

Chapter 2

Region-Based Spectrum Sensing

2.1 Introduction

In cognitive radio systems, spectrum sensing is critical since it determines which kind of spectrum sharing schemes can be used. For example, in cognitive small cell networks, a large number of small cells with short transmission range can share the same spectrum band with a macro cell. To avoid co-channel interference, small cell may access the idle bands of the macro cell, called *overlay spectrum sharing*, which works well in low and medium load scenarios [1, 2], i.e., the macrocell has enough idle bands to accommodate the small cells. However, when the macro cell is with high load, it may have few idle bands. This significantly reduces the transmission opportunities of the small cells.

To deal with the issue, another kind of spectrum sharing, called *underlay spectrum sharing*, is proposed, but it requires the cognitive small cells to control the interference to active *macro cell user equipments* (M-UEs). In the literature, most of existing contributions [3–6] determine an access probability of cognitive small cells to guarantee the outage probability of active M-UEs based on *Poisson point process* (PPP) model. However, those methods can only obtain limited transmission opportunities for cognitive small cells. This is because they are based on the statistic information of the networks and the worst case needs to be considered.

An effective approach to improve the transmission opportunities of the small cells is to allow them to access the busy bands of the macro cell, which requires to sense the location of the active M-UE. If the active M-UE is outside a small cell's coverage, the small cell is allowed to access the M-UE's busy band; if the active M-UE is inside the small cell's coverage, the small cell needs to keep silence to avoid the interference. Therefore, the effective spectrum sharing needs to identify the located region of the M-UE, i.e., whether the active M-UE is inside or outside the coverage of the small cell.

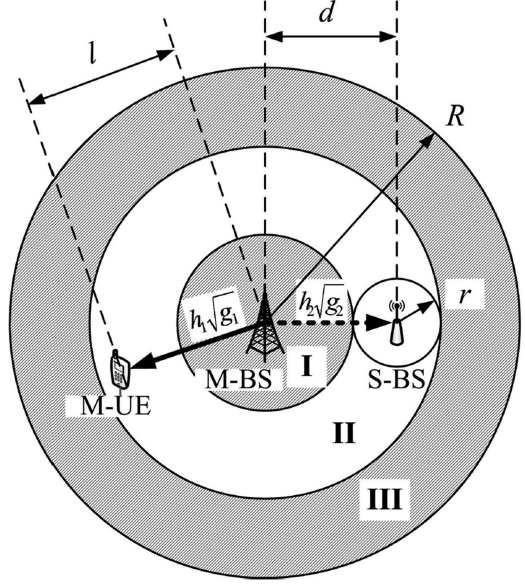
In practice, it is very difficult to detect the located region of the M-UE. This is because most of the existing spectrum sensing methods [7–9] belong to transmitter detection. They cannot be used to detect the M-UE. Specifically, in downlink transmission, since the active M-UE acts as the receiver and does not transmit signals, the small cell can not identify the active M-UE. In uplink transmission, since the small cell does not know the transmission power of the active M-UE, it still can not identify the active M-UE.

In this chapter, a region-based spectrum sensing method is proposed to detect the located region of the active M-UE, where the two-tier cognitive small cell network is considered. In our method, the detection is based on the measured energy of the received signal from a *macro cell base station* (M-BS). We design two detectors with one and two thresholds, respectively, which allow the small cell and the macro cell to simultaneously access the same band. With the proposed method, the *small cell base station* (S-BS) is able to identify the location of the active M-UE and further find the transmission opportunity of the busy band, i.e., the band is being occupied by the active M-UE, but the active M-UE is outside the coverage of the small cell. As a result, the cognitive S-BS can obtain significant transmission opportunities in an “opportunistic” way, i.e., identifying the active M-UE that is outside the coverage of the S-BS and accessing the busy band without interfering with the active M-UE. This is different from conventional overlay methods [7–9] that work in an “on and off” way, i.e., turning on and off the S-BS when a band is idle and busy, respectively. This is also different from conventional underlay methods [3–6] that work in a “blind” way, i.e., accessing the busy band with a certain probability to avoid interference to active M-UEs.

2.2 System Model

Figure 2.1 provides the system model of this chapter. Acting as the primary users, an M-BS serves each M-UE in a certain downlink frequency band. In particular, the M-UEs are uniformly distributed in the coverage of the M-BS with the radius R . On the other hand, acting as a cognitive user, an S-BS inside the M-BS’s coverage intends to access the same downlink band being used by the M-UE, where the radius of the S-BS’s coverage is r (Here, we use the term “S-BS’s coverage” to represent the interference region of the S-BS, then the S-BS does not cause interference to the active M-UE that is outside the S-BS’s coverage). Since both the M-UE and S-BS can receive the signal from the M-BS, we will introduce the signal model between the M-BS and M-UE and that between the M-BS and S-BS, respectively. Here, we only consider the three nodes, which do not include the small cell UE.

