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Research Article

Feasibility of UAV Link Space Diversity in Wooded Areas

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Space diversity techniques provide an effective way to mitigate the deep fades in received power in a scattering environment. Space diversity influence on narrowband UAV links, which are unique due to the elevation angle and mutual position of a moving transmitter in homogeneous environment and static receiver in scattering environment, is analyzed in a wooded area using a remotely controlled airship at 2 GHz. The experimental link forms a 1x4 SIMO configuration with influence quantified by values of diversity gain and subsequent comparison with Rayleigh fading series. The mutual antenna distance and elevation angle influence is also studied as the difference between the wooded area and an open field or urban environment.

1. Introduction

Unmanned aerial vehicles (UAVs) are deployed in many surveillance missions as they are safe and inexpensive.

These aircraft need a high data rate communication link for direct evaluating or storage of data which the control link cannot guarantee. Due to the specific elevation angle this link can be classified as a “low elevation link.”

Any link in a scattering environment suffers as multipath propagation causes deep fades degrading the link reliability.

One way to improve these fades is to use diversity techniques, many of which have been published for satellite or terrestrial links, for example, polarization diversity [1], angle diversity [2], frequency diversity [3], transmit diversity [4], and space diversity [2, 3]. Moreover, statistical models of signal-to-noise distribution or mathematical expression of outage probability have also been published [5, 6].

However the UAV links differ from satellite and terrestrial links not only by elevation angle, but also by transmitter and receiver configuration where, unlike in mobile satellite or terrestrial links, the transmitter is in motion in a homogeneous environment and the receiver is in a static position in the scattering environment. The receiver position can be operationally changed and this system is usually called “nomadic user.” Due to the differences, there is different distribution of received power and different spectrum [7] creating the need for new diversity analysis.

Preliminary results were presented in [8], so this paper presents the deep analysis of space diversity effectiveness, based on stable parts of the received signal, quantified by diversity gain and compared with the Rayleigh series for UAV links in wooded areas. We also analyze the influence of the antennas' mutual distance and elevation angle on diversity gain. Finally we compare the results from the wooded area to an open field to specify the wooded environment studied. Only the narrowband link is studied in this paper.

2. Experiment Description

A series of measurements was performed in a flat, open area several kilometers north of Prague using a remotely controlled airship [9] (Figure 1) which flew randomly within square boundaries at flight levels 300 and 500 meters above the ground (elevation angles 4.28° and 7.1°).

The equipment was similar to that used in our previous work [10] where we focused on diversity possibilities in an urban area.

The bottom of the remotely controlled airship held a continuous wave (CW) transmitter with a carrier frequency of 2 GHz and 27 dBm transmitting power using a planar spiral

Figure 1: Remotely controlled airship used in measurements.

Figure 2: Receiver antennas and surroundings.

antenna with left-hand circular polarization. Due to possible directivity loss caused by airship pitch and roll, the pitch and roll data from airship sensors together with GPS position was stored for further processing.

A four-channel receiver with −126 dBm sensitivity and a measurement bandwidth of 12.5 kHz was used. The recording rate was 100 samples per second. Two quarter-wave patch antennas were connected to the receiver and fed from two orthogonal points providing vertical and horizontal linear polarization for each antenna: left antenna vertical polarization (Lv), left antenna horizontal polarization (Lh), right antenna vertical polarization (Rv), and right antenna horizontal polarization (Rh). The antennas were placed on a wooden rod to provide two mutual distances placed 1.5 m above ground level. The receiver was positioned approximately four kilometers from the transmitter and was placed several meters from the edge of a small forest with most of the vegetation positioned in the transmitter direction (Figure 2). The system was classified as SIMO 1x4 and the experiment was performed in April without leaves on any trees.

3. Data Processing

Several preprocessing tasks were first carried out to verify the quality and branch consistency of the recordings before going on to combine the four received signals. Due to significant pitch and roll values, measured radiation patterns of the transmitter antenna to estimate the directivity loss for each pitch and roll value with respect to the mutual position of the transmitter and receiver were used. Receiver antennas were pointed to the transmitter and kept static.

