Study of the Diversity Reception in a Forested Environment

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***Abstract*—The feasibility of using spatial diversity within a foliage environment is examined in this letter. It is found that the presence of lateral waves in the forested environment is the main reason for the highly dependent multi-propagation paths. These highly dependent multipaths produce a high spatial correlation between diverse receptors when used in a forested environment. The mutual coupling effects between the receptors are analyzed through the study of the antennas' mutual impedance and angular pattern of the receiving array. It is founded that, in the forested environment where there is a large angular spread of multipaths, when spatial diversity is used, the coupling induced change in the antenna pattern becomes a dominant factor. This lowers the correlation property between the multiple receptors.**

***Index Terms*—Antenna coupling, diversity, forest, spatial correlation.**

I. Introduction

A forest has significant effect on the radio wave propagation, since it consists of random medium with many discrete scatterers such as the randomly distributed leaves, branches and tree trunks. These physical components can induce multiple scattering, diffraction, and absorption of electromagnetic waves propagating through the foliage medium. Tamir [1] raised the concept of lateral waves, dominant for the propagation over large foliage separations in the VHF and the low UHF bands. Since then, much effort has been put in by researchers to characterize the radio wave propagation within foliage areas [2], [3], [4], [5]. Recently, narrowband (0.9-1.8 GHz) investigations have been performed, looking into the foliage effects on cellular base-to-mobile propagation in outdoor environments [2], [3]. The temporal variation of the received signal due to the effects of wind has been examined and found to be Rician distributed. Besides outdoor environment measurements, detailed narrowband study of the wind effect (simulated) in a controlled environment (anechoic chamber) at 0.9, 2, 12 and 17 GHz has also been studied in [3]. Gans *et al*. [4] and Joshi *et al*. [5] examined the multipath characteristics of the forested channel through comparative studies of both narrowband and wideband signals. From literature, it is found that the foliage medium can influence the quality of the received signal significantly, resulting in an unreliable radio link. Moreover, weather effects such as wind, rain *etc.* can also vary the property of the forest medium, and result in an additional variation in the received signal strength [3], [5], [6], [7].

As a continued work of our previous ones [6], [7]; narrowband investigation of the combined wind and rain effect[6]; and wideband study of the rain fall effect [7] on a tropical forested channel, this letter investigates the possible application of a popular mitigation technique, the Multiple-Input-Multiple-Output (MIMO) technique [8], to improve the reliability of radio links in the forest. The performance of the entire MIMO system depends on the propagation channel (environment). For example, the correlation between the MIMO sub-channels is a critical factor that affects the channel capacity [9], [10]. Therefore, the understanding of the radio wave propagation with multiple antennas in the forest is important for the implementation of the MIMO system in a foliage environment.

The objective of this letter is to investigate the spatial correlation property between Single-Input-Multiple-Output (SIMO) sub-channels in a tropical forest with the antenna coupling effect considered. The evaluation of the potential use of a MIMO system in the forested environment for the improvement of channel performance is conducted. In Section II, the forest environment and the measurement setup are briefly described. In Section III, the correlation property between the SIMO sub-channels is investigated. The antenna coupling induced effects, such as the mutual impedance for the diverse receptors and the induced antenna angular pattern variations are studied in detail. This is followed by the conclusion in Section IV.

II. Description of the Measurements

The measurements were conducted in the palm plantation as reported in [6], [7], which spreads over a nearly flat terrain of more than 0.7 km^2. The palm trees are approximately 5.6 m in height and nearly equally spaced with a distance of 7 m. The average tree trunk diameter at antenna height (2.15 m) is around 0.4 m. The measurements were conducted at 240 MHz with foliage depths of 330 m, 400 m, and 710 m. A detail description of the measurement sites can be found in [6]. Details of the sounding technique and the description of the measurement setup can be found in [7]. During the measurement, the foliage was wet and there was very little or no wind, which is different from the weather conditions in [6], [7].

A wideband SIMO channel sounder is used. This is an upgraded version (two synchronized receiving branches are used to form an *antenna array*) of the previous one in [7]. For a comparative study of the mutual coupling effect between the two adjacent antennas, measurements with a single receptor (antenna) were performed at the corresponding

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locations where the *antenna array* for the SIMO measurement was placed. The measurements with the single antenna at each location were conducted consecutively within a short interval, and the captured data will be used to build a *virtual array* without the mutual coupling effect as reported in [11].

III. Results and Analysis

The complex channel impulse response $h_{m,n}(\tau)$ at the m^{th} receiving antenna is estimated with the same methodology as in [7], and given by

$$h_{m,n}(\tau) = \sum_{k=0}^{N} \alpha_k \exp(j\phi_k)\delta(\tau - \tau_k) \qquad (1)$$

where n is the consecutive impulse index, α_k, τ_k, and ϕ_k are the signal strength, propagation delay and phase shift of the k^{th} multipath component. N is the number of multipath clusters.

