Experimental Characterization of Indoor Multiuser Shadowing for Collaborative Cognitive Radio

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Abstract— **Cross-correlation of multiuser shadowing in an indoor environment at 2.55 GHz is presented, indicating that shadowing is mostly uncorrelated after 2-4 m in the indoor environment. Similar shadowing correlation was obtained for autocorrelation measurements, moving primary (versus moving secondaries), as well as near and far primary measurements.**

***Index Terms* - cognitive radio, shadowing, collaboration, cross-correlation, autocorrelation.**

I. INTRODUCTION

Cognitive radio is a potential technology for increasing spectral efficiency in wireless communications systems, by having sophisticated radios that can sense and take advantage of spectral opportunities [1]. In a hypothetical future overlay policy, cognitive radios (referred to as secondary users) may temporarily use spectrum as long as they do not interfere with primary users that own the license to that spectrum. Although there are many policy and legal issues that must be resolved, cognitive radio is in the meantime an interesting academic topic.

Dependable spectrum sensing is a challenging problem to be overcome when no support is available from primary users to identify spectral opportunities. The *hidden node* problem, for example, can occur when a secondary node is in a fade relative to a primary transmitter, but not in a fade relative to a primary receiver. In this case, the primary transmitter is hidden and if the secondary begins to transmit, he may interfere with the legitimate primary receiver. Although both multipath (small-scale fading) and shadowing (large-scale fading) can cause a fade, the multipath effect can be overcome by simple frequency diversity or wavelength-scale spatial diversity. Therefore, the shadowing effect is expected to be the main factor that limits sensing performance, since shadows may extend for 10s to 1000s of wavelengths, being larger for outdoor than indoor environments. Although mainly a problem for simplex systems where certain nodes never transmit, the hidden node problem is perhaps the main argument against allowing an overlay policy for cognitive radios.

There are two basic strategies that have been proposed for overcoming hidden node due to shadowing. First, techniques for sensing users with very low SNR (i.e. -20dB or lower) are being developed [2], allowing a node to be sensed even when the receiver is in a strong shadow. Such sensing methods are difficult and typically require very long observation times, leading to long delay in the spectral occupancy information, which in turn leads to lost spectral opportunities. An interesting alternative is to use collaborative sensing, where multiple cognitive radios cooperate to sense primary users [2],[3]. Although there is significant probability that a single secondary user is in a shadow, the probability of a large collection of users being simultaneously in a shadow should be low.

The purpose of this work is to perform a detailed study of multiuser shadowing from the standpoint of collaborative sensing in cognitive radio. The main goals of this work are as follows:

1. Understand how often hidden node is likely to occur in realistic communications scenarios.
2. Characterize simultaneous multi-node shadowing for representative environments by direct measurement, indicating under what circumstances collaboration is beneficial and how many agents are required for highly reliable sensing of primaries.
3. Apply advanced ray tracing or full-wave simulation techniques to these environments to understand if the same behaviors can be observed in a more controlled situation.
4. Develop approximate models that capture the salient effects observed in the measusrements and simulations, appropriate for collaborative cognitive radio algorithms that can be used in practice.

Note that although previous shadowing measurements and models lend some insight on the problem of multiuser shadowing [4]-[6], a detailed characterization suitable for general cognitive radio studies is still unavailable.

This paper presents shadowing measurements that were performed in an indoor environment as an initial step toward the goal of a full characterization of multi-node shadowing. Measurements were taken at 2.55 GHz in an indoor classroom environment, and the correlation in the mean local area power (shadowing) for two nodes was studied. In the initial measurements, a number of questions arose, which are partially answered by this paper:

1. To what extent does the smoothing window size (required to estimate the mean local area power level) change the correlation results?

2. Although true simultaneous multi-node measurements are desired, it is more efficient to use a single moving node to obtain multiple user positions. Is the cross-correlation in the multiuser setup sufficiently captured by autocorrelation measurements in the second setup?
3. To obtain an ensemble of random channels, transmitting and/or receiving nodes must be moved to multiple positions, and moving a single node is usually preferred. Does movement of a single primary user generate a similar statistical ensemble as when the secondary users are moved instead?
4. It is anticipated that the shadowing statistics may depend on whether a collection of secondary users is near to or far from the primary. Can the shadowing statistics be consistently extracted in both cases by removing pathloss according to power law models and geometric considerations?

The organization of this paper is as follows. Section II discusses briefly the pathloss and fading the signal undergoes in the sensing environment. Section III describes the measurement scenario and configurations that were used. Section IV presents the measured correlation results and provides partial answers to the questions above. Section V provides some concluding remarks.

