Wind-Induced Slow Fading in Foliated Fixed Wireless Links

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Abstract— **This paper investigates the characteristics of wind-induced slow fading in fixed wireless links where the first Fresnel Zone is partially obstructed by trees. Based on results from long term propagation measurements at 5.8GHz, we show that, besides seasonal and fast fading, the received signal in foliated fixed wireless links also experiences temporal fading of the order of minutes. This is contributed by the temporal shadowing effect owing to the mean deflection of the tree canopy under the influence of mean wind speed and direction. The characteristics of the slow fading observed during on- and off-leaf seasons will be presented. The correlation among received signal strength variation, tree canopy movement and wind will be discussed. A simple knife-edge diffraction model will be used to explain the trends observed in the slow fading. The analyses presented are useful for long-term operation of foliated fixed wireless links, the design of slow adaptive fade mitigation schemes and the development of vegetation fading simulators.**

Keywords- **fixed wireless; vegetation fading; wind-induced fading; shadow fading; link availability; knife-edge diffraction**

I. INTRODUCTION

A fixed wireless system is an economic and efficient solution for point-to-point and point-to-multipoint communication links. However, implementing reliable wireless links in a foliated environment could be a challenging task. When the first Fresnel zone is obstructed by trees, the fading introduced by wind-induced tree movement could be more severe than that experienced in typical mobile channels [1]. The trees will introduce different time scales of temporal fading to the received signal.

The various time scales of the fading introduced by trees are linked to different propagation modes. To date, the studies of signal fading in foliated fixed wireless links (FWL) are focused on two time scales, i.e., seasonal and fast fading [2-3]. The seasonal changes of physical characteristics of trees, i.e., on- and off-leaf, will introduce a seasonal variation to the mean received signal strength (RSS) of the order of months. The dominant propagation mode involved in seasonal fading is absorption. On the other hand, rapid and random movements of the tree components due to wind turbulence introduce fast fading of the order of sub-seconds. The dominant propagation mode involved in this case is scattering. There is another significant temporal fading phenomenon which has remained relatively unexplored. Earlier work by the authors shows that foliated FWLs also undergo temporal fading of the order of minutes to hours, which we called wind-induced slow fading. Due to the combined effects of wind speed, direction and the tree movement, the mean RSS could fluctuate in excess of 10dB [4]. This is comparable to slow fading caused by buildings in mobile channel where the standard deviation of the mean RSS time variation is typically in the range of 6 to 10dB [5].

The understanding of wind-induced slow fading is vital since it could affect the availability of the channel. Besides, the statistical models of fast fading assume local stationarity and are conditioned upon the slow fading statistics [6]. A better understanding of the slow fading phenomena will also assist in the design of fade mitigation technique with slower adaptation rate such as adaptive modulation and power control, and also the development of accurate vegetation fading simulators.

The aim of this paper is to relate the wind-induced slow fading to the physical processes and propagation mechanisms involved. The paper is organized as follows. First, a brief description of the test site is given in Section II. This is followed by the measurement results and analysis in Section III. Section IV discusses the causes of slow fading and relates the slow fading phenomena with simple knife-edge diffraction. Section V concludes the paper.

II. TEST SITE & EQUIPMENT

A long-term continuous (since Jul 2009) outdoor narrowband measurement campaign at 5.8GHz has been conducted using four point-to-point FWLs in Cambridge, United Kingdom (Link A-D). The details of the test links are given in [4]. The first Fresnel zones of Link A-C are partially obstructed by the tops of broad leaves deciduous trees. The tree geometries covered include a dense tree cluster (Link A), standalone trees (Link B) and a line of trees (Link C). Link D is used as the benchmark line-of-sight link to establish that signal fluctuation measured is mainly due to wind-induced tree movement and not other factors, e.g., weather conditions besides wind and antenna's movement.