A. Spatial correlation coefficient

In order to evaluate the potential implementation of the MIMO technique in the forest environment, the spatial correlation coefficient between the two adjacent receptors with an antenna spacing of *d* is obtained by using (2) as reported in [10].

$$\rho(d) = \frac{E\{h_{1,n}(\tau)h^*_{2,n}(\tau)\}}{\sqrt{E\{|h_{1,n}(\tau)|^2\}E\{|h_{2,n}(\tau)|^2\}}} \qquad (2)$$

where $h_{1,n}(\tau)$ and $h_{2,n}(\tau)$ are the two corresponding n^{th} complex channel impulse responses at the two individual receptors respectively, and $*$ denotes complex conjugate.

The mean correlation coefficients with different antenna spacing *d* for the two reception scenarios (*antenna array* and *virtual array*) at different forest depths (330, 400, and 710 m) have been estimated by performing an average of 1024 consecutive coefficients to minimize the potential temporal variation due to any slight wind. The mean correlation coefficients with different antenna spacing *d* at the forest depth of 710 m is plotted in Fig.1. From Fig.1, the estimated correlation coefficient is high for both the *antenna array* reception and the *virtual array* reception (larger than 0.5 even as the antenna spacing is more than 1.5λ, where λ is the wavelength of the propagating radio wave). High correlation coefficients are also observed at the other two forest depths with both measurement scenarios: *antenna array* and *virtual array*. In general, the coefficients change from 0.55 to 0.83 at 330 m, 0.63 to 0.87 at 400 m for the antenna spacing *d* as shown in Fig.1. The high correlation coefficient at large forest depth is mainly due to the appearance of lateral wave in the forest, which was first introduced by Tamir [1] and later, empirically verified by Tewari *et al.* [12]. The lateral wave travels mostly in the lossless air region and is dominant at large foliage depth, especially when both the transmitter and the receiver are placed inside the forest. In this case, there will be a strong dependence of the signals at the respective receiving branches due to the dominant lateral wave, which is highly coherent, therefore, resulting in high correlation coefficients.

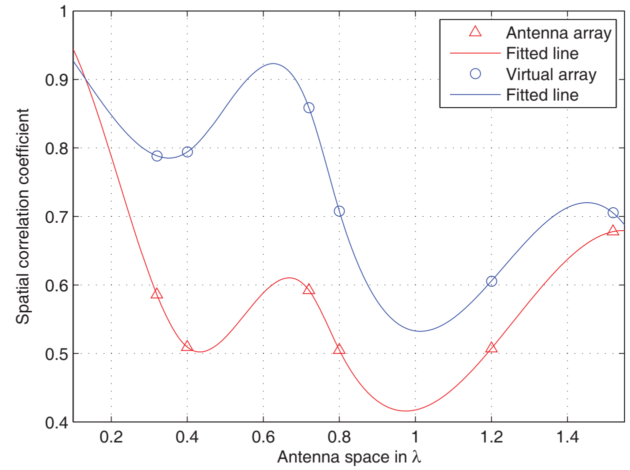


Fig. 1. Spatial correlation coefficients with different dual-receptor separation *d* at a forest depth of 710 m

B. Antenna coupling effect

Another interesting observation in Fig.1 is that, the correlation coefficients are smaller when the *antenna array* is used as compared to the *virtual array*. Since other influences and variations are kept to a minimum during the measurements, the difference in correlation coefficient is attributed mainly to the coupling effect in the *antenna array*. This means that the appearance of the mutual coupling between elements of the *antenna array* decreases the correlation of the signals captured by each element. In such an *antenna array*, the spacing between the antenna elements is very important. When the antenna spacing is small at less than 1λ, as seen in Fig.1, the spatial correlation coefficient for the *antenna array* is much smaller than that of the *virtual array*. However, when the antenna spacing is increased to more than 1λ, the spatial correlation coefficient between the *antenna array* and the *virtual array* approaches the same value. These findings also hold for measurements at 330 m and 400 m. As known, the mutual coupling can induce current/voltage on each receiving terminal (which can be characterized by the mutual impendence) and result in a variation of the antenna pattern. In the following part, both the mutual coupling induced effects; mutual impedance; and antenna angular pattern variation, on the correlation properties will be discussed in details.