We next subtracted the free space level from the measured received power series to compute the excess path gain, the inverse of the excess loss. Finally, we converted the excess path gain to linear units (normalized received voltage or signal envelope) for performing signal combining. After combining them, the resulting envelopes were converted back to logarithmic units for further analysis.

The resulting envelope is denoted by r_0 and the individual branch envelopes are denoted by r_i as in Appendix D of [11], where the concept of effective signal envelope is defined.

Three combining methods were tested:

(1) selective combining (SC), where

$$r_0 = \max\{r_1, r_2, \ldots, r_M\} \tag{1}$$

with M representing the number of branches,

(2) maximal ratio combining (MCR), where

$$r_0 = \sqrt{r_1^2 + r_2^2 + \cdots + r_M^2}, \tag{2}$$

(3) equal gain combining (EGC) where

$$r_0 = \frac{r_1 + r_2 + \cdots + r_M}{\sqrt{M}}. \tag{3}$$

Finally, we chose the stable parts of the data for trustworthy analysis.

4. Results

A measurement with elevation angle 4.28° and closer antenna configuration was chosen as a reference for further statistical analysis.

The cumulative distribution functions (CDF) for the individual diversity branches and combined signals from all four branches using the above mentioned diversity methods are shown in Figure 3. All signals were normalized with respect to their RMS level.

From the figure we can observe how the four branches show almost equal mean power which is one of the two requirements for achieving significant diversity gains. The other requisite is low cross-correlations. Thus, we also analyzed the correlation between the signal envelopes in the four branches in linear units. Results can be found in Tables 1, 2, and 3.

The channels seem to have low correlation coefficients resulting in a good opportunity to use diversity methods. Any significant correlation due to polarization was not observed.

The signals' CDF were compared with those predicted for a Rayleigh fading with an RMS level equal to one. Figure 4 shows the CDF for normalized measured and combined signals and those corresponding to the Rayleigh model. While

Table 1: Cross-correlation coefficients—elevation angle of 4.3° with closer antenna distance.

	Channels			
	Lh	Lv	Rv	Rh
Lh	—	0.165	0.076	0.094
Lv	0.165	—	0.093	0.134
Rv	0.076	0.093	—	0.080
Rh	0.094	0.134	0.080	—

Table 2: Cross-correlation coefficients—elevation angle of 7.1° with closer antenna distance.

	Channels			
	Lh	Lv	Rv	Rh
Lh	—	0.184	0.003	0.011
Lv	0.184	—	0.096	0.051
Rv	0.003	0.096	—	0.342
Rh	0.011	0.161	0.342	—

Table 3: Cross-correlation coefficients—elevation angle of 4.3° with wider antenna distance.

	Channels			
	Lh	Lv	Rv	Rh
Lh	—	0.190	0.006	0.191
Lv	0.190	—	0.030	0.372
Rv	0.006	0.030	—	0.383
Rh	0.191	0.372	0.383	—

the agreement is acceptable, some differences were seen. The measured signals do not fully follow the Rayleigh distribution; however, the Rayleigh distribution is the closest of any other known distribution. This disagreement is observed in all flights regardless of the elevation angle or mutual antenna distance. The successive incremental combinations of branches are also shown with significant improvements observed as new branches are introduced to the combiner.

For reference, we also present a comparison of the measured and predicted (assuming uncorrelated Rayleigh branches) diversity gains [11]. The diversity gain is defined as the dB difference for equal probability levels between the CDF of the strongest individual branch and the CDF of that for the combined signals.

In Figure 5 we show the incremental diversity gains assuming MRC based on the results presented in Figure 4. At the 0.01 probability level (1%) a gain of approximately 8 dB is obtained for two-branch diversity. Further branches bring about smaller, yet substantial, increments; for example, for the 1% probability level we gain about 12 dB when we introduce diversity which is incremented to about 14 dB when four branches are used. The diversity gain values for four branches are approximately 4 dB lower than those in the urban area described in [10].

We observe that the diversity gain values do not follow the gains of Rayleigh branches because the measured signals do not fully follow the Rayleigh distribution.