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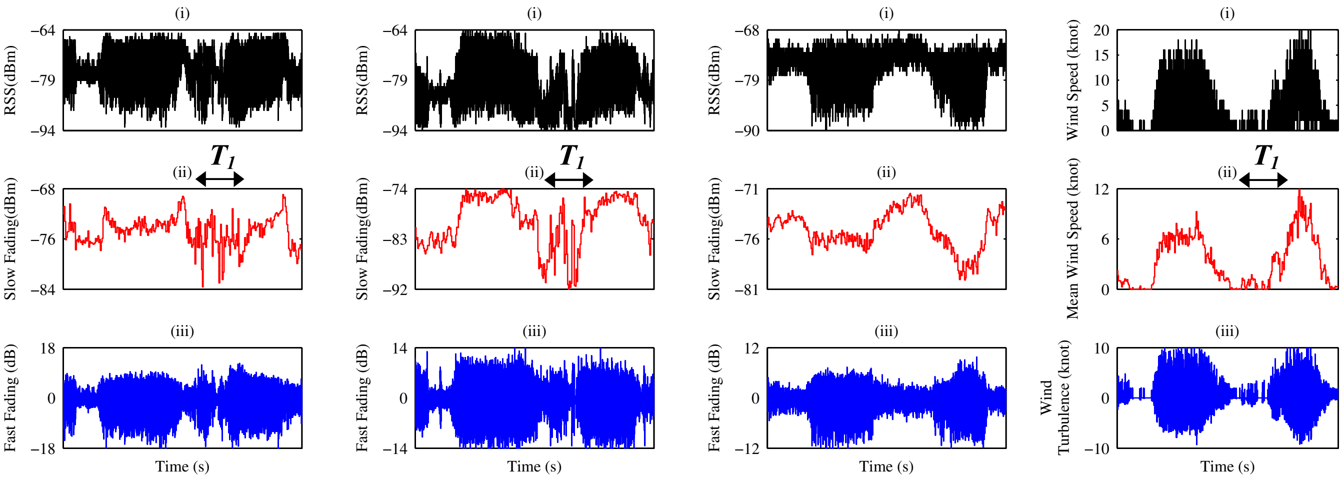

(a) Link A (b) Link B (c) Link C (d) Wind Speed

Figure 1: Time series of RSS and wind speed measured over two consecutive days (1st & 2nd Sept. 2011) during on-leaf season. (a) Link A (b) Link B (c) Link C (d) Wind speed. For (a)-(c), (i) 1s RSS time series (ii) RSS slow fading [mean RSS] (iii) RSS fast fading [*(iii) = (i)-(ii)*]. For (d), (i) 3s wind speed time series (ii) Mean wind speed (iii) Wind turbulence [*(iii) = (i)-(ii)*].

In order to minimize the influence of obstacles outside first Fresnel zone, high gain vertically polarized directional antennas are used (3dB beamwidth, vertical plane=10°; horizontal plane=16°). The transmitter and receiver antennas are mounted at 14m and ≈10m above ground level, respectively. Radios are setup to transmit at fixed power. To avoid frequency selective fading, both transmitter and receiver for each link are setup to transmit and receive at one fixed 5MHz frequency channel only.

In order to separate the wind-induced slow fading from the fast fading, the RSS, wind speed and wind direction data are averaged over a 10-minute window. Within this interval, the wind field can be considered stationary [7]. Hereafter, all 10-minutes averaged values will be referred as to mean values.

III. Results & Analysis

This section will present the characteristics of wind induced slow and fast fading during on- and off-leaf seasons. The impact of foliage density during on-leaf season will be discussed.

A. *Wind Induced Slow & Fast Fading*

An examples of the instantaneous RSS, wind-induced slow and fast fading time series recorded over two consecutive days in Link A, B and C during an on-leaf season are shown in Fig. 1(a), Fig. 1(b) and Fig. 1(c), respectively. The corresponding instantaneous wind speed, mean wind speed and wind turbulence time series are shown in Fig. 1(d). For all three foliated links, it can be observed from Fig. 1 that, the RSS slow fading is strongly correlated with the mean wind speed, while the fast fading component is correlated with the wind turbulence.

Previously, due to the unclear behavior of slow fading in foliated FWL, the typical assumption made by previous works is that mean RSS decreases as mean wind speed increases [8]. This is not always true as the mean RSS will depend on mean wind speed, direction and movement of the tree. For instance, mean RSS increases as mean wind speed increases in Link B, as shown in Fig. 1(b)(ii). In contrast, the mean RSS for Link C decreases within the same interval, as shown in Fig. 1(c)(ii).