1) Receiving mutual impedance: The mutual impedance is usually used to evaluate the coupling effect between the multiple terminals. For the estimation of the mutual impedance at the receiving terminals, Hui *et al.* [13] proposed a new method where the antennas are excited by a plane wave, instead of exciting one antenna with a voltage source and calculating the excited current at the second antenna. His results showed a high consistency between the measured and theoretically calculated receiving mutual impedance. In this letter, the method described in [13] is used. The theoretical receiving mutual impedance is calculated using a simulation tool, *4nec2* [14], which is the Numerical Electromagnetic Code (NEC), a method of moment based antenna modeler and optimizer. The simulated mutual impedance is shown in Fig.2. From Fig.2, it is observed that the mutual impedance between the two receiving terminals decreases gradually as

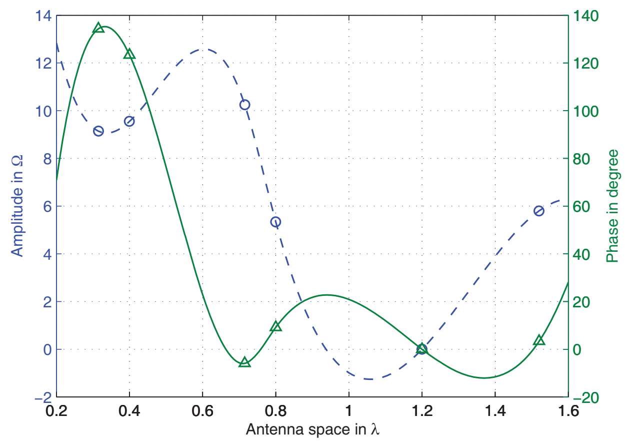


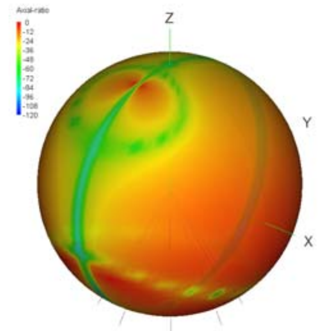
Fig. 2. The theoretical receiving mutual impedance with 50 Ω load; - - -O- - - Amplitude in Ω;—△—Phase in degree

the antenna spacing increases. Of particular interest is when the antenna spacing is 1.2λ, the mutual impedance is found to be zero. This shows a negligible antenna coupling induced current/voltage at one another's receiving terminal. Therefore, the correlation coefficient for both the *antenna array* and the *virtual array* at an antenna spacing of 1.2λ is expected to be the same. However, the empirically estimated correlation coefficient shows a difference of around 0.1 at this antenna spacing as shown in Fig.1.

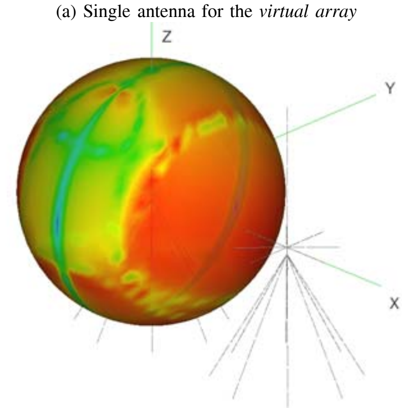
Theoretically, examining the correlation coefficient from the point of the receiving mutual impedance, the correlation coefficient should increase when there is a mutual coupling between the diverse receptor. This is because the coupling effect can induce an additional current/voltage on the other branch, and causes the received signals at the two separate branches to be dependent on each other. However, an opposite trend is observed in this experiment. The correlation coefficient is smaller when the *antenna array* is used as compared to the case when the *virtual array* is used.

These indicate that the mutual coupling induced current/voltage on each terminal is not the dominant effect which influences the correlation property between the diverse receptors. In the next part, another coupling induced effect: the variation of the antenna angular pattern is studied.

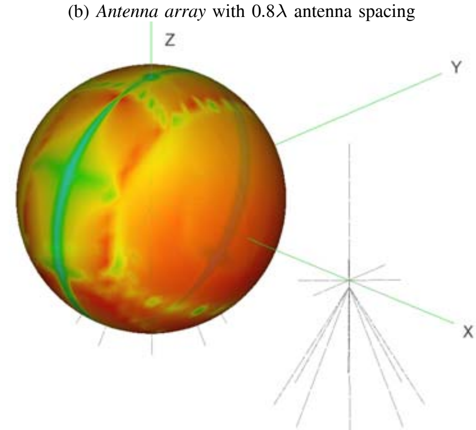
2) Angular pattern effect: In an *antenna array*, the coupling between the diverse terminals affects not only the induced current/voltage on each receiving element, but also the antenna angular radiation pattern of the *antenna array*. Through numerical simulation, 3-D receiving antenna pattern has been calculated using a vertically linear polarized plane wave propagating in the +y direction towards a two-element *antenna array*. Both antennas are terminated with 50 Ω load as in real measurements. The estimated 3-D angular patterns are shown in Fig.3. From previous discussions, the receiving mutual impedance for the antenna spacing of 1.2λ is zero, however, there is a difference of around 0.1 between the correlation coefficients of the *antenna array* and the *virtual array*. The antenna patterns shown in Fig.3 (a) and Fig.3 (c) provide a good explanation. It is observed that when the *antenna array* with a spacing of 1.2λ is used, the mutual coupling induces a change in the antenna angular pattern