Fig. 2.1 System model (the S-BS that acts as a cognitive user accesses the same frequency band as the M-BS and M-UE that act as the primary users)



2.2.1 Primary Transmission

Denote g_1 as the large-scale path-loss from the M-BS to the M-UE and h_1 as the small-scale fading from the M-BS to the M-UE, then the received signal at the M-UE can be expressed as

$$y_1(k) = h_1 \sqrt{g_1} p x(k) + n_1(k), \quad 1 \leq k \leq K, \quad (2.1)$$

where $x(k)$ is the transmit signal of the M-BS with the power p , k is the index of the K samples, and $n_1(k)$ is the *additive white Gaussian noise* (AWGN) at the M-UE with zero mean and variance σ_1^2 . Then the SNR of the received signal at the M-UE can be expressed as

$$\gamma_1 = \frac{h_1^2 g_1 p}{\sigma_1^2}. \quad (2.2)$$

We assume that the M-BS communicates with the M-UE for guaranteed wireless services. Then, for a certain data rate, the M-BS can automatically adjust the transmission power to meet a target SNR for the specific M-UE, defined by γ_r . This assumption is reasonable since maintaining SNR has been widely applied in practical systems, e.g., the M-BS usually adjusts the transmission power through *close loop power control* (CLPC) or power allocation to provide the required

data rate. Based on the above assumption, we replace γ_1 by γ_T in (2.2). Then we can obtain the transmission power of the M-BS by

$$p = \frac{\gamma_T \sigma_1^2}{h_1^2 g_1}. \quad (2.3)$$

Furthermore, we consider both large-scale path-loss and small-scale fading in wireless channels. According to [10], the path-loss follows the model

$$g_1 = C \left(\frac{\lambda}{4\pi l} \right)^\beta, \quad (2.4)$$

where C is a constant, λ is the wavelength, l is the distance between the M-UE and M-BS, and β is the path-loss factor ($\beta = 2 \sim 6$). The small-scale fading follows Rayleigh distribution with unit power, and the *probability density function* (PDF) is

$$f_{h_1}(z) = 2ze^{-z^2}, \quad z \geq 0. \quad (2.5)$$

2.2.2 Cognitive User Measurement

Similarly, denote g_2 as the large-scale path-loss from the M-BS to the S-BS, and h_2 as the small-scale fading from the M-BS to the S-BS, then the received signal at the S-BS can be expressed as

$$y_2(k) = h_2 \sqrt{g_2 p} x(k) + n_2(k), \quad 1 \leq k \leq K, \quad (2.6)$$

where $n_2(k)$ is the AWGN at the S-BS with zero mean and variance σ_2^2 . We adopt the same path-loss and small-scale fading models as in (2.4) and (2.5), i.e.,

$$g_2 = C \left(\frac{\lambda}{4\pi d} \right)^\beta \quad (2.7)$$

and

$$f_{h_2}(z) = 2ze^{-z^2}, \quad z \geq 0, \quad (2.8)$$

where d is the distance between the S-BS and M-BS.

Substituting (2.3) into (2.6), we have

$$y_2(k) = \frac{h_2}{h_1} \sqrt{\frac{\gamma_T \sigma_1^2 g_2}{g_1}} x(k) + n_2(k), \quad 1 \leq k \leq K. \quad (2.9)$$

Let

$$\Phi = \frac{g_2}{g_1} \quad (2.10)$$

and

$$\Omega = \frac{h_2^2}{h_1^2}, \quad (2.11)$$

and assume $\sigma_1^2 = 1$, the received signal at the S-BS in (2.9) can be simplified as

$$y_2(k) = \sqrt{\Phi\Omega\gamma_T}x(k) + n_2(k). \quad (2.12)$$

2.3 Detection Principle

In this section, we introduce the basic principle of our region-based spectrum sensing method that detects the located region of the active M-UE and finds the transmission opportunities for the S-BS. Generally, our region-based method uses the energy of the received signal from the M-BS since the energy carries the location information of the M-UEs. Specifically, as shown in Fig. 2.1, the whole coverage of the M-BS can be divided into three regions according to the location of the S-BS. The S-BS is always in Region II while the M-UEs are randomly located in one of the three regions. If an M-UE is located in Region I or III, the S-BS does not interfere with the M-UE. Otherwise, if an M-UE is in Region II, the S-BS may cause interference to the M-UE. Then we define the two cases as hypotheses $\mathcal{H}_0$ and $\mathcal{H}_1$, respectively, i.e.,

$$\begin{cases} \mathcal{H}_0 : \text{M-UE} \in \text{Regions I or III,} \\ \mathcal{H}_1 : \text{M-UE} \in \text{Region II.} \end{cases} \quad (2.13)$$

For a guaranteed wireless service to the M-UE with a target SNR requirement, the transmission power of the M-BS is mainly determined by the location of the M-UE. If the M-UE is in Region I, which is the center of the M-BS's coverage, the M-BS can meet the M-UE's target SNR with low power; if the M-UE is in Region II, the M-BS needs medium power to satisfy the target SNR; if the M-UE is in Region III, which is the edge of the M-BS's coverage, the M-BS has to use high power for the target SNR. In other words, it establishes the above corresponding relationship between the M-UE's located region and the M-BS's power. Based on the corresponding relationship, the S-BS can distinguish the two hypotheses by measuring the energy of the received signal from the M-BS: if the measured energy is very small or very large, the M-UE is probably in Region I or III, respectively; if the measured energy is medium, the M-UE is probably in Region II. Therefore, the S-BS can use the energy of the received signal from the M-BS as a test statistic to identify the located region of the M-UE.

