The OSA-MIMO Technologies for Future Wireless Communications

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Abstract The article analyses the role of Multiple Input - Multiple Output (MIMO) and Opportunity Spectrum Access (OSA) technologies in future Cognitive Radio (CR). The model of two networks operating in the same frequency band under Rayleigh fading conditions is studied in detail. The network of licensed users called the primary operates in SISO mode, while the secondary one - in MIMO mode. The results of the analysis are encouraging. For the future it is proposed that the networks should be equipped with a dense grid of spectrum sensing detectors and OSA-routers.

Keywords Spectrum Economy, Cognitive Radio, Opportunity Spectrum Access, MIMO Systems

1. Introduction

Since its appearance the OSA-MIMO idea has been struggling with a severe shortage of the EM spectrum and its wasteful exploitation by the licensed owners. According to the last reports they use the assigned spectrum no more than 10% of the time, on average [1], [2]. Due to the original Mitola's idea [1], the secondary users (SU) can transmit only, if the primary users (PU) are inactive. This is called the interweave strategy. There is also an underlay strategy, which allows SU to transmit even if the primary user is active. The only condition is that the secondary transmitter (ST) keep its interfere power below the predefined threshold at each primary receiver (PR) [3]. This requires delimitation of the power allocation schemes, Fig.1

In order to simplify the model, the receiver noise in both networks is normalized to be equal to one, N₀=1. If the useful signal Ni exceeds the level N₀, the network P starts to transmit data until SNR₀<1. Then, it is network S turn to transmit. It can be shown that a unit capacity Cᵣ is then as follows

\[ Cᵣ = \frac{1}{M} \sum_{i=1}^{M} \log₂\left(1 + \frac{N_i}{N₀}\right) \]  (1)

2. Simple SISO-MIMO Opportunity Scheme

Let us consider two networks operating in the same frequency band and the same area, Fig.1. The primary network P operates in SISO mode, while the secondary S - in MIMO. The slow Rayleigh fading is accompanying. When the receiver Pᵣ experiences an excessive fading so that SNR₀<1, the network S starts to transmit data, assuming SNRₛ>1. Occasionally, both may be blocked. The channels are duplex oriented and the transfer functions are gained via adaptation [5].

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\[ Cᵣ = \frac{1}{M} \sum_{i=1}^{M} \log₂\left(1 + \frac{N_i}{N₀}\right) \]  (1)
where \( M \) – total number of signal samples (packets); \( N_i \) – \( i \)-th packet power level (SNR\(_i\)).

The obtained results are shown in Fig 2. As we can see the supplementary capacity \( C_s \) of network \( S \) reaches quite large values. The highest ~9 b/s/Hz obtained for the 4-th order MIMO (1Tx-4Rx) is much greater than the capacity of an individual SISO channel without fading (6.6 b/s/Hz).

\[
y_s = H x_s + \sum_i T_i x_p + n_0 \quad (1)
\]

\( y_s \) – total received signal vector at the secondary receiver (\( S_R \)); \( x_s \) – useful signal vector of the secondary transmitter (\( S_T \)); \( H \) – MIMO channel matrix from \( S_T \) to \( S_R \); \( T_i \) – channel matrix from the primary transmitter \( P_T \) to the secondary receivers \( S_R \); \( x_p \) – signal vector at \( i \)-th transmitter \( P_T \); \( n_0 \) – normalized Gaussian complex noise vector with zero mean and the identity covariance matrix \( I \). Hence, the capacity of the secondary network is

\[
C_s = \log_2 |1 + R^{-1}HQH^*| \quad (2)
\]

where \( Q = E(x^*_s x_s^*) \) transmit covariance matrix of \( S_T \), \( R \) – noise plus interference covariance matrix of \( S_R \) is:

\[
R = [I + \sum_i T_i Q_{p,i} T_i^*] \quad (3)
\]

where \( Q_{p,i} = E(x^*_p x^*_p) \) – transmit covariance matrix of \( P_T \).

3. Advanced OSA-MIMO Model

As it was stated before, the main problem of CR is determination of the channel state to avoid the interferences caused to \( P_R \) by \( S_T \). The problem can be formulated as follows [10]

\[
\begin{align*}
\max \text{imize} & \quad \log_2 |I + R^{-1}HQH^*| \\
\text{subject to} & \quad \text{Tr}(Q) \leq P_T \\
& \quad \text{and to} \quad \text{Tr}[G_k Q G_k^*] \leq \Gamma_k \quad \forall k
\end{align*}
\]

where \( G_k \) – channels from \( S_T \) to \( k \)-th \( P_T \); \( \Gamma_k \) – interference power threshold at \( k \)-th \( P_R \).

The obtained results are shown in Fig 2. As we can see the supplementary capacity \( C_s \) of network \( S \) for absence (1) and presence (2,3) primary networks SISO,MIMO.

The dashed curve shows the theoretical unit capacity \( C_S \) vs SNR for an individual \( S \) network MIMO4x4. The next red curve shows the same capacity \( C_S \) in presence of the primary network operating in SISO mode and the last curve (blue one) shows \( C_S \) under both MIMO networks (primary 2x2). One can see that the most interesting is intermediate case. It shows that the secondary MIMO network can reach as much as 14 b/s/Hz supplementary capacity at SNR=20 dB under normal operation of primary SISO network in typical Rayleigh fading conditions.