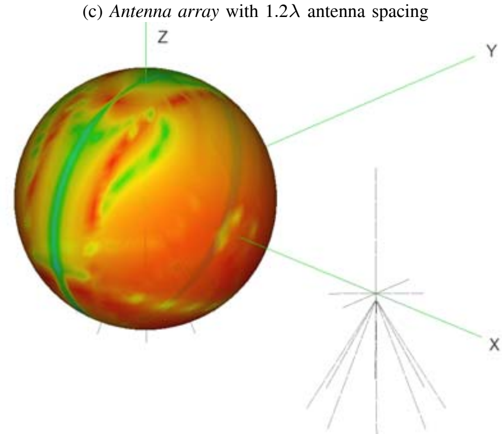
(a) Single antenna for the *virtual array*



(b) *Antenna array* with 0.8λ antenna spacing



(c) *Antenna array* with 1.2λ antenna spacing



(d) *Antenna array* with 1.52λ antenna spacing

Fig. 3. Antenna patterns at different scenarios in receiving modes and with a termination of 50 Ω load

resulting in the array being more directive. A large angular spread of the multipath (scattered) components in the forest is indicated by a comparative study in [5]. In [15] the angular spread of the multipath is reported to be at least $30°$ in azimuth and $20°$ in elevation when a scan was performed using a narrow beam-width ($1.2°$ and $4.8°$) receiving antenna by performing an azimuth scan over an angular range of $\pm 15°$ and an elevation scan over an angular range of $\pm 10°$. Therefore, it can be concluded that the mutual coupling induced directivity makes the received signal less dependent since the captured components are from radiation sources at different spatial directions (propagating paths). This results in a smaller correlation between the two receptors of the *antenna array*.

As the antenna spacing d increases, the coupling effect will decrease in theory. This is consistent with the fact that as the antenna spacing d increases to 1.52λ in the measurements, the correlation coefficients for both the *antenna array* and *virtual array* converges (Fig.1). This is because the antenna pattern for the *antenna array* (Fig.3 (d)) becomes similar to that for the single antenna in the *virtual array* (Fig.3 (a)). As the spacing between the antennas increases, the mutual coupling between the antennas becomes negligible, therefore the radiation pattern of each element in the *antenna array* becomes independent and increasingly similar to Fig.3 (a).

Furthermore, results in Fig.2 show that, the mutual impedance for the *antenna array* with an antenna spacing of 0.8λ and 1.52λ are very similar, in terms of both amplitude and phase. This implies that theoretically, their difference in correlation coefficient between the *antenna array* and the *virtual array* at these spacing should be similar. However, from Fig.1, the difference in the correlation coefficient between the *antenna array* and the *virtual array* at 0.8λ is 0.2, whereas the difference in the correlation coefficient at 1.52λ is only 0.03. With similar mutual impedance at 0.8λ and 1.52λ, the difference in the correlation coefficient is definitely due to the mutual coupling induced antenna angular pattern variations shown in Fig.3 (b) and Fig.3 (d). The mutual coupling at the small spacing of 0.8λ in the *antenna array* strongly affects the antenna angular pattern and makes it more directive as shown in Fig.3(b) and therefore, decreases the correlation coefficient quite a lot (0.2). Whereas at the antenna spacing of 1.52λ in Fig.3(d), antenna pattern is less affected, therefore produces a small difference in the correlation coefficient. This further validates the previous conclusion that the mutual coupling induced directivity of the receiving terminal makes the received signal less dependent since the captured components are from radiation sources at different spatial directions, and results in a smaller correlation coefficient.

IV. Conclusion

This letter investigates experimentally the spatial correlation property between the SIMO sub-channels in a tropical forest for the potential implementation of MIMO technology at military frequency band. The main focus of the paper is on the antenna coupling induced effect on the correlation property.

It is observed that for the radio wave propagation in the forested environment at VHF band, the appearance of lateral waves at large foliage depth results in a strongly dependent physical propagation channel. This produces an overall high correlation coefficient regardless of the antenna spacing, and indicates a poor potential for MIMO applications even in the rich scattering forested environments at VHF band.

Moreover, the theoretical and experimental results show that the antenna coupling effect on the correlation property between the diverse receptors depends on the interplay between the receiving mutual impedance and the antenna angular pattern. In our measurements, the mutual coupling induced variation of the antenna angular pattern is found to be the dominant factor, since it reduces the correlation properties between the SIMO sub-channels significantly. Therefore, when designing a system with multiple antennas for the applications in foliage environment, one has to look at both the mutual coupling impedance and the antenna angular pattern of the *antenna array*.

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