, 4, 5
MH (m)	1.5, 2, 2.5, 3, 3.5
SP (m)	2, 2.5, 3, 3.5, 4
T	0.0, 0.1, 0.2, 0.3, 0.4, 0.5
MD	[0.05–0.45]

II. LoS Probability Assessment

A. Dataset Generation by RT

Datasets have been collected utilizing the RT tool described in [8]. RT simulations have been carried out inside a 100 m × 100 m × 10 m industrial shed, where machines are simply represented as metal boxes with side MS and height MH for the sake of simplicity. They were at first deployed according to a perfectly regular layout with spacing SP. To make the digital industrial map more realistic, a fraction of T of machines have been then randomly removed, thus creating some emptier spaces among them (see Fig. 1). A total number of 600 scenarios have been considered, corresponding to the whole set of combinations of the parameters in Table I. Based on the values of MS, SP, and T, the machine density (MD) can be also estimated as

$$\mathrm{MD} \approx (1-\mathrm{T})\cdot\left(\frac{\mathrm{MS}}{\mathrm{MS}+\mathrm{SP}}\right)^2. \quad (1)$$

In real industrial scenarios, machines often vary in size. Therefore, parameters, such as MS, MH, and SP, should be interpreted as the mean values representative of the machines in the actual industrial environment.

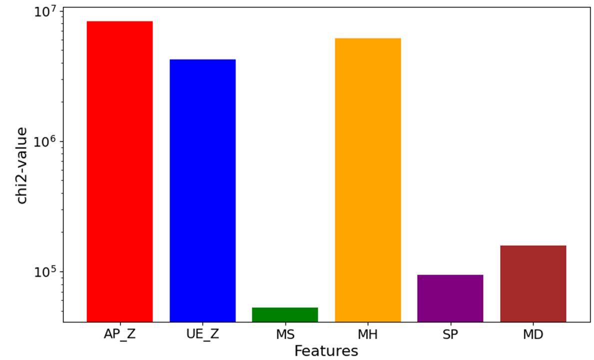

Fig. 2. Feature importance analysis.

For each scenario, five maps have been generated by randomly changing the set of removed machines, for the same T value. The total number of digital maps for RT simulation finally amounted to 3000. For each map, APs have been placed in four different positions on the shed wall at four different heights (h_{AP} = 1 m, 2.5 m, 4 m, and 5.5 m), corresponding to 12 APs overall. A multitude of UE has been spread throughout the area at four different heights (h_{UE} =1 m, 1.5 m, 2 m, and 2.5 m), e.g., representing automated guided vehicles moving along the aisles between the machines (see Fig. 1). For each AP–UE link of each map, the LoS condition was evaluated through RT simulations and recorded in a final output dataset for the following LoS/NLoS analysis. The RT runs were basically aimed at checking whether the AP–UE segment is blocked by the presence of the machines spread throughout the industrial layout. If the segment is actually blocked, the link is labeled as NLoS, whereas it is LoS otherwise. The total number of collected LoS/NLoS labels was greater than 50 million.

III. Results and Discussion

A. Feature Importance

A preliminary analysis based on the chi-square test has been carried out on the collected dataset to identify the key parameters affecting the LoS condition in industrial environments. Since the dataset includes a multitude of features (AP and UE height, MS, SP, MH, and MD), their impact on the overall LoS condition has been first investigated. Surprisingly, the chi-square analysis reveals that MS, SP, and MD play a relatively minor role compared with MH and with the AP and UE height (see Fig. 2), at least in the considered cases. Based on this evidence, the attention was then narrowed down to the three most critical parameters: MH, h_{AP}, and h_{UE}, in addition to link distance.

B. Analytical Formula

Since the relative height of APs and UEs with respect to the industrial clutter level is likely to be more important than the absolute height values for the occurrence of LoS/NLoS conditions, MH, h_{AP}, and h_{UE} have been replaced by $\Delta H_1 = (h_{\mathrm{AP}} - \mathrm{MH})$

ΔH1	ΔH2	distance	LoSlabel
-0.5	0.50	101.86	0
-0.5	0.50	99.42	0
-0.5	0.50	96.98	0
-0.5	0.50	94.55	0
-0.5	0.50	92.12	0
...	...	...	...
2.0	0.25	52.40	0
2.0	0.25	51.90	0
2.0	0.25	51.52	0
2.0	0.25	51.24	0
2.0	0.25	51.09	0

Fig. 3. Final dataset for LoS/NLoS analysis.