II. SIGNAL SENSING IN A FADING ENVIRONMENT

In practice, the sensing problem involves both small-scale (multipath) and large-scale (shadow) fading degrading its performance. These two effects are commonly treated as independent processes that combine to produce the overall fading effect. A three-parameter statistical description of the receive power level is often employed for wireless scenarios of practical interest [7]:

- the area mean resulting from pathloss which depends on the range from the transmitter to the area where the receiver is located,
- the local mean within that area, which is slowly varying and typically represented by a log-normal distribution, and
- the superimposed instantaneous fast fading which normally follows a Rician or Rayleigh distribution.

The average received signal at a distance d from the transmitter is described by many theoretical and empirical propagation models. Both theoretical and measurement-based propagation models indicate that the average received signal power can be expressed as

$$\overline{P_R}\,(d)\,[\mathrm{dB}] = \overline{P_R}\,(d_0)\,[\mathrm{dB}] - 10n\ \log_{10}\left(\frac{d}{d_0}\right), \quad (1)$$

where d is the distance between transmitter and receiver, n is the pathloss exponent and d_0 is the distance from the transmitter to a reference distance where the received power is known.

Multipath in the radio channel creates small-scale fading effects. These include rapid changes in signal strength over a small travel distance, varying Doppler shifts on different multipath signals and time dispersion. The distribution of the envelope of received signal in small-scale fading is commonly taken to be Rayleigh distributed making the received power exponentially distributed [8]. The probability density function (pdf) of faded envelope is given as

$$f_R\,(r) = \frac{r}{\sigma^2}\ e^{-\frac{r^2}{2\sigma^2}}, \quad r \geq 0, \quad (2)$$

where $2\sigma^2$ is the average power (p_o) and r is the envelope of the signal. The average power (p_o) of this faded signal is estimated using an averaging (smoothing) window of length 5λ to 40λ, where λ is the wavelength of the signal [9].

The slow varying local average power (p_o) due to shadowing follows a lognormal distribution

$$f_{P_o}\,(p_o) = \frac{1}{\sqrt{2\pi}\ \sigma_s\ p_o}\ e^{-\frac{(\ln\ p_o - m)^2}{2\sigma_s^2}}, \quad p_o \geq 0, \quad (3)$$

where m and σ_s^2 are mean and variance of the logarithm of the local mean power, respectively. Expressing the local mean power in dB scale, the lognormal pdf can be described as [8]

$$f_{P_o}\,(p_o) = \frac{\xi}{\sqrt{2\pi}\ \sigma_{dB}\ p_o}\ e^{-\frac{(p_{o,dB} - m_{dB})^2}{2\sigma_{dB}^2}}, \quad p_o \geq 0, \quad (4)$$

where $\xi = 10/\ln 10$, m_{dB} and σ_{dB} are the mean and standard deviation of $p_{o,dB} = 10\log_{10} p_o$, respectively. This m_{dB} corresponds to the average received power $\overline{P_R}\,(d)$ [dB] in (1).

The shadowing component can be extracted by subtracting m_{dB} from $p_{o,dB}$ which follows a lognormal distribution with mean 0 dB and standard deviation σ_{dB} dB.

III. MEASUREMENT SCENARIO

Initial measurements were taken on the ground floor of the Research I building on the Jacobs University Bremen campus, as depicted in Fig. 1. The walls in the building are of solid brick and masonry construction. A few large rooms where the measurements were taken are teaching laboratories with desks and computers. Several of the smaller adjoining rooms are offices and smaller labs.

In all experiments, we have considered two scenarios. In the first scenario, the transmitter is placed sufficiently far from the receiver, such that the pathloss over the whole measurement region (room) remains almost the same. Since the pathloss component is constant for this case, only a single scalar is subtracted from the measurement, avoiding the possibility of introducing error in estimation of the shadowing component.

When the transmitter-receiver separation is comparable to the dimension of the room where measurements are taken, there is significant pathloss variation for different measurement positions within the room. In this case, the proper pathloss component must be estimated and subtracted from the total received power. Note that the accuracy of this operation is critical, since error in the pathloss estimation also creates error in the estimated shadowing, and unless pathloss or shadowing is known a priori, it is not possible to detect this error.