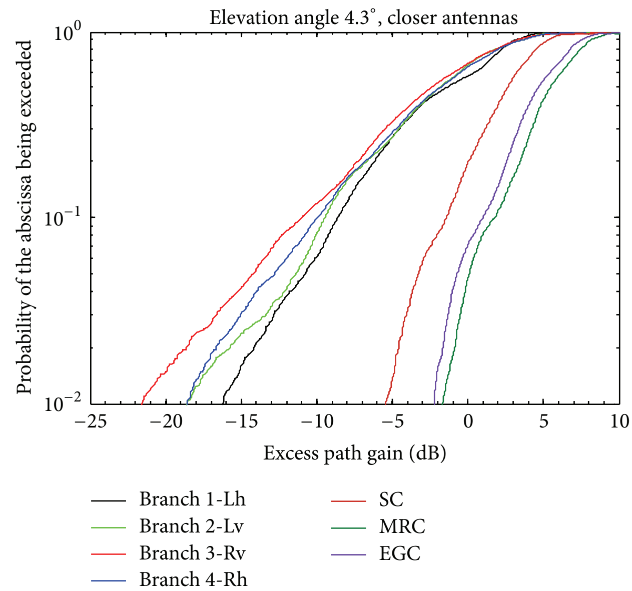

Figure 3: CDF of normalized series and combined signals.

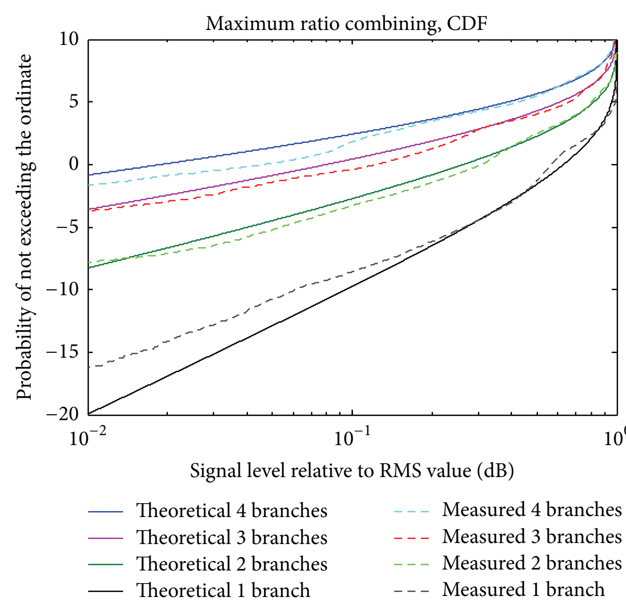

Figure 4: Comparison of CDF of MRC incremental combined signals from measurements with the MRC incremental combination of theoretical Rayleigh distribution CDF.

In Figure 6 we depict the diversity gains (using the MRC method) of the two different antenna configurations and different elevation angles. The closer antenna setting has 0.47 m (approx. 3λ) distance between the centers of the patch antennas, and the wider antenna setting has 0.82 m (5.5λ) distance between the centers. Both possible elevation angles were used: 4.28° and 7.1°. We did not find any significant dependence on elevation angle; however, a slight improvement in diversity gain for lower probabilities is found for the wider antenna configuration.

Finally, we compared the diversity gains obtained in the wooded area with the diversity gains from the open field area.

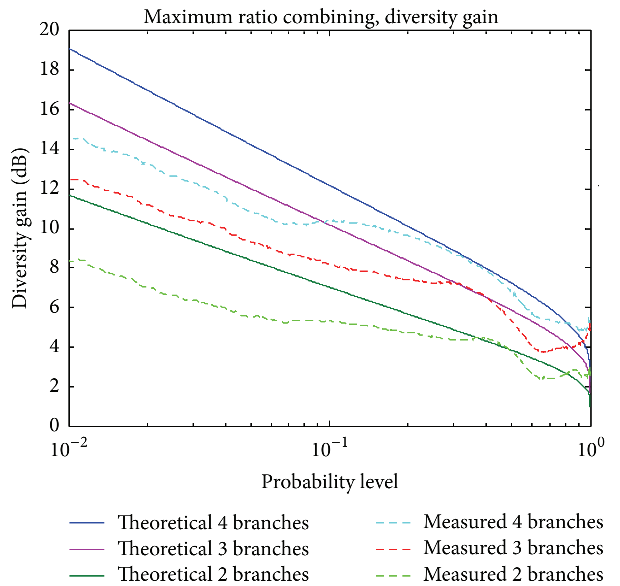

Figure 5: Measured and uncorrelated Rayleigh model 4-branch incremental diversity gains with MRC.