In the next section, we obtain the distribution of the test statistic and then design the detectors. In particular, we ignore the shadowing in algorithm development because it is very difficult to obtain the closed-form distribution of the test statistic with shadowing. Instead, we will consider it in the simulation section.

2.4 Detector Design

In this section, we first use three steps to obtain the distribution of the test statistic. Based on that, we design a one-threshold detector in Sect. 2.4.5 to maximize the small cell transmission opportunity subject to an interference constraint. Furthermore, we design a double-threshold detector in Sect. 2.4.6, which can achieve better performance.

2.4.1 The Test Statistic

When the S-BS uses K samples to calculate the energy of the received signal from the M-BS, we obtain the following test statistic,

$$E = \sum_{k=1}^K y_2^2(k). \quad (2.14)$$

Substituting (2.12) into (2.14), and simplifying the expression, we obtain

$$E = \sum_{k=1}^K \Omega \Phi \gamma_T x^2(k) + \sum_{k=1}^K 2\sqrt{\Omega \Phi \gamma_T} x(k) n_2(k) + \sum_{k=1}^K n_2^2(k). \quad (2.15)$$

In the above expression, Ω , $x(k)$, Φ , and $n_2(k)$ represent four random variables: Ω is determined by the ratio of the power of the two small-scale fadings h_1 and h_2 ; Φ is determined by the ratio of two path-loss values g_1 and g_2 ; $x(k)$ is the signal from the M-BS with normalized power; $n_2(k)$ is the AWGN.

It is very difficult to obtain the distribution of the test statistic in (2.15), since it is a combination of the four random variables. To obtain a closed-form expression, we ignore the noise and make the following approximation,

$$E \approx \sum_{k=1}^K \Omega \Phi \gamma_T x^2(k) = K \Omega \Phi \gamma_T. \quad (2.16)$$

Now, the energy of the received signal in (2.16) is determined by the two random variables Ω and Φ .

In the following, we first derive the *probability density functions* (PDFs) of Ω and Φ , respectively, and then obtain the *cumulative distribution function* (CDF) of the test statistic E .

2.4.2 Step 1: Obtain the PDF of Ω

Since the small-scale fading follows independent Rayleigh distribution, the power of them follows exponential distribution, i.e., $h_1^2 \sim e^{-u}$ and $h_2^2 \sim e^{-u}$. According to [11], the CDF of $\Omega = h_2^2/h_1^2$ can be calculated by

$$F_{\Omega}(\omega) = \int_0^{\infty} y f_{\Omega}(y\omega, y) dy = \frac{\omega}{1 + \omega}, \quad (2.17)$$

and the PDF of Ω can be obtained by

$$f_{\Omega}(\omega) = \frac{1}{(1 + \omega)^2}, \quad (2.18)$$

which follows F-distribution.

2.4.3 Step 2: Obtain the PDF of Φ

Since the M-UE is uniformly distributed in the coverage of the M-BS, the PDF of the distance between the M-UE and M-BS can be obtained by

$$f_l(l) = \begin{cases} \frac{2l}{R^2 - 4dr - \varepsilon^2}, & \varepsilon \leq l \leq d - r \text{ or } d + r \leq l \leq R \quad (\mathcal{H}_0), \\ \frac{2l}{4dr}, & d - r < l < d + r \quad (\mathcal{H}_1), \end{cases} \quad (2.19)$$

where ε is the minimum distance between the M-UE and M-BS. When the path-loss factor is $\beta = 2$, we substitute (2.4) and (2.7) into (2.10), and then obtain

$$\Phi = \frac{g_2}{g_1} = \frac{l^2}{d^2}. \quad (2.20)$$

Given a distance between the S-BS and M-BS, i.e., d , we can obtain the CDF of Φ , i.e.,

$$\begin{aligned} F_{\Phi}(\phi) &= P\left(\frac{l^2}{d^2} \leq \phi\right) \\ &= \begin{cases} \frac{\phi d^2}{R^2 - 4dr - \varepsilon^2}, & \varepsilon \leq l \leq d - r \text{ or } d + r \leq l \leq R \quad (\mathcal{H}_0), \\ \frac{\phi d^2}{4dr}, & d - r < l < d + r \quad (\mathcal{H}_1). \end{cases} \end{aligned} \quad (2.21)$$

