Combined Effects of Wind Speed and Wind Direction on Received Signal Strength in Foliated Broadband Fixed Wireless Links

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Abstract— **This paper examines the temporal variation of the received signal strength (RSS) in foliated fixed wireless links resulting from the combined effects of wind speed, changes of wind direction and movement of foliage. The results of a long-term measurement campaign at 5.8 GHz are presented. These measurements reveal some interesting and unexpected results: (a) RSS can be positively or negatively correlated with wind speed, depending on the physical foliage profile; (b) Wind direction may affect the degree of correlation between RSS and wind speed; (c) Wind direction may affect the mean level of the RSS distribution. These observations imply that the scattering effects owing to wind-induced foliage movement are not solely dependent on wind speed but also the orientation of the wind. The results presented here are useful for those deploying fixed wireless systems in foliated environments, the design of fade mitigation schemes and the determination of a more realistic wind-induced vegetation fading simulator.**

I. Introduction

Broadband fixed wireless systems are one of the possible solutions to high-speed last-mile data networks. Reliability of the fixed wireless link is important to cater for emerging broadband multimedia services such as Video on Demand and Voice over Internet Protocol. In order to guarantee link availability and provide targeted quality-of-service to the end-users, a thorough understanding of the temporal variation in the wireless channel is essential. Besides that, knowledge concerning channel time dynamic characteristics is also required to design effective fade mitigation schemes.

Wind-induced tree movement is one of the main factors which contribute to temporal variation in foliated fixed wireless links. The influences of this factor on temporal variability in broadband fixed wireless links have been examined previously. Studies in [1]-[4] have investigated the relationship between wind speed and Ricean K-factor in foliated fixed wireless links. Fading statistics such as fading rate and average fade duration have been addressed in [5]-[6].While much previous work has identified that wind speed and wind-induced tree movements play a significant role on signal fading in foliated broadband fixed wireless links, no detailed investigation has been reported on the combined effects of both wind speed and wind direction in such a propagation environment.

Therefore, the ultimate goal of this work is to investigate the combined effects of wind speed, wind direction and wind-induced tree movement on received signal strength (RSS) in a foliated broadband fixed wireless link. An extensive long-term outdoor measurement campaign is conducted for this purpose. The response of RSS to varying combinations of wind speed and wind direction in different foliage structures and densities has been studied. In this paper, results from the measurement campaign over a 6-month period are presented. This work contributes to a better understanding of influence of wind speed and wind direction on wind-induced vegetation fading.

This paper is organized as follows. First, a brief description of the measurement campaign is given in Section II. This is followed by the measurement results and analysis in III. Section IV concludes the paper.

II. Measurement Setup

An outdoor measurement test-bed has been setup in Cambridge, United Kingdom (UK) since July 2009. The terrain of the test-bed is relatively flat with medium deciduous foliage coverage. The propagation environment is similar to a typical urban centre or suburban residential area where fixed wireless links are commonly installed.

Four point-to-point fixed wireless links (referred to as Link A, B, C and D) have been deployed as shown in Fig. 1. Link A, Link B and Link C are foliated links with similar transmitter-receiver distance but different density of foliage obstructions. Link D is a relatively short line-of-sight (LOS) link, used as a reference channel. The physical site information is given in Table 1. All four transmitters are mounted on the same pole located on top of a three-storey building (≈14 m above ground level) while the receivers are mounted on different CCTV poles (≈10 m above ground level) on remote sites. Most of the trees within the propagation paths are taller than the height of the receivers and are of the same species with leaves sizes comparable or larger than the wavelength of the operating frequency at 5.8 GHz (≈5.17 cm).

Off-the-shelf 5.8 GHz transceivers based on the IEEE802.11a standard with directional antennas are used as measurement devices. Back-to-back calibration conducted before the installation process confirmed that the equipment is capable of providing instantaneous RSS value within ±1 dB accuracy. Wind speed and wind direction are measured by a weather station co-located with the transmitters. RSS data from all the links and wind data are measured simultaneously. RSS data are recorded at 1-second intervals while wind data are recorded at 3-second intervals. All data are averaged over intervals of 30-minutes during post-processing.