The data recorded in time interval T_1 in Fig. 1 highlights the significance of the slow fading. Within this interval, the amplitude of the RSS fast fading fluctuation is relatively constant, corresponding to the relatively constant wind turbulence. However the mean RSS fluctuates by 12dB and 15dB for Link A and Link B, respectively, as shown in Fig. 1(a)(ii) and Fig. 1(b)(ii). This shows that the wind-induced fast fading is conditioned on the slow fading, which varies at a slower rate than the fast fading.

B. *Dependency of Wind-Induced Slow & Fast Fading on Mean Wind Speed & Direction (On-leaf)*

In this section, the dependency of wind-induced slow and fast fading on mean wind speed and direction during on-leaf season will be explored based on a case study from Link B. The plan view of Link B with the obstructing foliage is shown in Fig. 2. The first Fresnel zone is partially obstructed by standalone trees and the edge of a tree cluster. In this link, the standalone trees are the dominant contributor to the wind-induced slow fading since they are closest to the receiver, located in an open field and able to move more freely in response to wind compared to the edge of the tree cluster.

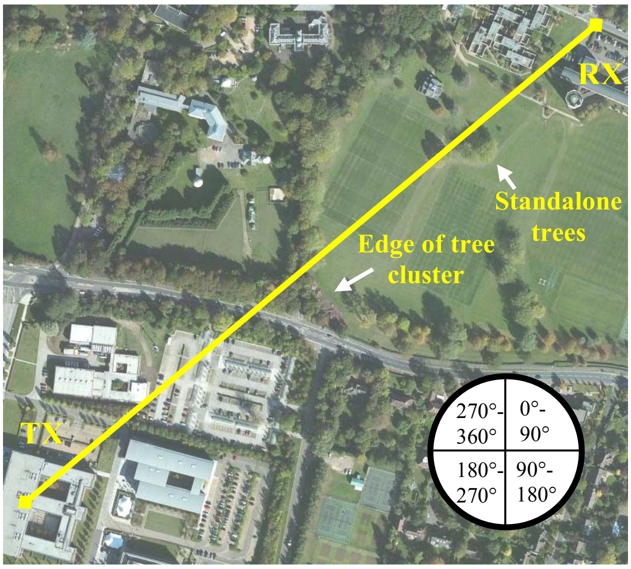

Figure 2: Plan view of Link B.

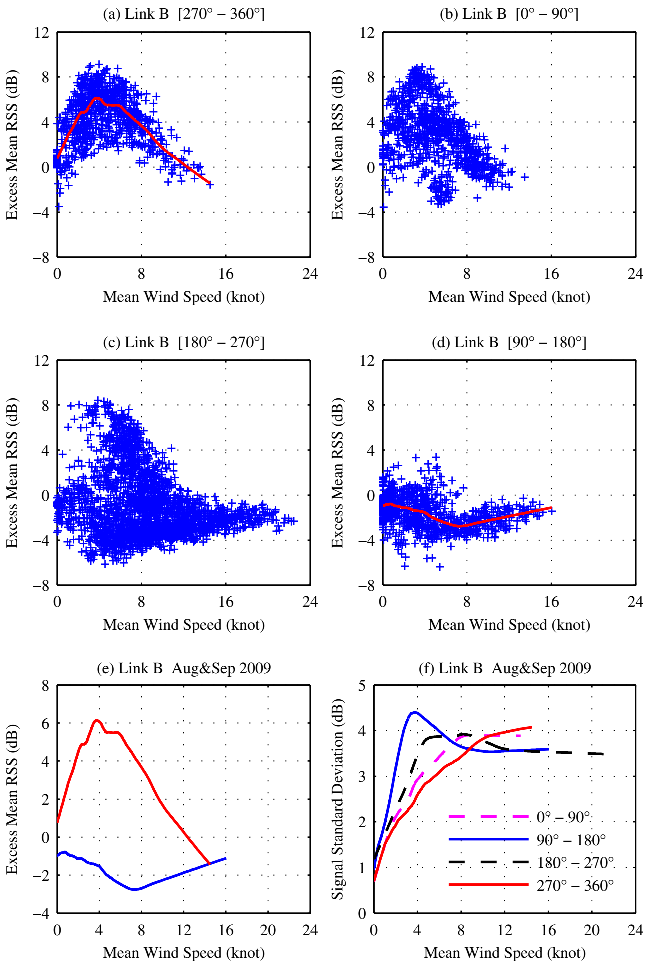

Figure 3: Distribution of excess mean RSS and standard deviation of RSS within 10-minute at different mean wind speed for four mean direction sectors in Link B (On-leaf). (a) 270°-360° (b) 0°-90° (c) 180°-270° (d) 90°-180° (e) Trends of slow fading (f) Trends of fast fading .