Then, the PDF of Φ becomes

$$f_{\Phi}(\phi) = \begin{cases} \frac{d^2}{R^2 - 4dr - \varepsilon^2}, & \mathcal{H}_0, \\ \frac{d^2}{4dr}, & \mathcal{H}_1. \end{cases} \quad (2.22)$$

2.4.4 Step 3: Obtain the CDF of E

As indicated in (2.16), i.e., $E = K\Omega\Phi\gamma_T$, our test statistic E has the same distribution as Ω for a given value of Φ (K and γ_T are constants). Then, we obtain the conditional PDF of E from (2.18) as follows,

$$f_E(\xi|\Phi) = \frac{K\Phi\gamma_T}{(K\Phi\gamma_T + \xi)^2}. \quad (2.23)$$

As a result, the closed-form CDF of E in both $\mathcal{H}_0$ and $\mathcal{H}_1$ can be obtained by

$$\begin{aligned} \Pr(\xi \leq E^* | \mathcal{H}_0) &= \int_{M-UE \in \text{I,III}} \int_0^{E^*} f_E(\xi|\Phi) f_{\Phi}(\phi) d\xi d\phi \\ &= \int_{\varepsilon}^{d-r} \int_0^{E^*} \frac{Kl^2 d^2 \gamma_T}{(Kl^2 \gamma_T + d^2 \xi)^2} \cdot \frac{2l}{R^2 - 4dr - \varepsilon^2} d\xi dl + \int_{d+r}^R \int_0^{E^*} \frac{Kl^2 d^2 \gamma_T}{(Kl^2 \gamma_T + d^2 \xi)^2} \cdot \frac{2l}{R^2 - 4dr - \varepsilon^2} d\xi dl \\ &= \frac{d^2 E^*}{(R^2 - 4dr - \varepsilon^2) K \gamma_T} \left[\ln \left(\frac{(d-r)^2 K \gamma_T + d^2 E^*}{\varepsilon^2 K \gamma_T + d^2 E^*} \right) + \ln \left(\frac{R^2 K \gamma_T + d^2 E^*}{(d+r)^2 K \gamma_T + d^2 E^*} \right) \right]. \end{aligned} \quad (2.24)$$

and

$$\begin{aligned} \Pr(\xi \leq E^* | \mathcal{H}_1) &= \int_{M-UE \in \text{II}} \int_0^{E^*} f_E(\xi|\Phi) f_{\Phi}(\phi) d\xi d\phi \\ &= \int_{d-r}^{d+r} \int_0^{E^*} \frac{Kl^2 d^2 \gamma_T}{(Kl^2 \gamma_T + d^2 \xi)^2} \cdot \frac{2l}{4dr} d\xi dl \\ &= \frac{d^2 E^*}{4dr K \gamma_T} \ln \left(\frac{(d+r)^2 K \gamma_T + d^2 E^*}{(d-r)^2 K \gamma_T + d^2 E^*} \right). \end{aligned} \quad (2.25)$$

Figure 2.2 plots the theoretical CDF curves and the corresponding scenarios of the test statistic E based on (2.24) and (2.25), where different distances between the S-BS and M-BS are considered. We also provide simulation curves for comparison, where the system parameters are the same as that in Sect. 2.5. From Fig. 2.2a, when the S-BS is close to the M-BS, i.e., $d = 100$ m, the CDF curves of $\mathcal{H}_0$ are on the right side of the CDF curves of $\mathcal{H}_1$. However, when the S-BS is far away from

