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Performance of Polarized Sensing in Real-World Cognitive Radio Scenarios

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Abstract

The sensing performance of a cognitive radio system using a tri-polarized antenna at the secondary terminal is investigated in a real-world scenario. The analysis is based on an outdoor-to-indoor measurement campaign, where the secondary network is deployed indoor and senses the signals received from an outdoor primary base-station. By considering a minimum acceptable detection probability of 0.95, the use of diversity increases the range of acceptable sensing up to 18 meters. The minimum acceptable signal-to-noise ratio (SNR) is reduced up to 14 dB. As expected, the best performance is reached with maximum ratio combining. However, the detection performance is only slightly decreased with square law combining (SLC). As an example, for the multi-polarized reception scenario, SLC increases the minimum acceptable SNR by less than 2 dB and decreases the range of acceptable sensing by less than 3 meters. Finally, we show that polarized sensing is a good performance trade-off in realistic scenario where the polarization of the primary transmitter is unknown.

Introduction

Cognitive radio (CR) enables to efficiently use the frequency resources through the deployment of a secondary network on the same frequency band as an existing primary network, but without interfering with it [1]. This technique relies on secondary users to retrieve via preliminary sensing the frequency bands not utilized by primary users. To guarantee a non-interfering use, secondary users must detect reliably adaptively the presence of primary users. Among numerous spectrum sensing techniques, energy detection (ED) has been widely applied thanks to a number of advantages (e.g., it does not require any a priori information about the primary signal and has much lower complexity).

In practice, the sensing performance can be considerably deteriorated by fading. While multi-antenna sensing mitigates fading via spatial diversity, it suffers from a number of issues: firstly, the diversity gain largely depends on the spatial correlation and is improved by large antenna spacing; secondly, cognitive terminals should remain compact; thirdly, the polarization mismatch between the primary electromagnetic wave and the secondary antenna might hamper the energy detector. One attractive solution is to rely on an array made of three orthogonally polarized co-located antennas, which would be almost as compact as a single antenna while enjoying improved diversity gain thanks to the low inter-antenna correlation between cross-polarized channels [2, 3].

In this communication, the sensing performance of a cognitive radio system using a tri-polarized antenna at the secondary terminal is investigated in a real-world scenario. The analysis is based on an outdoor-to-indoor measurement campaign, where the secondary network is deployed indoor and senses the signals received from an outdoor primary base-station.

1. Performance of sensing techniques

Let us consider a cognitive receiver made of M antennas ($M = 3$ for three cross-polarized antennas), sensing over an observation time T a signal of bandwidth $2W$ (with T chosen so that $2TW$ is an integer). The primary transmitted signal $s(t)$ is received at secondary receive antenna k over channel h_k with additive white Gaussian noise $n_k(t)$. The detection problem comes to determine whether the primary transmitted signal is present (hypothesis H_1: $r_k(t) = h_k\, s(t) + n_k(t)$) or not (hypothesis H_0: $r_k(t) = n_k(t)$). In the unrealistic scenario where the received signals on each antenna are uncorrelated, by maximum-ratio combining the signals received on each antenna, the channel fading can be mitigated, and the output signal-to-noise ratio (SNR) ρ_{out} is maximized. However, this optimal combining method requires the knowledge of the channel state information (CSI) from the primary base station at the secondary terminal. Since in a realistic cognitive scenario, the secondary user is not aware of the CSI from the primary base station, this method is only given as an optimal combining method for the sake of comparison with a second method known as square law combining (SLC), where the knowledge of CSI from the primary base station is not required [4]. A modified energy detector therefore enables to differentiate between H_0 and H_1, the decision relying on the normalized quantity $E = 2E_r/N_0$ where E_r is the energy of the baseband signal $y(t)$ at the combiner output, and N_0 is the one-sided noise power spectrum density (PSD),

$$E = \frac{2}{N_0}\int_0^T |y(t)|^2 dt = \frac{1}{N_0 W}\sum_{k=1}^{N} |y_k|^2 \tag{1}$$

with y_k denoting the samples obtained by sampling $y(t)$ at the Nyquist frequency $2W$ and $N = 2TW$ representing the total number of collected samples. A signal is considered to be detected if the resulting modified energy at the combiner output is higher than a fixed threshold. For a given detection threshold η, the probability of detection P_D and the probability of false alarm P_{FA} are given for SLC by:

$$P_D = P\left[E > \eta \middle| H_1\right] = Q_{NM}\left(\sqrt{2\rho_{out}}, \sqrt{\eta}\right) \tag{2}$$

$$P_{FA} = P\left[E > \eta \middle| H_0\right] = \frac{\Gamma\left(NM, \eta/2\right)}{\Gamma\left(NM\right)} \tag{3}$$

where $\Gamma(.)$ and $Q_N(.,.)$ respectively denote the Gamma function and the generalized Marcum Q function.

2. Measurement campaign

2.1. Experimental setup

To investigate the above-derived performance in a real-world scenario, a measurement campaign was carried out to measure the mean received power and SNR of tri-polarized arrays, for different distances between the outdoor primary transmitter and the indoor secondary terminal. The sensing measurement site was the third floor of an office building on Brussels University campus. The transmitter was fixed on the rooftop of a nearby building at a height of 15 m and was directed toward the measurement site, although the direct transmission was blocked by a brick wall. The sensing measurements were performed in 78 positions, located in seven neighboring rooms, separated by brick walls and closed wooden doors. The distance between the transmitter and the measurement points was in the range of 30–80 m.