The mean RSS from an on-leaf season (Aug & Sep 2009) in Link B are divided into four mean wind direction sectors: 0°-90°; 90°-180°; 180°-270°; 270°-360°. The mean RSS are normalized to the measured zero wind mean RSS (-71dBm). Thus the excess mean RSS are the time variation of mean RSS due to wind-induced tree movements. The standard deviation of the instantaneous RSS fluctuation within a 10-minute averaging window represents the fast fading characteristics. Robust local regression using the weighted linear least squares (rlowess) method is applied to smooth and extract the trends from the scattered data [9].

The distribution of excess mean RSS against mean wind speed for the four mean direction sectors are shown in Fig. 3. Mean wind directions perpendicular to the direct link between the transmitter and receiver have a distinct impact on the excess mean RSS, as shown in Fig. 3(a) for sector 270°-360° and Fig. 3(d) for sector 90°-180°. The remaining two sectors (0°-90° & 180°-270°) show behavior that is a mix of these two perpendicular sectors.

The smoothed trends of slow fading from the perpendicular direction sectors are compared in Fig. 3(e). It can be observed that, for the sector 270°-360°, the mean RSS increases above the zero wind mean RSS by up to 6dB in the low mean wind speed region (0-4 knots), then decreases to 1dB below the zero wind mean RSS as the mean wind speed increases. On the other hand, for the sector 90°-180°, the mean RSS decreases by up to almost 3dB at low mean wind speeds (0-8 knots), then rises to -1dB at higher mean wind speeds.

The smoothed trends of the standard deviation of the fast fading for the four mean direction sectors are shown in Fig. 3(f). It can be observed that the impact of mean wind direction is less significant for fast fading compared with slow fading. For all mean direction sectors, the instantaneous RSS standard deviation increases as mean wind speed increases. The standard deviation saturates at 4-8 knots, i.e., further increases of mean wind speed do not introduce a further significant rise of instantaneous RSS standard deviation. This trend is in agreement with the model recommended in [10].

C. Dependency of Wind-Induced Slow & Fast Fading on Mean Wind Speed & Direction (Off-leaf)

A similar analysis to that performed in an on-leaf season is conducted on data from the off-leaf season (Feb & Mar 2010) in Link B. The mean RSS are normalized to the zero wind mean RSS (-66dBm). The smoothed trends of slow fading from the perpendicular direction sectors are compared in Fig. 4(a). Compared to on-leaf season shown in Fig. 3(e), the trends of excess mean RSS as mean wind speed increases are similar for both directions during off-leaf season. Generally, for both perpendicular direction sectors, the mean RSS decreases as mean wind speed increases, with excess mean RSS for sector 270°-360° almost constantly 4dB higher than for sector 90°-180° at all mean wind speeds.

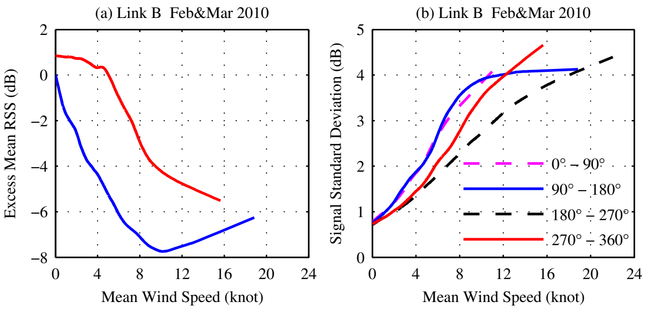

Figure 4: Distribution of excess mean RSS and standard deviation of RSS within 10-minute at different mean wind speed for four mean direction sectors in Link B (Off-leaf). (a) Trends of slow fading (b) Trends of fast fading.