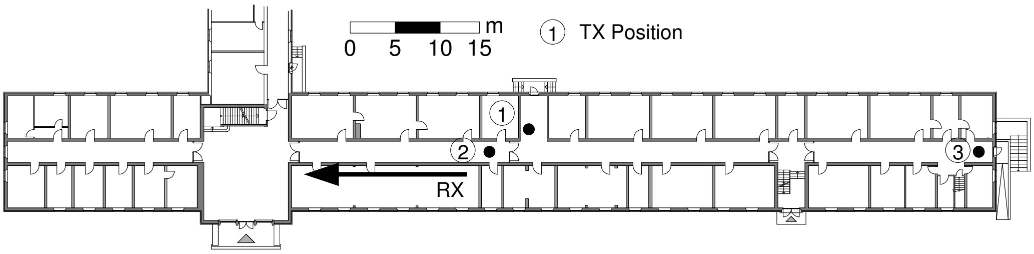

Fig. 1. Floorplan of building where indoor shadowing measurements were taken

Fig. 2. Experimental setup of transmitter (left) and receiver (right) for shadowing cross-correlation

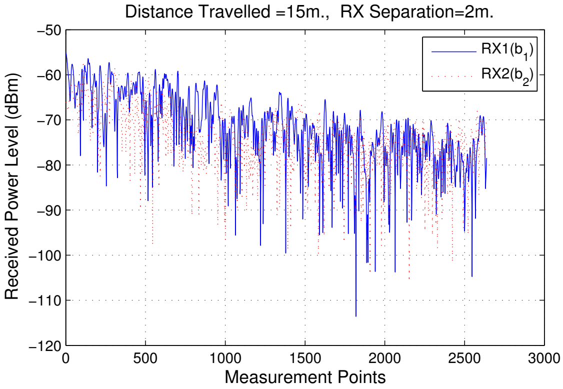

Fig. 3. Received faded signal in the two secondary receivers separated by 2 m. for moving secondaries case with transmitter at (TX2) position

The near transmitter case was implemented by placing the transmitter at positions (TX1) and (TX2) whereas the measurement at position (TX3) is considered for the far transmitter case.

All measurements in this study were taken at 2.55 GHz using $\lambda/4$ monopole antennas with a truncated groundplane for both transmit and receive. Frequencies of the transmitter and receiver LOs were kept well within 1 Hz of each other by disciplining the instruments with calibrated Rubidium references at the two sides. For the near primary case, the transmitter consisted of a single antenna connected directly to a microwave source with 10 dBm output power. For the far primary case, an additional power amplifier was used to obtain 30 dBm transmit power, necessary to maintain sufficient SNR, which was kept better than 10 dB with large-scale shadowing for all cases. The data was captured by connecting the two receive antennas to the two ports of a vector network analyzer programmed to have its internal source off and measure a single-frequency time sweep of b_1 and b_2, which are the standard incoming wave quantities for ports 1 and 2 associated with an S-parameter measurement.

The spacing between receive nodes was held constant during a measurement by attaching the antennas to a long plank fixed to the cart, and spacings of 0.25 m, 0.5 m, 1 m, 2 m, 4 m, and 6 m were considered. Transmit and receive carts with the respective instruments and antennas are shown in Fig. 2. Post-processing of the data was trivial, since received power in dBm for port i is $20\log_{10}|b_i|$. An example measurement result, showing the received power computed from b_1 and b_2 (ports 1 and 2), is shown in Fig. 3. The data was either analyzed by taking the cross-correlation of the smoothed signal from the two receive antenna elements or by taking the autocorrelation of the smoothed signal from one element, referred to as cross-correlation (CC) and autocorrelation (AC) methods, respectively.

A. *Case I: Moving Secondaries*

This measurement scenario represents two secondary users that are trying to sense a primary user, where the ensemble of measurements is for varying position of the secondaries. The primary transmitter assumed three fixed positions in the hallway. The receiver was moved at a nearly constant speed along a straight path in the room. The cart was pulled with a rope in order to avoid shadowing from the body of the person performing the measurements.

B. *Case II: Moving Primary*

In this second measurement scenario, the receiver setup was placed in the same room but was stationary, while the transmitter was moved in a hallway. This scenario represents a single moving primary user with stationary secondary cognitive radios. The receivers were placed at fixed separation distances of 0.25 m, 0.5 m, 1 m, 2 m, 4 m, and 6 m as in case I. Since the primary user moves along the hallway and is close to the secondaries at the end of the measurement, the pathloss is expected to change significantly over the course of the measurement, and must be accounted for before studying the shadowing correlation. However, the pathloss component was considered constant over the observation period for the far primary case.

IV. RESULTS

High correlation is undesirable for collaborative sensing, since it indicates that nodes observe the same information. Therefore, the main effort of this study is to characterize the required separation for shadowing correlation to drop below some specified threshold (termed the decorrelation distance), indicating the minimum separation needed for a desired level of collaborative gain.