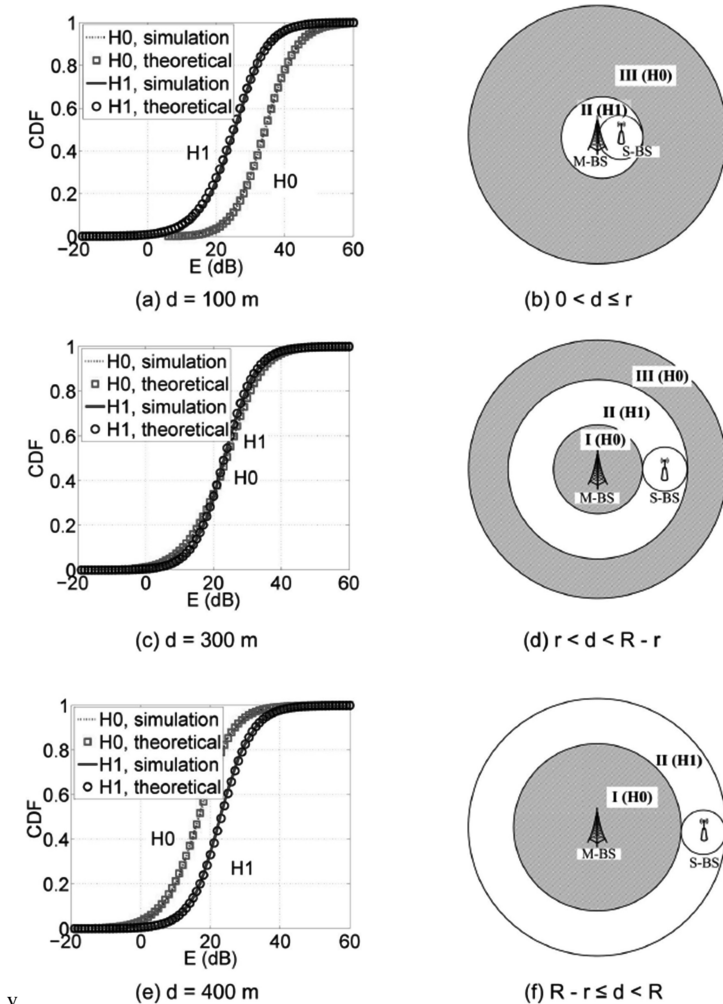


Fig. 2.2 CDF curves of the test statistic E and the corresponding scenarios (d is the distance between S-BS and M-BS, $r = 100$ m, and $R = 500$ m)

the M-BS, i.e., $d = 300$ m and $d = 400$ m in Fig. 2.2c, e, the CDF curves of $\mathcal{H}_0$ dramatically shift to the left side of the curves under $\mathcal{H}_1$. On the other hand, the CDF curves of $\mathcal{H}_1$ slightly shift to the left as the S-BS moves away from the M-BS and the shift is too small to be observed.

This shift is reasonable since the whole coverage of the M-BS is divided into three regions according to the location of the S-BS. When the S-BS is close to the M-BS, Region I is small and Region III is large, and the M-UE is more likely to appear in Region III, resulting in that the M-BS uses higher power to serve the M-UE. Otherwise, when the S-BS is far away from the M-BS, Region I is large and

Region III is small, and the M-UE is more likely to appear in Region I, resulting in that the M-BS uses lower power to serve the M-UE. Thus, the CDF curves of $\mathcal{H}_0$ shift to the left as the S-BS moves away from the M-BS. However, the shift of the CDF curves of $\mathcal{H}_1$ is almost indistinctive. This is because under $\mathcal{H}_1$, the M-UE and S-BS are both in Region II and experience similar path-losses and receive similar energies.

Furthermore, when we compare the theoretical curves with the simulation ones, they overlap very well except for a small gap that appears in the curves of $\mathcal{H}_0$ when $d = 400$ m and $0 \text{ dB} < E < 13 \text{ dB}$. The reason is that the approximation in (2.16) is inaccurate when the S-BS is far away from the M-BS and experiences low SNR. But this does not affect the performance of the proposed methods, which will be shown in the next section.

2.4.5 One-Threshold Detector

Two Special Scenarios

In Fig. 2.2a, b, when the S-BS is close to the M-BS, i.e., $0 < d \leq r$, it has only Regions II and III, which are corresponding to $\mathcal{H}_1$ and $\mathcal{H}_0$, respectively. Since the $\mathcal{H}_0$ CDF curve is on the right side of the $\mathcal{H}_1$ CDF curve, we can find a threshold η' to distinguish $\mathcal{H}_0$ and $\mathcal{H}_1$, i.e.,

$$\text{Decision result} = \begin{cases} \mathcal{D}_0, & E > \eta', \\ \mathcal{D}_1, & E \leq \eta', \end{cases} \quad (2.26)$$

where $\mathcal{D}_0$ and $\mathcal{D}_1$ are denoted as the decisions on $\mathcal{H}_0$ and $\mathcal{H}_1$, respectively.

On the other hand, in Fig. 2.2e, f, when the S-BS is far away from the M-BS, i.e., $R - r \leq d < R$, it has only Regions I and II, which are corresponding to $\mathcal{H}_0$ and $\mathcal{H}_1$, respectively. Since the $\mathcal{H}_0$ CDF curve in this scenario is on the left side of the $\mathcal{H}_1$ CDF curve, we can find a threshold η'' to distinguish $\mathcal{H}_0$ and $\mathcal{H}_1$, i.e.,

$$\text{Decision result} = \begin{cases} \mathcal{D}_0, & E \leq \eta'', \\ \mathcal{D}_1, & E > \eta''. \end{cases} \quad (2.27)$$

The General Scenario

In Fig. 2.2c and d, when the S-BS is in the medium range of the M-BS's coverage, i.e., $r < d < R - r$, it has three regions. Then, the detection becomes complicated because we have only one threshold η . On one hand, if the threshold η is relatively high, the case $E > \eta$ indicates that the M-UE is inside Region III ($\mathcal{H}_0$) and the S-BS is able to access the busy band. In contrast, the case $E \leq \eta$ indicates that the M-UE may appear in either Region I ($\mathcal{H}_0$) or II ($\mathcal{H}_1$). Then, the S-BS still has the

opportunity (i.e., the probability that the M-UE is in Region I) to assess the busy band. On the other hand, if the threshold η is relatively low, the case $E \leq \eta$ indicates that the M-UE is inside Region I ($\mathcal{H}_0$) and the S-BS is able to access the busy band. In contrast, the case $E > \eta$ indicates that the M-UE may appear in either Region II ($\mathcal{H}_1$) or III ($\mathcal{H}_0$). Then, the S-BS still has the opportunity (i.e., the probability that the M-UE is in Region III) to assess the busy band. As a result, on both sides of the threshold, i.e., $E > \eta$ and $E \leq \eta$, the S-BS has the opportunity to access the busy band.