In order to exclude the influences of rain and snow, data with such events are removed. Two main sets of data are analysed here: (a) *On-leaf* season: consists of 46-days of data from August to September; (b) *Off-leaf* season: consists of 19-days of data from the end of November to December. Due to heavy rain in November and snow events at the end of December, the data for the off-leaf season is relatively less than for the on-leaf, but still sufficient for analysis in this paper. Data from October to mid of November when the trees changed from on-leaf to off-leaf season is not included here. The behaviour of the data during this transition state fluctuates between on-leaf and off-leaf season.

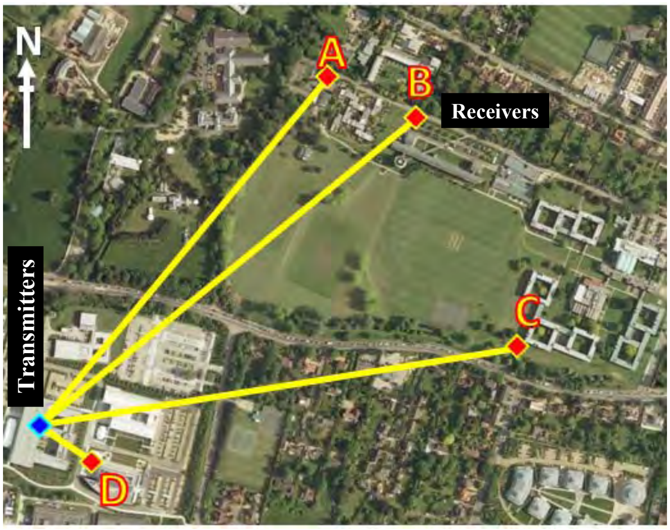

Fig. 1. Locations of four foliated fixed wireless links in Cambridge, UK.

TABLE I
DESCRIPTIONS OF FIXED WIRELESS LINKS

Link	Path Distance	Description
A	0.60 km	- Non-LOS (NLOS) with dense foliage obstructions - Clusters of trees near the receiver
B	0.64 km	- Partial-LOS with light foliage obstructions (Stands & Top edges of foliage canopy) - No trees near the receiver
C	0.63 km	- NLOS with building and dense foliage obstructions - Stands of trees near the receiver
D	0.10 km	- LOS

III. RESULTS & ANALYSIS

A. Typical Average RSS and Average Wind Speed Time Series

Time series of 30-minutes averaged RSS collected over a three-day period for Link A to Link D during the on-leaf season are plotted with same scale in Fig. 2. The average RSS for Link A, Link B and Link C are highly non-stationary with fluctuations within the range of 8 dB (Fig. 2a - Fig. 2c). The temporal dynamics of the average RSS are closely correlated with the corresponding average wind speed. As the reference link, Link D shows little correlation (Fig. 2d). This confirms that the temporal variation observed in Link A, Link B and Link C are due to wind-induced tree movements.

Generally, Link B and Link C show a very strong negative correlation between average RSS and wind speed. This is in line with the intuitive expectation that greater tree movements induced by higher wind speed will introduce greater signal fluctuation and larger path loss.

However, this is not the case for Link A. The high positive correlation between average RSS and wind speed observed in Link A is unexpected. This positive relationship is consistent throughout the 6-month measurement period. It implies that path loss on Link A is significantly decreased when wind speed increases.