4. Large Ad Hoc MIMO System

Large Ad Hoc MIMO system composed of 100 transmit-receive nodes has been considered by Carvalho et al. [12]. In this experiment it is assumed that nodes are randomly displaced over a flat area of 1600x1600 m. The sensing range is 225 m, the useful range - 150 m. Each node can act both as transmitter or as a receiver. The two ray propagation model and the clear channel access mode (CCA) are assumed.

The goal of the approach taken by Carvalho et. al. is to assess the overall capacity of the system from the viewpoint of fading conditions and MIMO as well as from the effects of multiple access interference (MAI). The mathematical formulae are as follows:

\[
\begin{bmatrix}
\gamma_1 \\
\gamma_2
\end{bmatrix} = \begin{bmatrix}
h_{11} & h_{12} \\
h_{21} & h_{22}
\end{bmatrix} \begin{bmatrix}
s_1 \\
s_2
\end{bmatrix} + \begin{bmatrix}
n_1 \\
n_2
\end{bmatrix} = H_s s + n, \quad H^*_A H_A = ||H||^2 I_2
\]

where \( \gamma_{1,2} \) – received signals at antennas 1, 2 each for two sent signals \( s_1, s_2 \) and noise; \( I_2 \) – identity matrix 2x2; \( ||H||_F \) –
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Frobenius norm, \( ||H||_F = \sum_{i} \sum_{j} |h_{ij}|^2 \).

By defining a new vector \( \mathbf{z} = H^H \mathbf{y} \) one gets

\[
\mathbf{z} = ||H||_F^2 s + \mathbf{n}, \quad z_i = ||H||_F^2 s_i + n_i^r
\]  

where \( \mathbf{n} = H^H \mathbf{n} \) is a complex Gaussian noise vector. The multiple access interference is added to the noise product \( \mathbf{N}_0 \) and the signal-to-interference-plus-noise ratio is as follows

\[
\text{SINR} = \frac{||H_i||_F^2 E_s / 2}{\mathbf{N}_o + \sum_{k=1}^{K} ||H_{kj}||_F^2 E_s / 2}
\]

where \( i \) – transmitted node; \( j \) – receiving node; \( H_{kj} \) – channel matrix from node \( k \) to \( j \); \( K \) – number of simultaneous transmissions.

The simulation has been carried out on the basis of the popular ns-3 simulator [13]. The details of experiment assumptions are as follows:

- Energy threshold of reception: -73 dBm
- Clear Channel Access threshold: -80.92 dBm
- Transmission power/noise figure: 10 dBm/7 dB
- Signal mode: DSSS, modulation: DPSK
- Transmission rate/packet size: 1 Mbps/1412 bytes
- One simulation run corresponds to 60 sec.

The results of the experiment are shown in Fig. 4. One can see that the overall growth of the system capacity due to the MIMO for Rayleigh fading is small and it reaches merely \(~70\%\). If the Rice parameter of fading increases, this gain still decreases. It is also evident that using more than 2x2 antennas brings a negligible growth. According to the authors opinion the small gain obtained in the experiment is a result of completely random access to the common channel by all the users (MAI).

5. Homogeneous MIMO Network

Let us consider the network composed only of the MIMO channels and some number of special access points (OSA-routers). They contain all the necessary information on the current traffic and power distribution within the network. Similarly to the case presented in chapter 2, the two groups of users are specified, the primary P and the secondary S. The only interference is the thermal noise and the Rayleigh fading. Hence, the supplementary capacity of the secondary network S for equal access (50%) is as follows:

\[
C_s = 0.5 \log_2 \{ \det[I_m + (SNR / M)HH^H]\}
\]

Fig. 5 shows the values of \( C_s \) versus SNR obtained in the simulation. The results show that MIMO applied in both networks, P and S, brings the small capacity \( C_S \) in the secondary network. It approaches 5 b/s/Hz for MIMO 3x3.

6. Conclusion

In the article a comparative analysis of primary-secondary OSA-MIMO systems operating in Rayleigh fading environment has been done from the viewpoint of the spectrum economy. The assumptions from this work are as follows:

1). The fluctuations of signals are due to attenuation and due to slow and flat Rayleigh fading.
2). The instant levels of signals are detected and spread over by the special OSA-routers.
3). The correlation between channels is neglected.
4). The information transmitted tolerate delays caused by channels fading and switching.

The obtained supplementary capacity \( C_s \) in the secondary network depends on the organization of a system. The most interesting is the case when the secondary network is organized in MIMO mode, while the primary - in SISO mode. Then, the supplementary capacity \( C_S \) reaches 8-14 b/s/Hz at SNR=20 dB for MIMO 2x2 and 4x4 antennas, resp.

It is worth to note that the capacity of an individual channel (without fading) provides merely 6.66 b/s/Hz/20 dB.

In all honesty, we have to admit that the above results are obtained in Rayleigh fading conditions. In the absence of fading \( C_s=0 \). However, such a condition never exists and the Rayleigh fading is only a model of the real world. As we
already said, the licensed primary networks remain inactive over 90% of time (on average). This is much more than the Rayleigh model admits (~30%).

Starting from this point, the remaining problem of the spectrum economy shifts to the system of sensing and management instruments. It should answer the question when and where the free channels exist and how to use them. Therefore, the organization of the future wireless networks have to be modeled - to some extent - on the Internet philosophy [14].

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