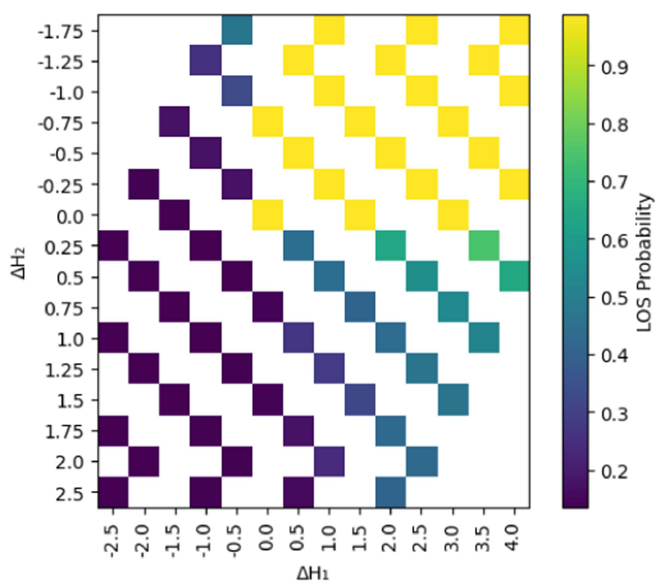

Fig. 4. Heatmap of LoS probability as a function of ΔH_1 and ΔH_2.

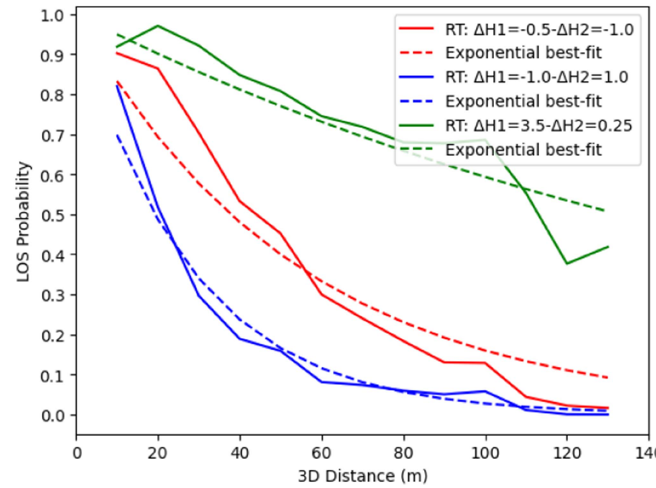

Fig. 5. LoS probability as exponential decay.

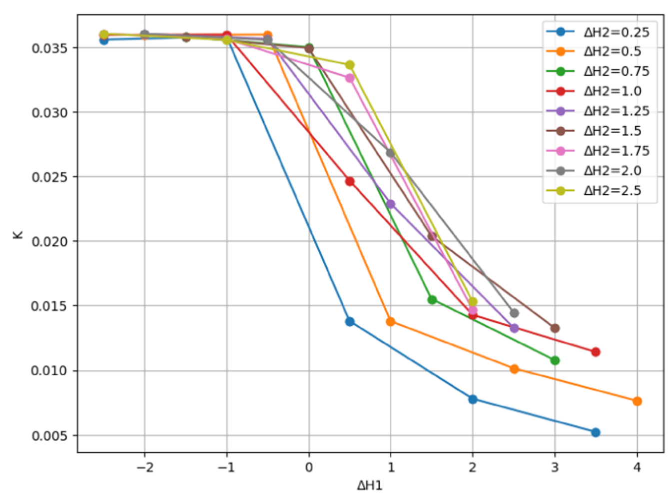

Fig. 6. K versus ΔH_1 for different ΔH_2 values.

and $\Delta H_2 = (\mathrm{MH} - h_{\mathrm{UE}})$, thus leading to a final dataset, as shown in Fig. 3.