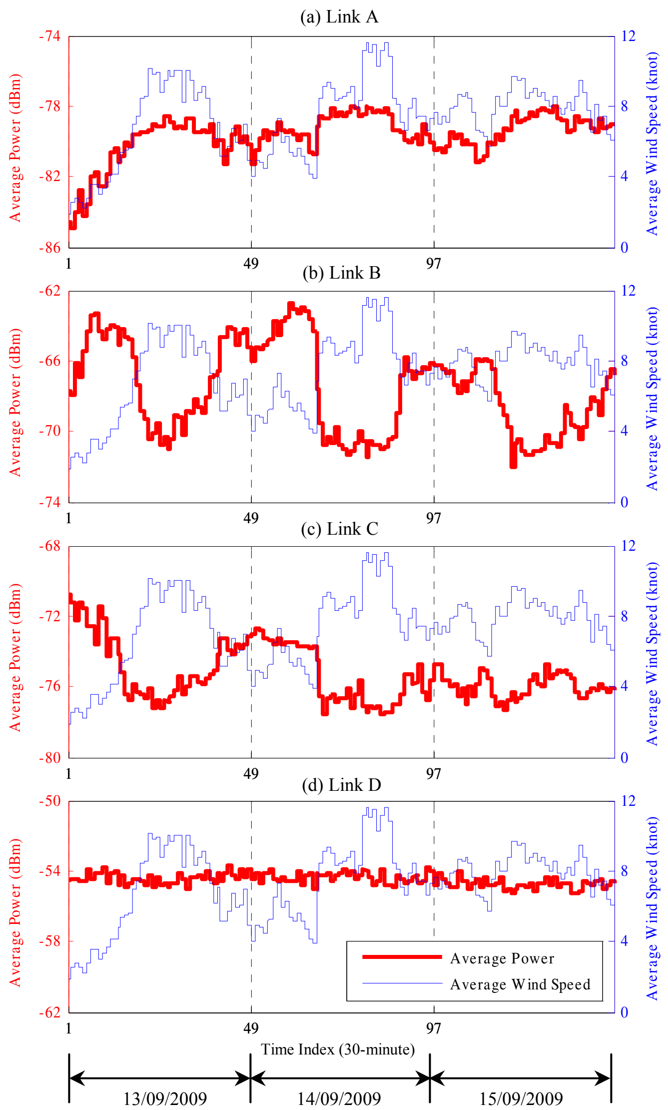

Fig. 2. Typical average RSS and corresponding average wind speed time series (On-leaf) (a) Link A (b) Link B (c) Link C (d) Link D.

B. Link C

Link C is a non-LOS (NLOS) link with obstructions of buildings and clusters of trees along the path and stands of trees near the receiver end. Contour plots of average RSS, wind speed and wind direction for Link C during the on-leaf season is shown in Fig. 3. Several trends are apparent:

- *Correlation between average RSS and wind speed*: Average RSS is negatively correlated with average wind speed for on-leaf season, consistent with observation in Fig. 2c.
- *Correlation between average RSS and wind direction*: For a given average wind speed, the average RSS is higher at certain average wind directions compared to others. For instance, for 0-4 knots, the average RSS is higher within the 90°-270° sector compared to the 0°-45° and 270°-360° sectors. This indicates wind direction is a significant factor influencing the temporal variation of RSS.

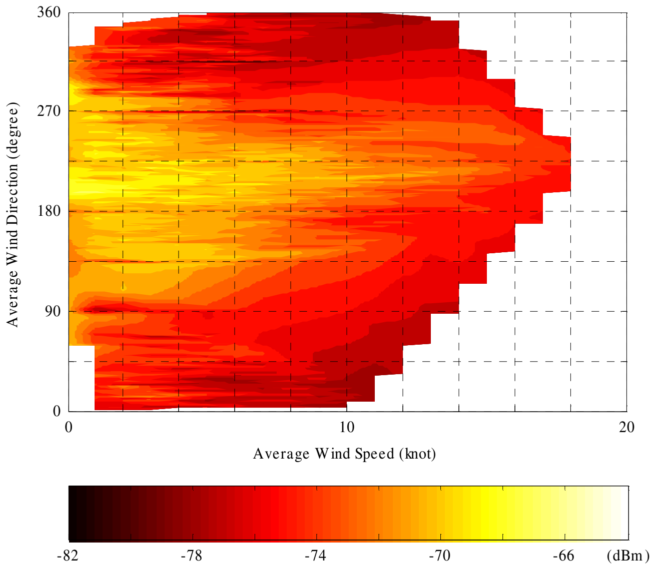

Fig. 3. Contour plot of average RSS, average wind speed and average wind direction for Link C (On-leaf).

