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LETTER

Estimation formula of unmanned aerial vehicle base stations density for required line-of-sight probability in urban environments

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Abstract The line-of-sight (LOS) probability in an urban environment assuming unmanned aerial vehicle base stations (UAV-BSs) is studied. We establish an estimation formula to calculate the minimum density of UAV-BSs required to achieve a certain LOS probability over an area.

Keywords: LOS probability, UAV-BS, drone, urban environment, mobile communication system

Classification: Antennas and propagation

1. Introduction

In fifth-generation (5G) mobile communication systems and beyond, the use of higher-frequency bands, such as millimeter and terahertz waves, is assumed for the purpose of acquiring a wide frequency bandwidth to realize high-speed and large-capacity communications. In the high-frequency bands, narrow-beam directional antennas must be used to compensate for the large propagation losses; as a result, line-of-sight (LOS) communication is often assumed. Therefore, it is necessary to maintain a high LOS probability between base stations and mobile stations. As one approach to achieving this scenario, a method involving deploying unmanned aerial vehicle base stations (UAV-BSs) (such as a drone) in the air has been proposed [1].

Compared with terrestrial base stations, UAV-BSs have greater chances of LOS links to ground users because of their higher altitude. Therefore, UAV-BSs are suitable for communication systems that operate in high-frequency bands. Because of this advantage, research has been conducted on systems that use multiple UAV-BSs. For example, such a system is investigated in [2] and the minimum number of UAV-BSs to provide communication services to a set of arbitrarily placed users is studied.

We presented in reference [3] an estimation formula to compute the minimum UAV-BS density that achieves the required LOS probability in an urban area. To further confirm the estimation accuracy of the formula, we used newly added area, but significant estimation errors were observed. In this letter, some modifications were made to the urban model and the definition of the parameters in order to improve the estimation accuracy.

2. UAV-BS density estimation formula

2.1 LOS probability and outline of estimation formula

In this letter, we develop an estimation formula for simply calculating the minimum UAV-BS density (D) that achieves the required LOS probability (α) in an urban area. Here, D refers to the number of UAV-BSs within an area of 1 km^2. Since shielding by buildings is main cause of NLOS (Non-LOS) in an urban area, we express the formula using parameters related to the buildings' structures. Although shiding caused by other objects such as trees also affect the LOS probability, here we focus on the influence by buildings, which is thought to have a greater influence on the LOS probability particularly in an urban area.

Here, the LOS probability refers to the ratio of the LOS area among the all road area outside buildings in a certain area. In order to construct the formula, first, the functional form of the estimation formula is established through consideration of the positional relationship of buildings' structures, UAV-BSs, and mobile stations. This functional form of the formula is given by the dominant parameters for the estimated target (D) as variables in the formula. Next, we calculate the value of D by simulation in urban areas. By using the value as training data, the coefficients of the estimation formula are determined. Using this approach, we develop an estimation formula that is adaptable to changes of the parameters.

The appropriate UAV-BS height depends on assumed system. So, one of our objectives is to research UAV-BS density in response to changes in UAV-BS height. In the model where we consider the formula, we use the ratio between the UAV-BS height $h_{\mathrm{b-m}}$ and the average building height $h_{\mathrm{r-m}}$ as γ as a height parameter of UAV-BSs. Here, $h_{\mathrm{b-m}}$ and $h_{\mathrm{r-m}}$ are the heights based on the height of the mobile station (h_{m}). For simplicity, we refer to the horizontal plane of the height h_{m} as the ground.

2.2 Simulation of minimal UAV-BS density

Figure 1 shows urban maps of real cities in Japan, which are simulation environments for the training data [4, 5, 6]. In this letter, we call a simulation environment as "a target area". Figure 2 shows an example of the simulated results for a minimal UAV-BS placement that achieves a LOS probability of 0.95 in Area 1 ($\gamma = 3$). In the simulation, a UAV-BS is placed in the location where the LOS probability increases the most; this process is repeated until the LOS probability

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exceeds the required value. In this letter, we use this method to approximately find the minimum density of UAV-BSs (the value of D).