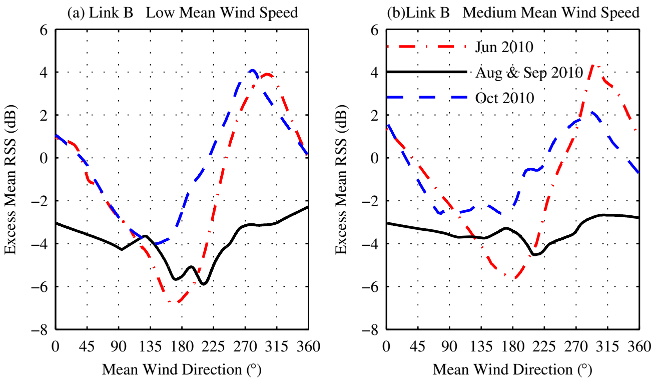

Figure 5: Distribution of excess mean RSS at different mean wind direction for two mean wind speed regions in Link B (On-leaf) (a) Low mean wind speed 1-6 knots (b) Medium mean wind speed 6-10 knots.

The smoothed trends of the standard deviation of the fast fading at the four mean direction sectors are compared in Fig. 4(b). The fast fading characteristics is similar to the on-leaf season, except the rate of increase in instantaneous RSS standard deviation as mean wind speed increases is much slower than for the on-leaf season shown in Fig. 3(f). The mean wind speed where the RSS standard deviation saturates is also higher than for the on-leaf situation, at approximately 8-12 knots. A reasonable explanation for these observations is that, during off-leaf season, the main scatterers are the twigs and branches which require higher wind turbulence to induce movement. The main scatterers during on-leaf season are leaves and their lighter weight and greater area mean they move more readily in response to wind turbulence.

D. *Dependency of Wind-Induced Slow Fading on Foliage Density*

During the on-leaf season, the density of the tree canopy changes according to the maturity states of the foliage. The foliage density is at maximum when the leaves are matured (Aug & Sep). The foliage density is lower when the leaves are still not fully grown (Jun), and when the leaves are starting to dehydrate and have begun falling (Oct). These different stages of foliage density will affect the mechanical response of tree canopy to wind loading and subsequently affects the characteristics of the slow fading.

Fig. 5 shows the distributions of excess mean RSS for different mean wind direction in Link B during low (Jun 2010 & Oct 2010) and high (Aug & Sep 2010) foliage density, at low (1-6 knots) and medium mean wind speed (6-10 knots). For both mean wind speed regions, it can be observed that the slow fading trends for all three periods are similar: lower excess mean RSS at sector 90°-180° and higher excess mean RSS at sector 270°-360°. However, the range of excess mean RSS values at low foliage density is significantly greater than those observed for high foliage density. A reasonable explanation for these observations is that, as the foliage density increases, the tree canopy movement will be more damped. Thus, the extent of physical tree canopy displacement will decrease as foliage density increases [11].

IV. Discussion

In this section, we will relate the characteristics of the wind-induced slow fading to the wind-induced tree canopy movement and the associated propagation mechanisms.

A. *Basic Mechanical Response of Tree under Wind Loading*

The wind field can be represented as a random turbulence superimposed on a mean wind velocity [7]. These two components exert a mean wind force and a random fluctuating force to the tree canopy, respectively. Under the mean wind force, the tree canopy will bend leeward. The extent of deflection is proportional to the mean wind speed [12]. Depending on the direction of the mean wind force, the tree canopy deflects further into or away from the first Fresnel zone, effectively allowing more Fresnel zone obstruction or clearance. This introduces temporal shadowing to the receiver and contributes to slow fading.

The random fluctuating force will cause the tree canopy to sway about the mean deflected position and also induce random motion of the tree components such as leaves and twigs [12]. This subsequently contributes to the fast fading phenomena. The effect of mean wind direction on fast fading is less prominent because the random movement of the leaves and twigs is not greatly influenced by wind direction and so the signal scattering induced is random in nature. As the mean wind speed increases, the wind turbulence also increases. This induces greater amplitude and faster physical movement of the scatterers. However, when the saturation mean wind speed is reached, further increase in mean wind speed will not induce larger or more rapid movement of the scatterers. This explains the fast fading trends observed in Fig. 3(f) and Fig. 4(b).

