Performance Analysis of Adaptive TPC Spectrum Sharing under Multicell Environments

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Abstract

A spectrum sharing method has been proposed for wireless communication systems with different priorities and the theoretical capacities achieved by low-priority systems were given [1]. However, the analysis assumed the hotspot environment. In this paper, we give the attainable capacity of this method in multicell environments, where neighboring BSs are assumed to operate using the spectrum sharing method. Numerical results show that the proposed method can attain almost double the capacity of ideal DFS with constant transmit power.

1. Introduction

Spectrum sharing remains one of the most important issues for wireless communication systems. Up until recently, the principle was to assign exclusive frequency bands to different systems or different operators, and systems that used adjacent frequency channels were expected to use appropriate spectrum masks to avoid harmful interference with each other. Recently, more challenging approaches that completely overlap the occupied frequency bands of several systems have been studied, such as cognitive radio. In this case, each wireless terminal has to recognize its ambient status and judge whether or not it can start sending signals.

A transmission method for low-priority systems in spectrum sharing environments has been proposed [1]. The method adaptively controls the transmission power of the high-priority system receivers according to the ambient status information, such as positions of interfering transmitters and victim receivers, and allowable interference level of the receivers. [1] elucidates the achievable capacity in the hotspot environment (isolated cell) and the numerical example given shows a significant increase in the capacity of such low-priority systems. However, its effectiveness in the multicell environment, where inter-cell interference may significantly impact the attainable capacity, remains to be investigated. In this paper, we extend the analysis to multi-cell environment and a numerical example show effectiveness of the spectrum sharing method [1] under multi-cell environment.

2. Spectrum sharing method with Adaptive TPC [1]

This section outlines the adaptive TPC sharing spectrum method [1]. Fig. 1 shows a feasible implementation of the proposed spectrum sharing method. The low-priority system BS is surrounded by receivers of high and low priority systems; we focus on downlink transmission in the low-priority system and the case where the bands of high and low priority systems fully overlap.

Figure 1: System model

Figure 2: Example of TPC
With the method, the high-priority system receivers and the low-priority system BS register their locations with a server that manages spectrum sharing. Each high-priority system receiver also registers its activity, frequency bands used, tolerable interference level and so on.

The spectrum sharing server calculates and informs the low-priority system BS of the maximum allowable power density on each frequency band as follows (Fig. 2): the frequency resource available is divided into many bands with constant bandwidth, which are called reference bands (RBs). For each high-priority receiver, the server sets the allowable interference power density \( I_{allow,pr} \) [dBm] of its own RB and neighboring RBs according to the information from the receiver.

\[
I_{allow,hp} = N_\text{thermal} + NF_{hp} + M_{IN}
\]

(1)

, where \( M_{IN} \) [dB] is a predetermined margin, \( N_\text{thermal} \) [dBm] is the thermal noise power density, and \( NF_{hp} \) [dB] is the noise figure of the receiver.

Next, the server estimates the path loss \( L_{path} \) [dB] between the low-priority system BS and each high-priority system receiver based on their registered positions, and calculates the allowable transmit power densities

\[
I_{allow,tx} \text{[dBm]} = G_{ant,tx} - L_{path} + G_{ant,rx,hp} + I_{allow,hp}
\]

(2)

, where \( G_{ant,tx} \) [dB], \( G_{ant,rx,hp} \) [dB] are the antenna gains of the low-priority system BS and the high-priority system receiver, respectively. If there is more than one high-priority receiver, the above calculation is performed for each high-priority system receiver and the smallest value is selected.

The low-priority system BSs are informed of \( I_{allow,tx} \) of each RB, and they then set their transmit power so as to satisfy the allowable transmit power density on each RB considering its in-band and out-band emission characteristics.

### 3. Analysis

First, we explain the analysis of [1] in Section 3.1 and then extend it to yield the capacity in the multicell environment of interest in Section 3.2.

#### 3.1 Capacity attained by adaptive TPC spectrum sharing under hotspot environment [1]

In the spectrum sharing environment, the received interference power at high-priority system receivers with antenna gain of \( G_{ant,rx,hp} \) [dB] should be below the acceptable interference level \( I_{hp,allow} \) [dBm],

\[
I_{hp,allow} > P_{tx} - BW_{lp} + G_{ant,tx} - L_{path} + G_{ant,rx,hp}
\]

(3)

, where \( P_{tx} \) [dBm] and \( G_{ant,tx} \) [dB] are the transmit power and antenna gain of the low-priority system BS, respectively; \( BW_{lp} \) [dBHz] is the occupied bandwidth of the low-priority system.