2.3 Construction of estimation formula

The concept for determining the UAV-BS density that achieves the required LOS probability is shown below. We consider a group of several UAV-BSs as a subset and construct the required LOS probability by overlaying them. We express the LOS probability achieved by the subset as $1-\beta$ (where β represents the probability of NLOS) and its density as D_β. We simplify the formulation of D_β by assuming a relatively low density as a subset. The reason for this assumption is that we can consider a simple situation where there is little overlap between the LOS areas covered by each base station included in one subset. Also, we express the number of subsets required to achieve the required LOS probability as N. So, the estimation formula of D is expressed as

$$D = D_\beta \times N \tag{1}$$

2.4 Base station density of a subset (D_β)

We formulate the equation for D_β as shown below. First, we define an area from directly below a UAV-BS to the ground horizontal distance x as coverage area. Here, x is defined as the maximum LOS distance from a UAV-BS. Based on this definition, we assumed D_β to be such a density that can be approximated as follows.

- Coverage areas of each UAV-BS included in one subset covers a whole target area.
- There are no gaps or overlaps between the coverage areas.

From this assumption, D_β and the square measure of a coverage area are inversely proportional.

To consider the relationship between the square measure of a coverage area and the parameters related to the buildings' structures, we assume a simple urban model that abstracts an actual urban environment. First, we convert the two-dimensional urban structure into a simple one-dimensional model. This is because many actual cities' layouts approximate a grid plan. As shown in the left side of Fig. 3, a grid plan is an urban structure in which parallel roads are stacked at right angles. Both of the two direction roads have one-dimensional structures. We therefore consider that the urban structure can be simplified to a one-dimensional structure as shown in the right side of the figure.

Next, we simplify the urban structure by using statistics calculated from building coordinate data in target areas, such as average building heights. The details of simplification are summarized below.

- The building height is constant at $h_{\mathrm{r-m}}$ (the average value in a target area).
- The road width is constant at d (the representative value in a target area).
- The buildings are plates with no thickness.

Based on the above simplification, we assumed an urban model as shown in Fig. 4. From Fig. 4(a), x is calculated from the parameters related to the buildings' structure (d, $h_{\mathrm{r-m}}$, and $h_{\mathrm{b-m}}$). When modeled using this approach, the square measure of a coverage area is proportional to x. And, from the above description, D_β and the square measure of a coverage area are inversely proportional. Therefore, D_β is expressed as

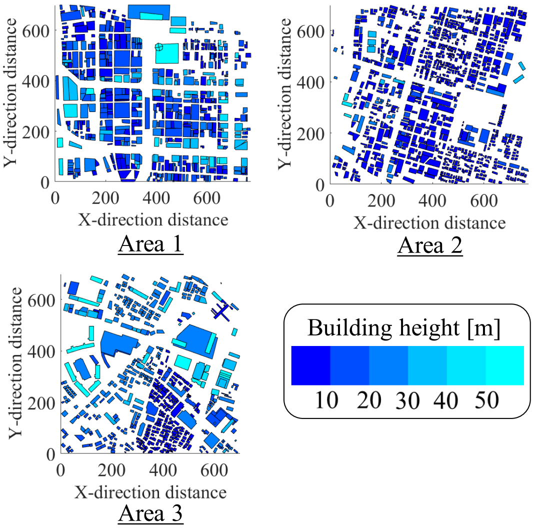


Fig. 1 Urban maps of target areas (training data).

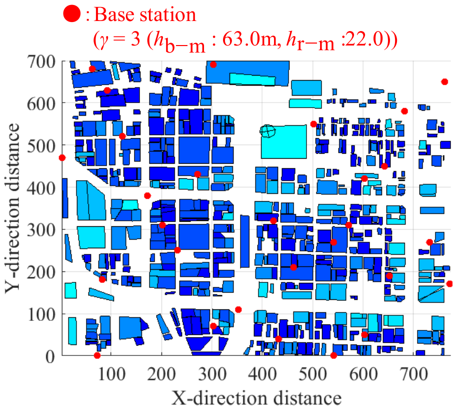


Fig. 2 Example of a UAV-BS arrangement.

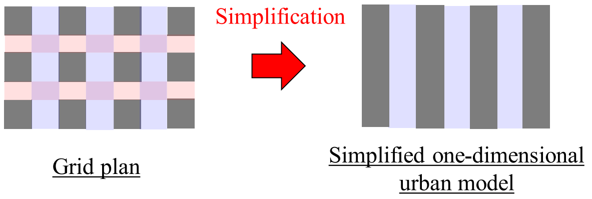
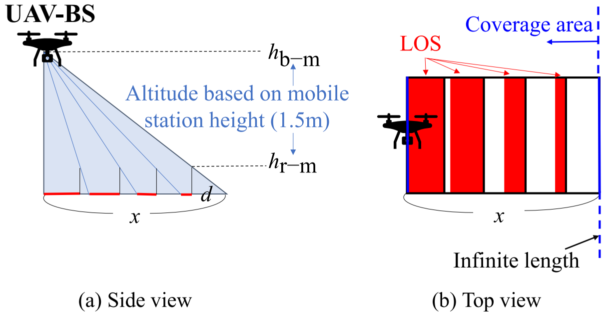


Fig. 3 Simplification of an urban model.