To study the combined effects of wind speed and direction, the data are plotted as scatter plot in Fig. 4. The data are separated into two categories according to their average wind direction: (a) *Northern wind*: 0°-90° and 270°-360°; (b) *Southern wind*: 90°-270°. The following trends are apparent:

- *Correlation between average RSS and seasons*: Average RSS is higher during the off-leaf season. The average foliage attenuation is approximately 10 dB. This suggests that tree foliage transmission/penetration and scattering is significant here.
- *Correlation between average RSS and wind speed*: The negative correlation between average RSS and wind speed is stronger during on-leaf season compared to the off-leaf season. This can be explained by the greater scattering effects caused by wind-induced leaves and branches movement during on-leaf season compared to branches only during the off-leaf season.
- *Correlation between mean level of average RSS distribution and wind direction*: During the on-leaf season, both Northern and Southern wind data have similar degree of negative correlation. However, a Southern wind increases the mean level of the average RSS distribution by approximately 5 dB compared to a Northern wind. This indicates that path loss is averagely reduced by 5 dB irrespective of average wind speed for wind blowing from a Southern direction. This separation is not so obvious for the off-leaf season and this suggests that the prominent separation during the on-leaf season is caused by wind-induced leaf movements.

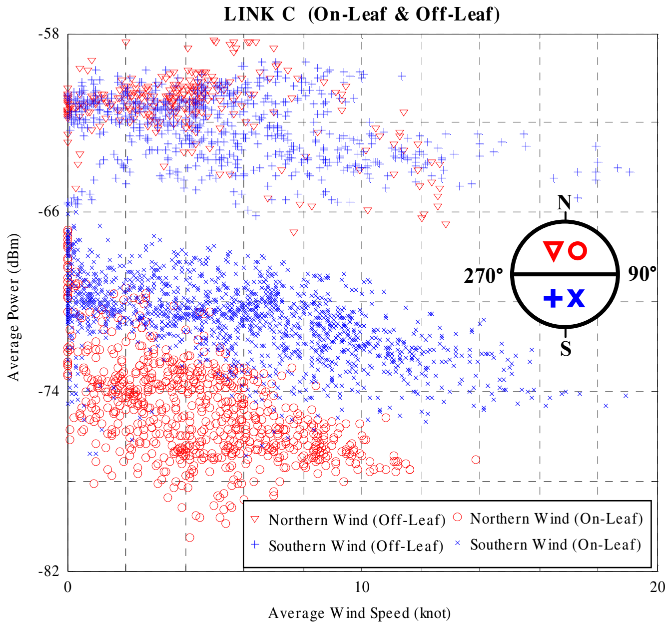

Fig. 4. Scatter plot of average RSS, average wind speed and average wind direction for Link C (On-leaf & Off-leaf).

In a foliated channel, the transmitted signal may reach the receiver via multiple paths: (a) Diffraction at the top and side edges of foliage; (b) Ground reflection under the foliage; (c) Transmission and scattering through foliage. Each path has a different path length, and thus varies in its signal amplitude- and phase-of-arrival. The instantaneous amplitude of the RSS is the vector sum of these paths. Each path may combine constructively or destructively at the receiver antenna, depending upon its relative phase. If the relative phases of the paths are aligned, a relatively large RSS will be indicated, and vice versa. Wind-induced foliage movement will incur changes to the path length of a given path and thus its amplitude and phase. Consequently, the amplitude of RSS fluctuates over time.

The negative correlation between RSS and wind speed suggests that greater foliage movement incurred by higher wind speed causes one or more of the following events: (a) The amplitude of constructive interference decreases; (b) The amplitude of destructive interference increases; (c) The relative phases of the multipath become more misaligned. These possibilities are reversed for the situation where positive correlation exists between the average RSS and wind speed, as we will see in the case of Link A and at low wind for Link B.

The occurrences of the events mentioned above are dependent on wind direction. Due to the wind force, the foliage tends to sway and bend leeward from its rest position in high wind [10]. It may cause the level of foliage obstructions to be varied depending on the prevailing wind direction. This may explain the constant difference in mean level of the average RSS distribution irrespective of average wind speed as observed in Link C during on-leaf season.

C. Link B

Link B is a partial-LOS path with blockage from only a few stands of trees and the edge of a foliage canopy. The receiver can be seen visually from the transmitter during the off-leaf season. Contour plot of average RSS, wind speed and wind direction is shown in Fig. 5. Several trends are apparent:

- *Correlation between average RSS and wind speed*: Generally, average RSS is positively correlated with average wind speed from 0-4 knots and followed by negative correlation for wind speed greater than 4 knots. This is consistent with observation in Fig. 2b. In Fig. 2b, an obvious positive correlation can be observed when the average wind speeds are below 4 knots at the beginning of the time series and then changed to negative correlation when average wind speeds become greater than 4 knots.
- *Correlation between average RSS and wind direction*: For a given average wind speed range, the average RSS is higher at certain wind directions compared to others.