Although cross-correlation (CC) and autocorrelation (AC) both exhibit the expected decreasing trend with distance, it is not decreasing monotonically but shows rise and fall in a somewhat periodic manner, complicating the identification of the required decorrelation distance. We believe this periodicity is due to the shadowing structures like windows, doors, cupboards, tables, workstations, etc., which exhibit a partially regular pattern, especially when the movement of the secondary is not random, but along a specified path (parallel to the walls in our case). To define a threshold for the non-monotonic correlation functions, the decorrelation distance is defined as the separation beyond which the peak correlation is always observed below the threshold.

Note that a further investigation of the periodic behavior of correlation as well as negative correlations is still under study.

A. *Effect of Smoothing Window Size*

A smoothing window must be applied to the single frequency measurements in order to remove the multipath (fast fading) effect and estimate the average local area power, referred to loosely as the "shadowing level". There is a tradeoff in specifying this window size, since it should be small enough to track variations in the shadowing level due to various shadowing objects in the environment, but not so small that the effect of multipath is not sufficiently removed. It is expected that having a window that is too large will lead to artificially long decorrelation lengths, since local area power will be spread out over multiple shadowing fades. On the other hand, having a window that is too small will lead to an artificially low correlation, since multipath fading will still be present.

Fig. 4 plots an example result from Case I-CC, indicating that although the correlation trends are similar, the exact correlation levels depend on the window size for the same data sequence. Note that the 5λ and 10λ windows give similar results, whereas the 15λ and 20λ results appear to be much more smoothed out. For this work, a 10λ window appears to be a good compromise between resolution and error in the local area power estimate. Fig. 4 also demonstrates one of the clear results of this study, that the shadowing has a decorrelation distance (for a threshold of 0.5) in the range of 2-4 m, with most cases below 2 m, regardless of the window size or the way correlation is measured

B. *Cross-correlation (CC) vs. Autocorrelation (AC) Arrangements*

Although actual simultaneous measurement of the power level at multiple nodes (CC) most nearly approximates a true cognitive radio scenario, having a single moving node (AC) may be more convenient in practice. Fig. 5 plots the autocorrelation from a single receiving antenna element which can be compared with Fig. 4. The results show that although the short-time correlations are similar for both the AC and CC cases, the long-term behavior looks quite different, possibly due to non-static behavior or time-variation of the shadowing due to people. The results suggest that for a distance of 2 m or less, the single sensor AC arrangement can be used instead of the more complicated CC arrangement.

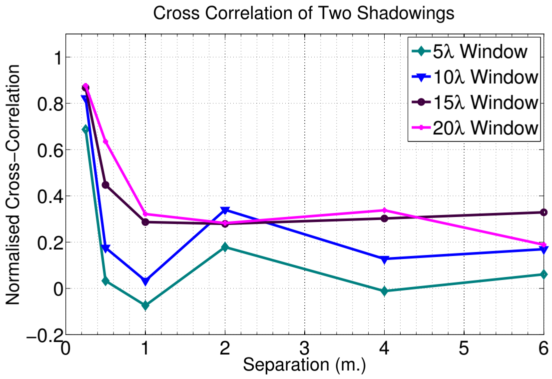

Fig. 4. Effect of window size on shadowing cross-correlation for Case I

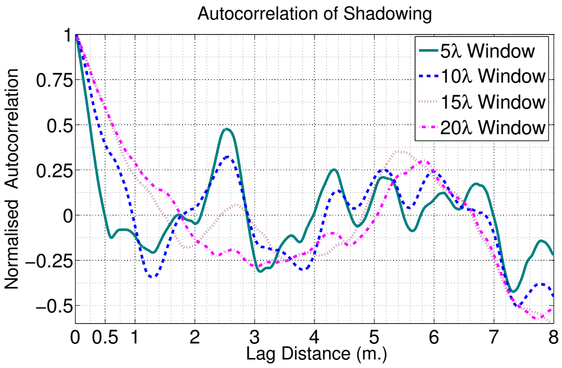

Fig. 5. Computed unbiased autocorrelation for single sensor for Case I

C. *Near vs. Far Primary*

The distance between the secondary users and the primary user will determine how much change in the power level is simply due to changes in the bulk pathloss (signal spreading). When the primary is far away from the secondaries, pathloss should not vary significantly and can be estimated as the average power over the measurement record. For the case when the primary is close, the deterministic change in the power level due to spreading should be removed. This was performed using a simple power-law model as described in (1), where the distance along the track was estimated from geometrical considerations. The value of the pathloss exponent n was estimated to be 2.64 from the analysis of the recorded data.

A measurement was also carried out for the far transmitter case. The result of shadowing cross correlation and autocorrelation are shown in Fig. 6 and Fig. 7, respectively.