(a) Side view (b) Top view

Fig. 4 Simplified urban model.

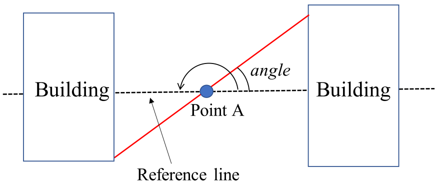


Fig. 5 Definition of road width.

$$D_\beta = \frac{k}{x} = \frac{k}{d\gamma} \tag{2}$$

where k is a proportionality constant. Also, calculated from the model in Fig. 4, the value of β is determined to be 0.5. This value is used in the equation for N (in Section 2.5).

The definition of the road width used in this study is defined as follows. A point (Point A in Fig. 5) in an area outside buildings is considered. We consider the distance between buildings in a certain angular direction overcrossing the point A; it is the length of the red line in the figure. We then calculate the minimum value of the distance over the whole angle. This minimum value is obtained at all points and the median and the quartile deviation in the area are obtained and denoted by d_m and d_s, respectively.

In Eq. (2), d is a representative value of the road width. We use a smaller value, rather than the intermediate value of the distribution of the road widths because we considered that locations in a narrow road mostly determine the required UAV-BS density particularly for high LOS probability. As a result of numerical analysis, we set $d = d_\mathrm{m} - d_\mathrm{s}$.

The new proposed method has been modified from the conventional method regarding the urban model and the road parameters. In this study, we simplify the urban structure in the coverage area. In the conventional method, we simplified the urban structure by assuming the coverage area to be a set of radial line segments starting from the base station. On the other hand, in the new method, we simplify the urban structure to one-dimension based on the simpler concept shown in Fig. 3, which assumes a grid plan. Regarding the parameter definition, in the conventional method, we used a parameter called the road size. The road size is defined as the average value of the distance between buildings over the whole angle, but we considered that the minimum value of the distance between buildings over the whole angle is more suitable for the concept in Fig. 3. Therefore, in this paper, we defined the minimum value as the road width and used it as a parameter instead of the road size.

2.5 Number of subset (N)

We formulate the equation for N as shown below. First, we assume a simple situation to simplify the construction of the estimation formula. The assumption is that the location of LOS areas covered by each subset are independent of each other. Based on the assumption, a subset is expected to convert a proportion of $1 - 0.5$ $(1 - \beta)$ of the NLOS area to LOS and leave the remaining 0.5 (β) still NLOS. Generalizing this assumption, we assume that overlaying n subsets achieves an LOS probability of $1 - 0.5^n$ $(1 - \beta^n)$. However, because we place UAV-BSs in the position that increases the LOS probability the most in the simulation, relatively wide roads become LOS areas first. Therefore, when the UAV-BS density is high and the LOS probability is already high, NLOS areas are mostly limited to narrow roads. On the basis of this consideration and the observation on the simulation results, we hypothesized that the number of subsets required to convert a proportion of $1 - 0.5$ of the NLOS area to LOS increases exponentially as the LOS probability becomes high. In this case, we assume n^ε subsets are required to achieve an LOS probability of $1-0.5^n$. Thus, $\alpha = 1-0.5^n$ and $N = n^\varepsilon$ holds. Here, ε represents the degree of exponential increase in the number of subsets with respect to the increase in α. From these considerations, n and N are expressed as

$$n\frac{\log(1-\alpha)}{\log(0.5)} \tag{3}$$

$$N = n^\varepsilon = \left(\frac{\log(1-\alpha)}{\log(0.5)}\right)^\varepsilon \tag{4}$$

2.6 Final form of estimation formula

Since D_β and N are formulated as Eqs. (2) and (4) respectively, the final functional form of the estimation formula can be completed by multiplying them. Then, we determine the values of k and ε by fitting with the value of D obtained from the simulations using the training data. As a result, we obtained the values as $\varepsilon = 1.83$, and $k = 117$. So, D is formulated as

$$D = D_\beta \times N = \frac{117}{(d_\mathrm{m} - d_\mathrm{s})\gamma}\left(\frac{\log(1-\alpha)}{\log(0.5)}\right)^{1.83} \tag{5}$$

Figure 6 shows the fitting results with the training data. From the figure, the estimation formula and simulation results fit well. The values of D for high required LOS probability are also well expressed. This is considered to be because the functional form of the estimation formula is appropriate.