To study the effects of wind speed and direction, the data are plotted as a scatter plot in Fig. 6. Off-leaf data are shifted by +12 dB for better visualization. Based on analysis, there are three wind direction sectors which provide distinct correlation pattern between average RSS and wind speed: (a) *Northern wind*: 0°-45° and 270°-360°; *Southern wind*: 45°-225°; (c) *Border wind*: 225°-270°. The following trends are obvious:

- *Correlation between average RSS and seasons*: Average RSS is only slightly higher during off-leaf season. The average foliage attenuation is approximately 5 dB. This is reasonable since Link B has light foliage blockage.
- *Correlation between average RSS and wind speed*: The combination of positive and negative correlations between average RSS and wind speed is obvious during on-leaf season. For off-leaf season, the positive correlation at 0-4 knots is less prominent and the difference between Northern and Southern wind data is less distinct. This suggests that the positive correlation is mainly contributed by wind-induced leaf movement.
- *Dependency between degree of average RSS-wind speed correlation and wind direction*: During the on-leaf season, Northern wind data has a higher degree of positive and negative correlation compared to the Southern wind. At 0-4 knots, the rate of path loss reduction for Northern wind data is faster than those of the Southern wind; for above 4 knots, the rate of path loss increment is faster in the Northern wind data than Southern wind data. The Border wind data fluctuates between Northern wind and Southern wind divisions and they are not included in Fig. 6 to aid clarity.

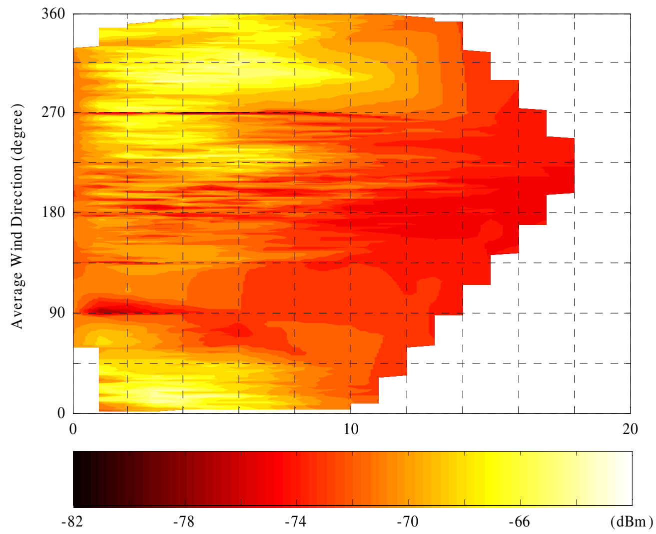

Fig. 5. Contour plot of average RSS, average wind speed and average wind direction for Link B (On-leaf).

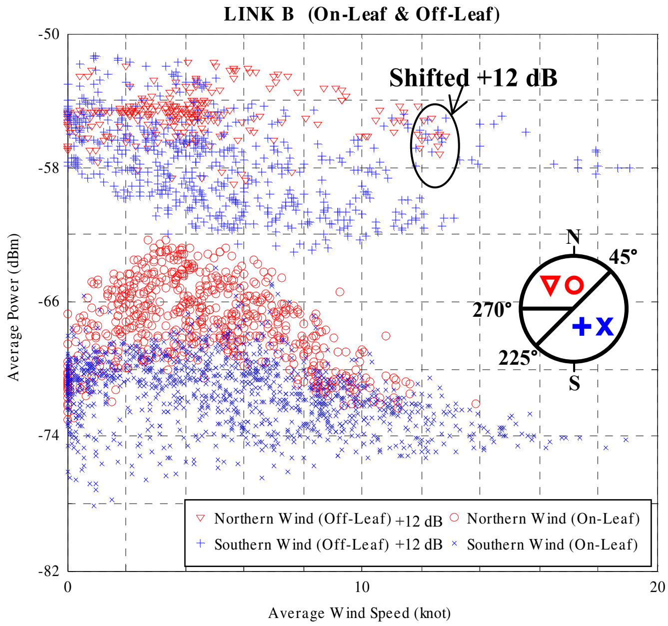

Fig. 6. Scatter plot of average RSS, average wind speed and average wind direction for Link B (On-leaf & Off-leaf).