To maximize the small cell transmission opportunity, it is reasonable to introduce two access probabilities q_1 and q_2 for $E > \eta$ and $E \leq \eta$, respectively, where $0 \leq q_1 \leq 1$ and $0 \leq q_2 \leq 1$. Then, the S-BS can make full use of the transmission opportunities under both cases (i.e., $E > \eta$ and $E \leq \eta$). In particular, with the two access probabilities, the S-BS is able to automatically adjust the decision rule between (2.26) and (2.27), which makes the OTD work in all three scenarios. For example, when $q_1 = 1$ and $q_2 = 0$, the S-BS accesses the busy band if $E > \eta$, which is equivalent to (2.26); when $q_1 = 0$ and $q_2 = 1$, the S-BS accesses the busy band if $E \leq \eta$, which is equivalent to (2.27).

Next, we obtain the optimal access probabilities q_1^* and q_2^* as well as the corresponding optimal threshold η^* so that the small cell transmission opportunity can be maximized.

Calculate the Threshold and Access Probabilities

Based on the above discussion, the probability that the S-BS may access the busy band, i.e., the small cell transmission opportunity, becomes four components, i.e.,

$$P_O = q_1 (Pr\{E > \eta | \mathcal{H}_0\} Pr\{\mathcal{H}_0\} + Pr\{E > \eta | \mathcal{H}_1\} Pr\{\mathcal{H}_1\}) \\ + q_2 (Pr\{E \leq \eta | \mathcal{H}_0\} Pr\{\mathcal{H}_0\} + Pr\{E \leq \eta | \mathcal{H}_1\} Pr\{\mathcal{H}_1\}). \quad (2.28)$$

Similarly, the interference probability to the M-UE has two components, i.e.,

$$P_I = (q_1 Pr\{E > \eta | \mathcal{H}_1\} Pr\{\mathcal{H}_1\} + q_2 Pr\{E \leq \eta | \mathcal{H}_1\} Pr\{\mathcal{H}_1\}) \zeta(d), \quad (2.29)$$

where $\zeta(d) = S_s/S_{II}$ is the area ratio between the coverage of the S-BS and Region II. The expression of $\zeta(d)$ varies with different ranges of d and we obtain them in [12].

Given an interference constraint I_c , which is the maximum allowable interference probability to the M-UE, the optimal threshold as well as the optimal access probabilities can be obtained by

$$\max_{q_1^*, q_2^*, \eta^*} P_O, \\ s.t. \ P_I \leq I_c, \ 0 \leq q_1 \leq 1, \ 0 \leq q_2 \leq 1, \text{ and } \eta \geq 0. \quad (2.30)$$

We can substitute (2.28) and (2.29) into (2.30). But, the obtained expression is very complicated since different distance ranges between the S-BS and M-BS need to be considered. Thus, it is very difficult to obtain the closed-form expressions of q_1^* , q_2^* , and η^* . Instead, we will obtain them numerically.

2.4.6 Two-Threshold Detector

In this subsection, we will design another detector using two thresholds. As shown in Fig. 2.2c, when the distance between the S-BS and M-BS is $d = 300$ m, half of the $\mathcal{H}_0$ curve is on the right side of the $\mathcal{H}_1$ curve ($E > 25$ dB), and the other half of the $\mathcal{H}_0$ curve is on the left side of the $\mathcal{H}_1$ curve ($E < 25$ dB). This indicates that the S-BS in such a location should access the busy band if the test statistic of the S-BS is either large enough or small enough. Then, we set two thresholds η_L and η_H to distinguish $\mathcal{H}_0$ and $\mathcal{H}_1$, i.e.,

$$\begin{cases} \mathcal{H}_0 : & E \leq \eta_L \text{ or } E \geq \eta_H, \\ \mathcal{H}_1 : & \eta_L < E < \eta_H. \end{cases} \quad (2.31)$$

This rule also works for the other two cases when the S-BS is close and far away from the M-BS, respectively, e.g., Fig. 2.2a, e. Then, the small cell transmission opportunity can be expressed as

$$\begin{aligned} P_O = & \Pr\{E \leq \eta_L \text{ or } E \geq \eta_H | \mathcal{H}_0\} \Pr\{\mathcal{H}_0\} \\ & + \Pr\{E \leq \eta_L \text{ or } E \geq \eta_H | \mathcal{H}_1\} \Pr\{\mathcal{H}_1\}. \end{aligned} \quad (2.32)$$

The interference probability to the M-UE can be expressed as

$$P_I = \Pr\{\eta_L < E < \eta_H | \mathcal{H}_1\} \Pr\{\mathcal{H}_1\} \zeta(d), \quad (2.33)$$

where $\zeta(d)$ is also obtained from [12].