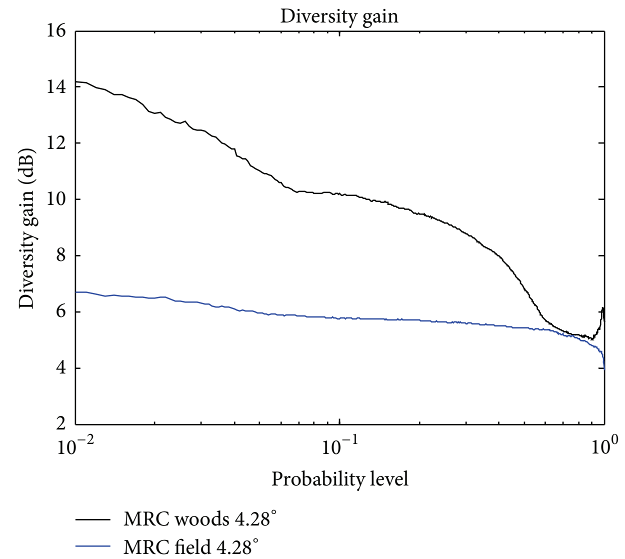

Figure 7: Comparison of diversity gains for two different areas—elevation angle 4.28°.

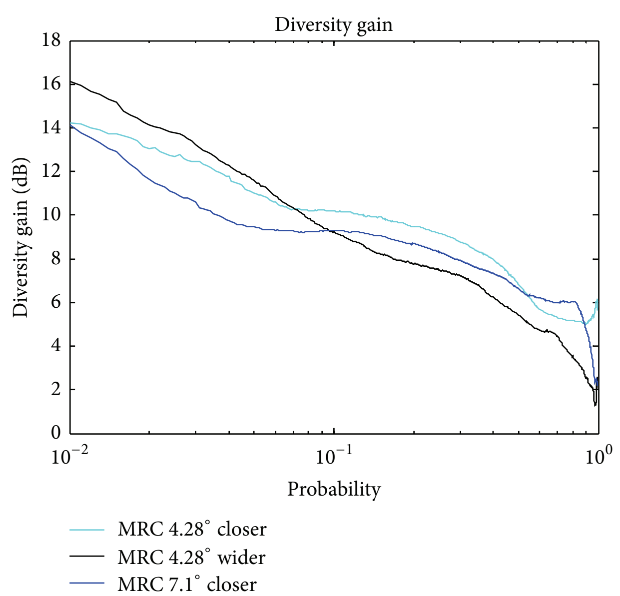

Figure 6: Comparison of diversity gains for two elevation angles in a wooded area.

Figure 7 shows an area comparison using a flight with an elevation angle of 4.28°. We see that the values of diversity gain in the open field are not negligible. We see from these results that even when the link is set to the open field under low elevation angles, there are fast variations in the received power allowing the use of diversity methods to mitigate the deep fades.

5. Summary

A quantification of space diversity gain for low elevation links in wooded areas was presented. The analysis is based on a unique measurement campaign using a remotely controlled aerial platform for simulating low elevation path geometries.

The analysis results show that significant gains are possible, especially for the low outage probability levels. The received signals and combined series follow Rayleigh distribution quite well. However, the fit is less successful due to single branch distribution which does not fully follow Rayleigh distribution as in the urban area [10].

The elevation angles studied do not significantly affect the diversity gain. On the other hand, the distance between antennas seems to be more important for low probabilities.

As expected, the wooded area allows us to reach higher diversity gains than the open field. However, for lower elevation angles, the open field allows for a noticeable diversity gain. In comparison with the urban area studied in [10], the diversity gains reached are approximately 4 dB lower.

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