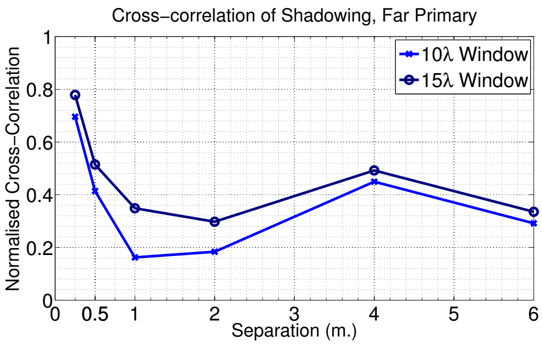

Fig. 6. Shadowing cross-correlation for far primary with moving secondaries (case I)

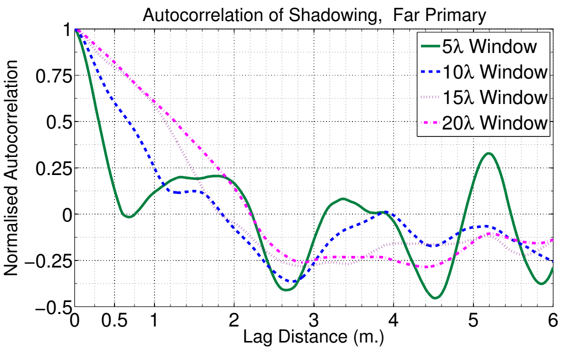

Fig. 7. Computed unbiased autocorrelation for single sensor for far transmitter case (different window sizes used)

Interestingly, the cross-correlation of the shadowing versus separation for the near case (with pathloss removed) is quite similar to the far case where pathloss does not change.

D. Moving Primary vs. Moving Secondaries

The autocorrelation for moving primary vs. moving secondaries for either a near or far primary is plotted in Fig. 8. For the case of a near primary, the results are quite close to each other. For a far primary, the results are somewhat different, likely due to the fact that the hallway and room environments look quite different for far transmit-receive separation. Also plotted for comparison is the autocorrelation for the moving primary case, giving shadowing versus primary (as opposed to secondary) separation, which may have different characteristics. Note that the unusually low correlation at 25 cm and 50 cm for the far and near moving primary cases is not well understood, and requires further investigation. However, it appears clear that decorrelation distances are below 2 m for this case as well.

V. CONCLUSION

This paper presented an initial study on the correlation of multiuser shadowing in an indoor environment at 2.55 GHz. The results indicate that although window size plays a strong role in the absolute correlation levels, shadowing is mostly uncorrelated after 2-4 m in this indoor environment, indicating that collaboration will be effective at this or greater separation of secondary nodes. It was also found that autocorrelation of a single moving sensor can be employed instead of multiple moving sensors below 2 m, simplifying the measurement system. Finally, similar shadowing correlation was obtained for a moving primary (versus moving secondaries) as well as near and far primary measurements.

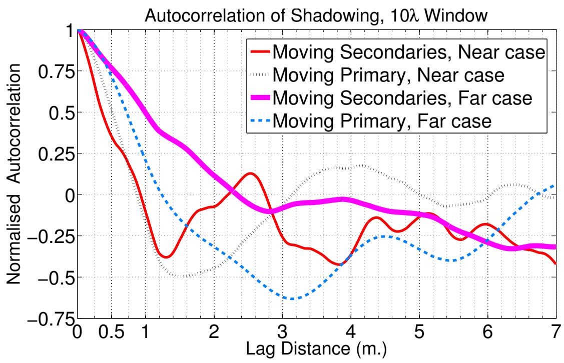

Fig. 8. Computed unbiased autocorrelation of the shadowing for near and far transmitter case with moving primary and moving secondaries

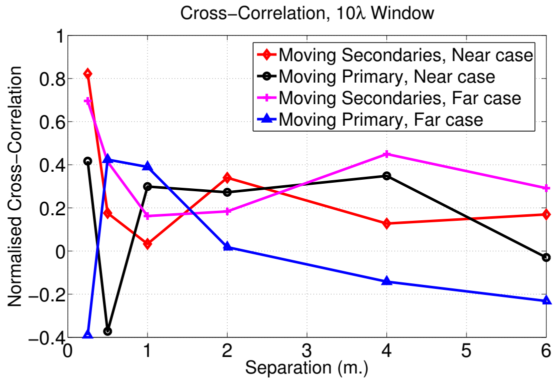

Fig. 9. The Cross-correlation of the shadowing component for near and far transmitter case with moving primary and moving secondaries

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