The condition defines the interfering distance \( d_{ia} \). We model path losses as:

\[
L_{path} = \alpha \log_{10}(d) + \beta
\]

(4)

, where \( d \) is the distance between the transmitter and its receiver. \( \alpha \) and \( \beta \) are constants that depend on the radio channel conditions including the frequency and the antenna heights. \( d_{ia} \) becomes

\[
d_{ia} = 10^{\frac{P_{tx} + G_{ant,tx} + G_{ant,rx,hp} - BW_{lp} - I_{hp,allow} - \beta}{10}}
\]

(5)

The receivers of the high-priority system are assumed to be distributed uniformly over the area, so the number of high-priority system receivers in the interfering area, \( N_{user,hp} \) is \( \rho_{hp} \frac{\pi d_{ia}^2}{\alpha} \), where \( \rho_{hp} \) is user density of the high-priority system.

When the probability that a high-priority system receiver is active is \( p_{hp,active} \), the probability that the low-priority system BS can transmit signals with power below \( P_{tx} \), \( F_{tx}(P_{tx}) \), becomes

\[
F_{tx}(P_{tx}) = (1 - p_{hp,active})^{N_{user,hp}}.
\]

(6)

The probability that the low-priority system BS transmits at \( P_{tx} \) is, with the proposed method, obtained by differentiating \( F_{tx}(P_{tx}) \) as follows:

\[
f_{tx}(P_{tx}) = -F(P_{tx}) \ln(1 - p_{hp,active}) \rho_{hp} \pi \frac{2}{\alpha} \ln(10) 10^{\frac{P_{tx}}{\gamma} - \beta}
\]

(7)
The coverage is regarded as the area delineated by distance \( d_{cr} \) from the BS. \( d_{cr} \) is calculated as

\[
d_{cr} = \min \left( 10^{\frac{N_{tx} + G_{ant,tx} - BW_{lp} + G_{ant,rx,lp} - P_{\text{noise}} - Z_{\text{min}} \cdot \beta}{10}}, d_{cr,\text{target}} \right)
\]

(8), where \( d_{cr,\text{target}} \) is target cell radius, \( Z_{\text{min}} \) [dB] is the minimum SNR required for low-priority system receivers, and \( G_{ant,rx,lp} \) [dB] is the antenna gain of the receivers. The number of active low-priority receivers \( N_{user,lp} \) in the area covered by \( P_{tx} \) is, under the assumption that low-priority system receivers are distributed uniformly with density \( \rho_{lp} \), \( N_{user,lp} = \rho_{lp} \pi d_{cr}^2 \).

Finally, the attainable capacities of the adaptive TPC spectrum sharing system and ideal DFS with constant transmission power are given as follows:

\[
C_{\text{cell,adapt}} \text{ [dBm/Hz]} = \int_0^\infty C_{\text{cell}} \left( \min(P_{tx}, P_{\text{max}}), N_{user,lp} \right) f_{\text{exp}}(P_{tx}) \, dP_{tx}
\]

(9)

\[
C_{\text{cell,DFS}} = C_{\text{cell}}(P_{tx}, N_{user,lp}) f_{\text{exp}}(P_{tx})
\]

(10), where \( P_{\text{max}} \) [dBm] is maximum transmit power of the low-priority system BS and \( C_{\text{cell}}(P_{tx}, N_{user,lp}) \) is the averaged cell capacity when transmit power of the BS equals \( P_{tx} \) (see [1] for details). With ideal DFS, low-priority system terminals transmit signals only if they do not interfere with high-priority receivers.

### 3.2 Capacity attained by adaptive TPC spectrum sharing in the multicell environment

When inter-cell interference is considered, the interference signals have to be considered in addition to the noise. Here the interfering BSs are assumed to operate with the same condition as the BS, which means that the transmit power of those BSs fluctuate independently according to their surrounding high priority system receivers. We omit the fast fading and shadowing effects when calculating inter-cell interference for simplicity.