Using Rohde & Schwarz SMATE200A Vector Signal Generator as transmitter (Tx) and Rohde & Schwarz FSG Signal Analyzer at receiver (Rx) at 3.5 GHz, a total of 320 snapshots were recorded, consisting of 5 temporal measurements over 64 spatially separated points forming an 8 × 8 grid, with half-wavelength spacing (4 cm). At Tx, a unipolar directional antenna with one vertical and one horizontal polarization (Rohde & Schwarz HE300) was used, while the Rx antenna (Satimo Insite Free 3–6 GHz [5]) consisted of three co-located perpendicular omnidirectional short linear antennas. The antenna input power was 19 dBm and the minimum noise-free range was around 15 dB.

2.2. Measurement results

As assumed in Section 1, the measured fading distribution was first checked against the Rayleigh distribution. The Kolmogorov-Smirnov test at a significance level of 5 % was satisfied for 75 of the 78 positions. The mean power values (averaged over the 320 snapshots at each location) enabled us to derive a model for the received power,

$$P = P_0 - 10n\log_{10}\left(\frac{d}{d_0}\right) \tag{4}$$

where P is received power in [dB], d is the distance in [m], d_0 = 1 m, and the values of P_0 and n are summarized in Table I.

Transmit and receive polarizations	**P_0 [dB]**	***n***
$Tx_V - Rx_V$	44.6	7.6
$Tx_V - Rx_{H1}$	32.1	7.2
$Tx_V - Rx_{H2}$	22.9	6.6
$Tx_H - Rx_V$	53.1	8.4
$Tx_H - Rx_{H1}$	65.3	8.8
$Tx_H - Rx_{H2}$	46.1	7.7

Table I. Received power model parameters

Polarizations H_1 and H_2 refer to both horizontal polarizations. It can be observed that the model naturally includes depolarization.

3. Polarized sensing : performance analysis

The probability of detection versus both the distance between the primary base station and the secondary terminal and the SNR on Rx horizontal antenna is shown for different diversity cases in Figure 1. The sensing performance levels of single-antenna sensing, polarization diversity and spatial diversity ($M = 3$) are compared, the threshold η being numerically obtained for each distance to meet the false-alarm probability constraint. In the simulations, the probability of false alarm P_{FA} was fixed to 0.01, with a time bandwidth product $TW = 5$ ($N = 10$). The noise variance N_0W was taken as –70 dBm, the received power models of Table I being used on each polarized link to obtain E_r. The inter-antenna correlation is approximated as zero (this is a good approximation for the multi-polar case, and also for spatial diversity, provided that the antenna spacing is large enough).

Clearly, the use of diversity considerably improves the sensing performance. By considering a minimum acceptable detection probability of 0.95, the use of diversity increases the range of acceptable sensing up to 18 meters. The minimum acceptable SNR is reduced up to 14 dB. As expected, the best performance is reached with MRC (only the multi-polar curve is represented for MRC). However, the detection performance is only slightly decreased with SLC. As an example, for the multi-polarized reception scenario, SLC increases the minimum acceptable SNR by less than 2 dB and decreases the range of acceptable sensing by less than 3 meters.

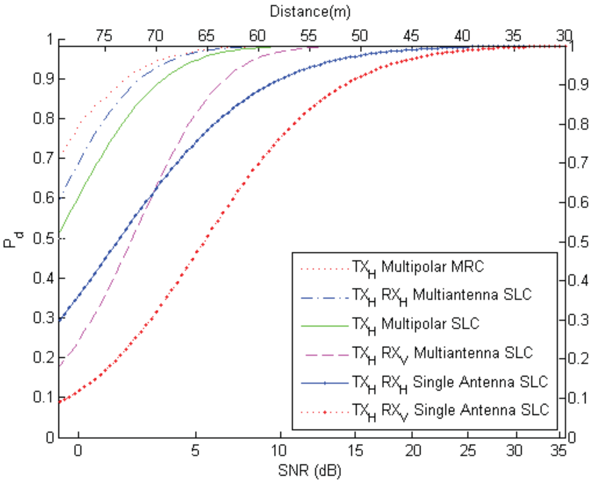

Figure 1. Probability of detection vs. SNR (or distance) for various sensing schemes.

For a given combining method, the best performance is naturally obtained when sensing via three spatially separated receive antennas with the same orientation as the primary transmitter, the performance of the tri-polarized sensing lying in between the spatial diversity sensing respectively with no and full orientation mismatch. At low SNR in the full mismatch case, the sensing performance of a CR system relying on spatial diversity even becomes worse than a single antenna detector with the best orientation. In a practical case where the orientation of the secondary terminal does not remain constant over time, the use of a tri-polarized antenna scheme at the secondary terminal appears therefore as a good trade-off.

Conclusions

Thanks to the array compactness, the low correlation and the robustness it provides, multi-polarized sensing has been shown to be a promising alternative for efficient cognitive radio applications. Furthermore, SLC methods do not cause severe degradation with respect to classical MRC.

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