The existence of positive correlation at low wind speed and negative correlation at higher wind speed can be explained by the different responses of tree components to low and high wind load. Tree components such as leaves, branches and trunk adapt in a complex manner to dissipate the drag force brought by the wind [11]-[12]. The Beaufort Wind Force Scale provides a general picture on how tree components behave in various wind speeds [13]. Generally, during low wind the tree moves in a looping motion around its neutral rest position and the leaves rustle. For higher wind, the tree becomes streamlined. It sways backward and forward, with displacement on average leeward relative to its neutral rest position [14]-[15]. In addition, the leaves tend to reconfigure into a different shape and its motion also differs from that at low wind [16].

D. *Link A*

For Link A, the only obstacles in direct link between transmitter and receiver are dense foliage canopies. To study the combined effects of wind speed and direction on Link A, the data are plotted as a scatter plot in Fig. 7. The off-leaf data are shifted by +10 dB for better visualization. The data are separated into two categories according to their average wind direction: (a) *Northern wind*: 0°-140° and 225°-360°; (b) *Southern wind*: 140°-225°. The following trends are obvious:

- *Correlation between average RSS and seasons*: Average RSS is only slightly higher during the off-leaf season. The average foliage attenuation is approximately 5 dB. This is reasonable since for Link A with dense foliage blockage, through foliage transmission and scattering is most probably not the dominant propagation mechanisms.
- *Correlation between average RSS and wind speed*: Generally, average RSS is positively correlated with average wind speed for both on-leaf and off-leaf seasons, consistent with observation in Fig. 2a. However, the correlation is not consistent. The degree of correlation is stronger within the 0-6 knots range and become weaker in the higher wind region. Figure 2a shows that stronger positive correlation between average RSS and wind speed at the beginning of the time series where the average wind speed is below 6 knots. This is mainly because tree-wind interaction is not a linear function of wind speed and direction [17].
- *Correlation between average RSS and wind direction*: For a given average wind speed range, the impact of average wind direction on average RSS is not as prominent as in Link B and Link C. This can be explained by the more restricted wind-induced tree components movement in dense tree canopy resulted from close contact with neighbouring trees. Therefore, changes of wind direction should not affect the average RSS significantly.

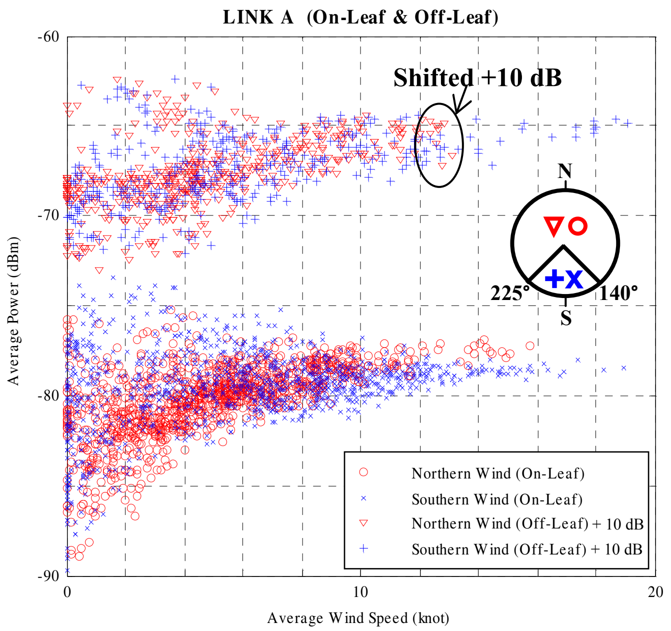

Fig. 7. Scatter plot of average RSS, average wind speed and average wind direction for Link A (On-leaf & Off-leaf).

IV. Conclusion

The combined effects of wind speed, wind direction and wind-induced foliage movement on RSS in foliated fixed wireless links has been investigated in this work using measurement data collected from a long-term measurement campaign. The measurement results revealed that temporal variation of RSS in foliated fixed wireless link is not solely dependent on wind speed but also wind direction. Therefore, wind direction factor should be taken into consideration in the design and development of fixed wireless systems.

Acknowledgment

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