In agreement with common sense, the heatmap in Fig. 4 clearly shows that the LoS probability increases at larger ΔH_1 and lower ΔH_2, whereas it reduces otherwise. Furthermore, it is, of course, equal to 1 when the AP and the UE are standing above the machine layer, i.e., $\Delta H_1 \geq 0$ and $\Delta H_2 \leq 0$. The analysis has been then focused on nontrivial cases.

In the end, this study is aimed at looking for a simple, analytical formulation of the LoS probability in an industrial environment (LoSP in the following) as a function of ΔH_1, ΔH_2, and distance d.

The empirical evidence in Fig. 5 supports an exponential decrease in LoSP with distance, which is also consistent with previous investigations. The decay rate coefficient should be clearly tailored to the specific case. This leads to the following expression:

$$\mathrm{LoSP} = \begin{cases} e^{-K(\Delta H_1, \Delta H_2)\cdot d}, & \Delta H_1 \leq 0 \text{ or } \Delta H_2 \geq 0 \\ 1, & \text{otherwise.} \end{cases} \quad (2)$$

To discern the relationship between K, ΔH_1, and ΔH_2, Fig. 6 shows the best-fit values of the K parameter computed for different ΔH_1 and ΔH_2. The observations suggest that a sigmoid-like relationship exists between the optimal K and ΔH_1 values. In the framework of the sigmoid functions, the following expressions have been in particular considered:

$$K = \frac{0.03}{1 + k_1(\Delta H_2)\cdot e^{\Delta H_1{}^2}} + 0.007. \quad (3)$$

To model the dependence of the coefficient k_1 on ΔH_2, the optimal values of k_1, i.e., corresponding to the optimal K values in (3), have been first computed for different ΔH_2, and finally plotted against ΔH_2 (see Fig. 7, continuous line). Overall, k_1 exhibits a clearly decreasing trend with ΔH_2, which

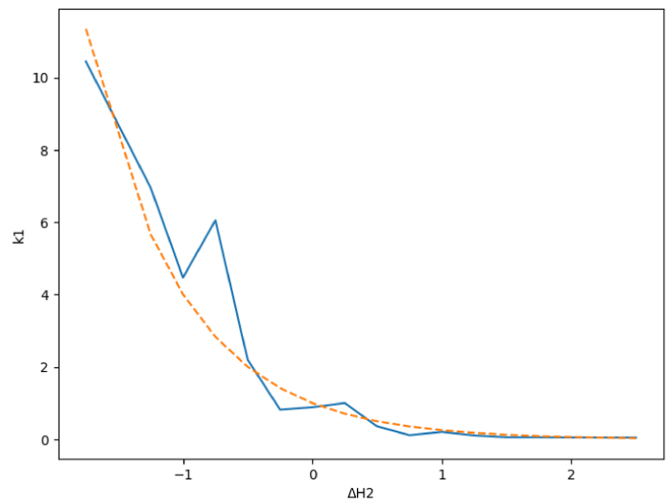

Fig. 7. k_1 versus ΔH_2.

TABLE II
COMPARISON BETWEEN ACCURACY OF DIFFERENT MODELS

Model	RMSE
New formula	0.076
ETSI	0.254
ITU	0.304

was then modeled as a further exponential decay function, i.e., $k_1 = e^{-\gamma \cdot \Delta H_2}$. The best value of the decay rate coefficient was found through the least square method and turned out equal to $\gamma = 1.38$ (see Fig. 7, dashed line).

The ultimate formulation of the K coefficient appears in (2) therefore established as follows:

$$K = \frac{0.03}{1 + e^{-1.38 \Delta H_2} \cdot e^{\Delta {H_1}^2}} + 0.007. \quad (4)$$

C. Validation

RT simulations have been repeated for $(\Delta H_1, \Delta H_2) \in \{(-0.75, -2), (4, 0.5)\}$, i.e., in conditions not considered for deriving the LoSP function. The LoSP values extracted from the new simulations have been then compared with the new proposed formula. The comparison has also been extended to the models included in the ITU and ETSI reports [6], [7]. The accuracy of each model is reported in Table II through its root-mean-square error (RMSE) with respect to the ground truth represented by the raw LoS probability provided by RT simulations.