B. *Knife-Edge Diffraction Model*

Knife-edge diffraction has been successfully applied in modeling the static mean RSS in foliated FWLs [3]. In [10], it is suggested that static mean RSS in foliated link can be predicted using three mechanisms: (i) Knife-edge diffraction around the edges of the canopy (ii) Scattering, and (iii) Ground reflection. The dominant mechanism associated with wind-induced slow fading is the edge diffraction.

In this section, we relate the slow fading trends observed in the measurement results to the effect of diffraction height variation using a single knife-edge model. The aim here is not to predict the absolute excess mean RSS but to relate the trends observed to the propagation mechanism involved.

In Link B, the transmitted signal will diffract around the top edge (vertical plane diffraction) and side edges (horizontal plane diffraction) of the standalone trees. Based on Fig. 3 and Fig. 4, the dominant diffracting edge is the side edge because winds from sectors 90°-180° and 270°-360° have more distinct impact. The side edges of the standalone trees in Link B which partially obstruct the first Fresnel Zone are modeled as a single effective knife-edge. In Fig. 6, the mean RSS behind a single effective knife-edge at different effective knife-edge heights is shown. The mean RSS values are normalized to the zero wind mean RSS. The effective knife-edge height will be less than the physical dimension of the tree edges, since the knife-edge assumption is that the diffracting edge is opaque perfect absorbing material [3]. The zero wind effective knife-edge height for on- and off-leaf seasons are shown in Fig. 6. The height for on-leaf season is greater than off-leaf because foliage with higher density has greater shadowing effect compared to low density foliage.

When the tree edges move in response to mean wind speed, the effective knife-edge height will vary around the zero wind height. Referring to Fig. 6, the wind from the sector 270°-360° will push the tree canopy away from the first Fresnel zone. This introduces more first Fresnel zone clearance, thus the effective knife-edge height decreases (moves to the left in Fig. 6). Wind from the sector 90°-180° will push the tree canopy further into the first Fresnel zone. This introduces more first Fresnel Zone obstruction, thus the effective knife-edge height increases (moves to the right in Fig. 6).

The wind-induced slow fading trends observed in the measurement are due to the variation of constructive and destructive interference between the diffracted ray and the direct ray when the effective knife-edge height changes. In Fig. 6, during on-leaf season, wind from the sector 270°-360° will cause the excess mean RSS first to increase above the zero wind mean RSS and then decreases. On the other hand, wind from the sector 90°-180° will cause the excess mean RSS first to decrease below the zero wind mean RSS and then increases. These trends are similar to the slow fading trends observed in Fig. 3(e). During off-leaf season, both winds from sectors 270°-360° and 90°-180° will cause the excess mean RSS to decrease below the zero wind mean RSS. These trends are corresponding to the slow fading trends observed in Fig. 4(a).

The observations in this section show that the wind-induced slow fading phenomena in foliated links could be reasonably explained using the variation of effective knife-edge diffraction height. Currently, we are investigating the possibilities to model the wind-induced slow fading phenomena using multiple knife-edge diffraction models.

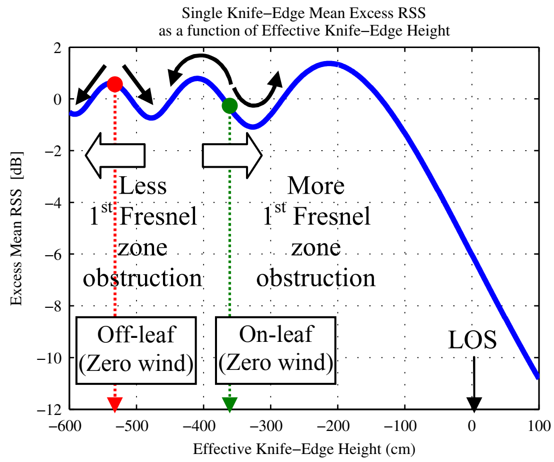

Figure 6: Excess mean RSS as a function of the height of a single knife edge.

V. CONCLUSION

This paper shows the significance of wind induced slow fading in a foliated FWL environment. This slow fading is due to the temporal shadowing effect owing to the directional mean deflection of the tree canopy under a mean wind force. This slow fading phenomenon is significant as it could cause temporal variation of mean RSS in excess of 10dB. The slow fading characteristics are dependent on the foliage density. The trends observed in the slow fading could be reasonably explained using a knife-edge diffraction model.

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