The distribution of received signal power from interfering BS \( b \) is calculated as

\[
f_{\text{interf},b}(P_{\text{interf},b}) = f_{\text{exp}} \left( P_{\text{interf},b} - (G_{ant,tx} - BW_{lp} - L_{\text{path}}(d_b) + G_{ant,rx,lp}) \right)
\]

(11), where \( d_b \) is the distance between interfering BS \( b \) and user \( k \). Here we assume 6 adjacent BSs with the typical hexagonal cell arrangement. The distribution of total interference power received at the low-priority receiver becomes

\[
f_{\text{interf}}(P_t) = f_{\text{interf},1}(P_t) \otimes_{\text{dB}} f_{\text{interf},2}(P_t) \otimes_{\text{dB}} \ldots \otimes_{\text{dB}} f_{\text{interf},6}(P_t)
\]

(12), where \( \otimes_{\text{dB}} \) is the operation defined as follows:

\[
F_3(x) = F_1(x) \otimes_{\text{dB}} F_2(x) = \int_{-\infty}^{x-\Delta} F_1(t) \times F_2 \left( 10^{10 \log_{10}(10^{t/10} - 10^{t/10})} \right) \, dt
\]

(13)

Here, \( \Delta \) is an infinitely small value.

When the total interference power is determined to be \( P_{\text{interf}} \), the total amount of interference and noise \( P_{IN} \) [dBm] becomes

\[
P_{IN} = 10 \log_{10} \left( P_{\text{interf}} + 10^{P_{\text{noise}}/10} \right),
\]

(14)

and the corresponding SINR is written as

\[
\tilde{Z}_k = 10^{\left( P_{tx} + G_{ant,tx} - BW_{lp} - L_{\text{path}} + v_{sf} + G_{ant,rx,lp} - P_{lp} \right)/10}
\]

(15)

The cell capacity in the multicell environment when the transmit power is \( P_{tx} \) is given by

\[
C_{\text{cell,mc}}(P_{tx}, N_{user,lp}) = \frac{N_{user,lp}}{s_A} \int_{A} \int_{-\infty}^{\tilde{Z}_k} \int_{-\infty}^{\tilde{Z}_k} C_k(\tilde{Z}_k, P_{tx}, N_{user,lp}) \, p_{sh}(v_{sf}) \, f_{\text{interf}}(P_{\text{interf}}) \, dv_{sf} \, dP_{\text{interf}} \, da
\]

(16), where \( C_k(\tilde{Z}_k, P_{tx}, N_{user,lp}) \) is a capacity achieved by user \( k \) (see [1]), \( v_{sf} \) is a shadowing factor, and \( p_{sh}(v_{sf}) \) is the PDF of \( v_{sf} \) with variance \( \sigma^2 \).

\[
p_{sh}(v_{sf}) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{v_{sf}^2}{2\sigma^2}}.
\]

(17)
Lastly, replacing $C_{cell}(P_{tx}, N_{user.lp})$ by $C_{cell,mc}(P_{tx}, N_{user.lp})$ of equation (9) yields the attainable capacity by the adaptive TPC spectrum sharing system in a multi-cell environment.

The capacity of ideal DFS is derived by using the following distribution of received interference power instead of equation (7).

$$f_{txp}(P_{tx}) = F_{txp}(P_{tx})\delta(P_{tx})$$

(18)

### 4. Numerical results and performance comparisons

Table 1 shows the parameters used in determining the numerical results. As the path loss model, we used the COST-231 HATA model [2] for urban areas and omni-directional antennas are assumed at the low-priority system BSs and all terminals. Moreover, a proportional fair scheduler is considered for scheduling in low-priority system BSs.

Fig. 3 shows the cell capacities achieved by the low-priority system versus the user density of the high-priority system $\rho_{hp}$. The “constant transmission power” case refers to the conventional method, in which DFS works ideally. The constant transmit powers considered are 10 dBm, 20 dBm, and 30 dBm. The results show that the proposed method offers higher capacity than the conventional method for all $\rho_{hp}$s also in the multicell environment. As $\rho_{hp}$ increases, the capacity falls even if the proposed method is applied; note that the proposed method attains triple the capacity of ideal DFS with $P_{tx} = 30$ dBm when $\rho_{hp} = 80$ [terminals/km$^2$].

### 5. Conclusion

We gave a theoretical analysis of the capacity achieved by a spectrum sharing method [1] in a multicell environment. Numerical analyses that compared the capacities achieved by the proposed method to those of ideal DFS with constant transmission power were then described. They prove the potential for successful spectrum sharing between systems with different priorities even in the multicell environment.

### Reference


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![Figure 3: $\rho_{hp}$ vs. high-priority system density](image-url)