It is worth pointing out that the LoS probability formula suggested by ETSI also takes into consideration machines' size and density, besides the heights of devices and machinery. Despite this greater flexibility, the RMSE of the model is greater compared with the new formula proposed in this work.

The reason is explained in Figs. 8 and 9. Although the ETSI model turns out to be basically as reliable as the model described by (2) when limited MD and larger machine size are considered (see Fig. 8), its performance clearly drops when it comes to a greater density of the industrial clutter with a smaller dimension

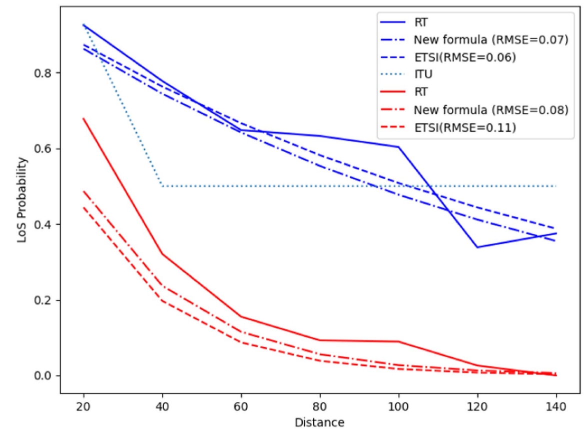

Fig. 8. Models comparison for MD=0.15 and MS = 4. Blue and red curves, respectively, refer to ($\Delta H_1 = 2.5$ m and $\Delta H_2 = 0.5$ m) and ($\Delta H_1 = -1$ m and $\Delta H_2 = 1$ m).

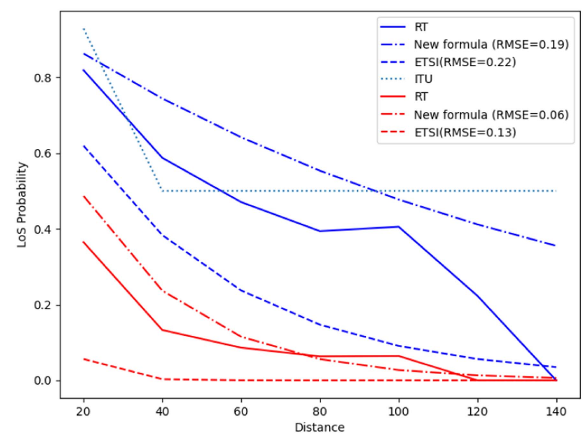

Fig. 9. Models comparison for MD = 0.25 and MS = 2. Blue and red curves, respectively, refer to ($\Delta H_1 = 2.5$ m and $\Delta H_2 = 0.5$ m) and ($\Delta H_1 = -1$ m and $\Delta H_2 = 1$ m).

of machines (see Fig. 9). Conversely, the new model exhibits an overall fair accuracy in both cases. The legends in Figs. 8 and 9 include the RMSE of the models concerning the RT ground truth for the sake of comparison. Figs. 8 and 9 also explain why the ITU model has the largest RMSE. In fact, it consists of a very simple expression that cannot be tuned to the different ΔH_1 and ΔH_2 values as it includes the link distance only.

On the whole, the inclusion in the LoSP model of extra parameters, such as MD and MS, which are not of primary importance in LoS evaluation (as shown in Fig. 2), may result in an overall worsening of the prediction accuracy.

IV. CONCLUSION

This study has presented a robust formulation for LoS probability in the industrial context. Preliminary analyses based on RT simulations and chi-square test have shown that MD, size, and spacing affect the LoS to a quite limited extent. Therefore, the new formula only accounts for the relative height of the wireless devices with respect to the machinery level, in addition to link distance. The proposed formula has demonstrated better performance when compared with established existing models.

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