Given an interference constraint I_c , the optimal thresholds that maximize the small cell transmission opportunity can be obtained by

$$\begin{aligned} & \max_{\eta_L^*, \eta_H^*} P_O, \\ & s.t. \ P_I \leq I_c \text{ and } 0 < \eta_L \leq \eta_H. \end{aligned} \quad (2.34)$$

Similarly, we can also substitute (2.32) and (2.33) into (2.34). However, it is very difficult to obtain the closed-form expression of the optimal thresholds. Therefore, we will calculate them numerically.

2.5 Simulation Results

In this section, we demonstrate the advantages of the proposed detectors, called *one-threshold detector* (OTD) and *double-threshold detector* (DTD). To compare with the conventional transmitter detection, we also provide the performance of the *energy detector* (ED) [13, 14], where the threshold is calculated under Neyman Pearson criteria with 1 % false alarm probability. In the simulation, we assume that the M-UE is uniformly distributed inside the macro cell, where the radius of the macro cell's coverage and that of the small cell's coverage are $R = 500$ m and $r = 100$ m, respectively, the target SNR at the M-UE is $\gamma_T = 20$ dB, the interference probability constraint is $I_c = 0.01$, the minimum distance between the M-UE and M-BS is $\varepsilon = 36$ m [15], the number of samples is $K = 2$, and $N = 10^4$ Monte Carlo trials are conducted for each simulation curve.

In the following, we first compare the performance of the OTD, the DTD, and the ED. Then, we present their performance as a function of the target SNR and the radius of the S-BS. After that, we demonstrate that our methods work well even if the target SNR of the M-UE is unknown to the S-BS. Finally, we provide the performance of our methods in the case of shadowing.

2.5.1 Comparison of the OTD, the DTD, and the ED

Figure 2.3 compares the transmission opportunities identified by the three detectors, the OTD, the DTD, and the ED, where both simulation and theoretical curves are provided for the OTD and the DTD. From the figure, the simulation and theoretical curves overlap very well, and the proposed OTD and DTD significantly outperform the conventional ED. In particular, the OTD and the DTD have an “U” shape for $d < 500$ m and are with the lowest transmission opportunities when $d \approx 300$ m. The reason is that the CDF curves of $\mathcal{H}_0$ and $\mathcal{H}_1$ in Fig. 2.2 overlap when $d \approx 300$ m, and then it is hard for the OTD and the DTD to distinguish the two hypotheses. When $d > 500$ m and the S-BS moves out of the coverage of the M-BS, the S-BS may always access the busy band without interfering with the M-BS. Thus, the transmission opportunity approaches 1 for $d > 560$ m. Furthermore, when comparing the OTD and the DTD, they have the same performance for most of the S-BS locations except for a small gap when $250 \text{ m} < d < 350 \text{ m}$. In this range, the DTD slightly outperforms the OTD.

Figure 2.4 compares the interference probabilities of the OTD, the DTD, and the ED. From the figure, the OTD and the DTD can control their interference under the preset interference probability constraint $I_c = 0.01$ for $d < 500$ m. This is because the optimal thresholds of the OTD and the DTD are designed under the interference probability constraint. In addition, the interference probability of the ED is around 0.002 for $d < 500$ m, since the ED is designed under the false alarm probability constraint rather than the interference probability constraint. When $d > 500$ m