We evaluated the estimation performance of the estimation formula using test data different from the training data. Figure 7 shows the urban maps of the target areas of the test data. Area 4 is an urban environment with a very dense structure, while Area 5 has both dense and sparse areas. By using the two environments as test data, we checked the generality of the estimation formula. Figure 8 shows the estimation results for the test data. The two figures shown above are the

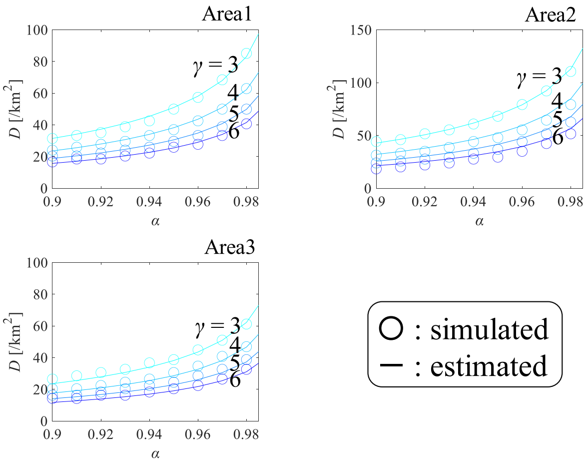


Fig. 6 Fitting results with training data.

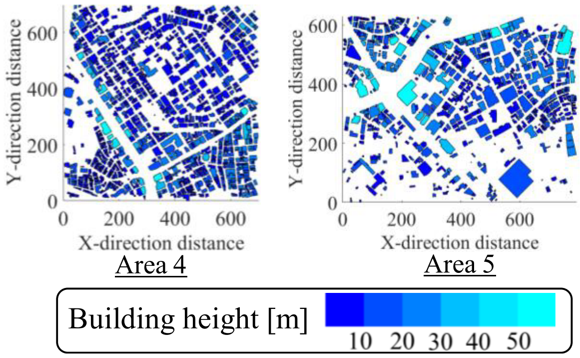


Fig. 7 Urban maps of target areas (test data).

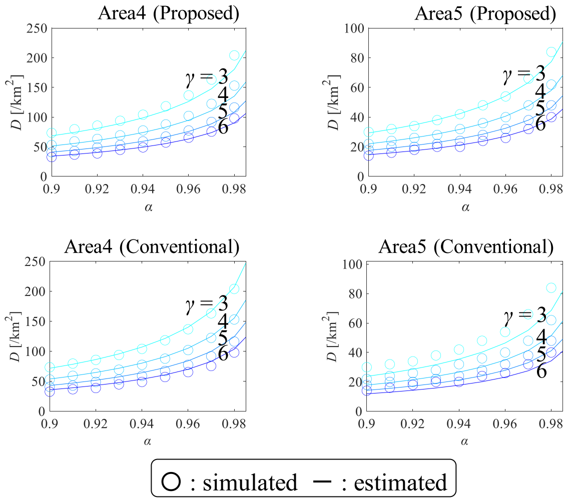


Fig. 8 Estimation results for test data.

estimation results computed by the conventional estimation formula [3]. Even using the conventional method, D can be well estimated in Area 4, but significant estimation errors are found in Area 5 particularly for the larger γ values. On the other hand, the two figures shown below are the estimation results by the new formula. Compared with the conventional formula, the estimation accuracy improves in Area 5 and remains high in Area 4. It suggests the road width is more consistent than the road size as a parameter representing the distance between buildings. The high estimation accuracy with the test data indicates the larger generality of the new estimation formula. Therefore, this estimation formula can estimate the value of UAV-BS density in response to changes in areas and system parameters such as γ and α.

3. Conclusion

In this letter, an estimation formula to assess the minimum UAV-BS density that achieves the required LOS probability was considered. To improve the estimation accuracy of the previously presented formula, some modifications were made to the urban model and the definition of the parameters. As a result, we were able to improve estimation accuracy in the newly added area. In conclusion, we finally established a formula corresponding to changes of areas and system parameters.

Acknowledgments

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