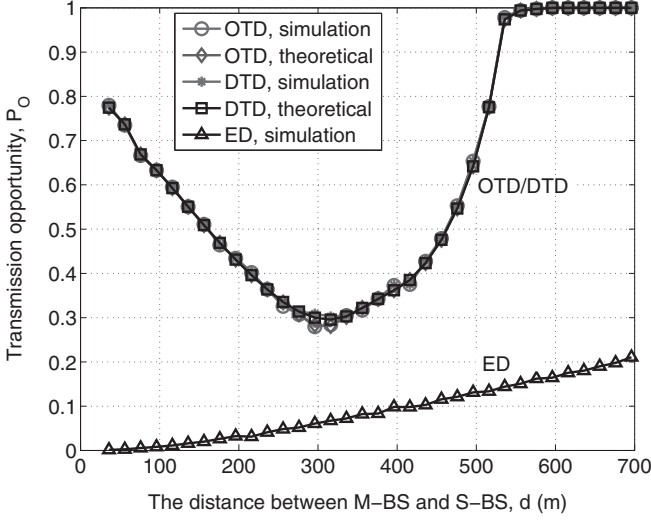


Fig. 2.3 Transmission opportunities of the OTD, the DTD, and the ED

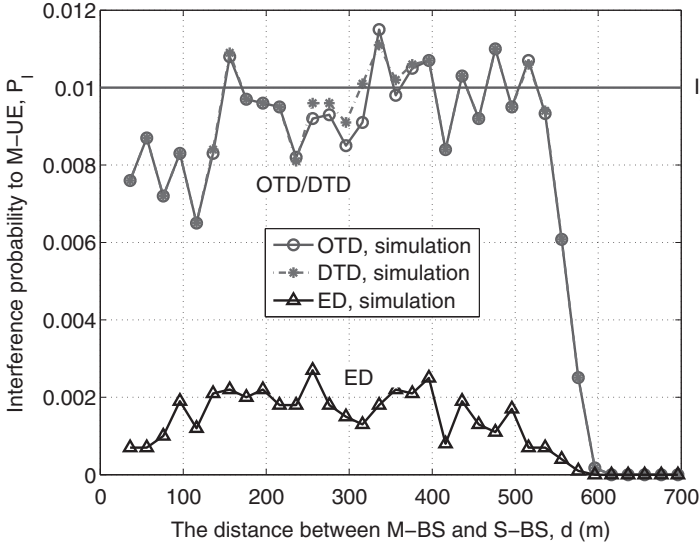


Fig. 2.4 Interference probabilities of the OTD, the DTD, and the ED

and the S-BS moves out of the coverage of the M-BS, there is no M-UE inside the M-BS's coverage and the S-BS causes no interference to the M-UE. Then, the interference probabilities of all three methods approach 0 when $d > 500$ m.

Figures 2.5 and 2.6 provide the optimal threshold and the optimal access probabilities of the OTD, respectively, where the threshold of ED is also provided

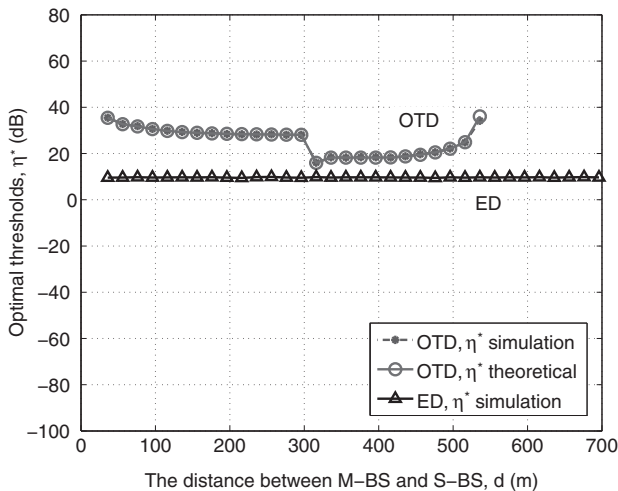


Fig. 2.5 Optimal thresholds of the OTD and the ED

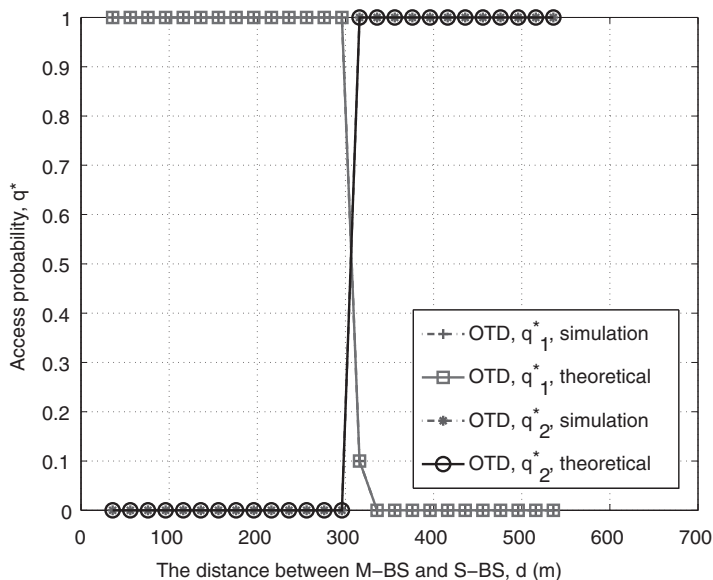


Fig. 2.6 Optimal access probability of the OTD

in Fig. 2.5 for comparison. From Fig. 2.5, the threshold of ED is a constant since it is determined by a fixed false alarm probability and does not change with d . But the optimal threshold of the OTD varies with d since it is calculated based on an interference probability constraint. From Fig. 2.6, when the S-BS is close to the M-BS, i.e., $d < 300$ m, $q_1^* = 1$ and $q_2^* = 0$, which means that the S-BS accesses the

busy band when $E > \eta^*$; when the S-BS is far away from the M-BS, i.e., $d > 300$ m, $q_1^* = 0$ and $q_2^* = 1$, which means that the S-BS accesses the busy band when $E < \eta^*$. Thus, the OTD only needs to design one threshold and switch the decision rules between (2.26) and (2.27). This significantly reduces the complexity of the OTD and makes the OTD easy to implement in practice.

Figure 2.7 shows the optimal thresholds of the DTD as well as the threshold of the ED. From the theoretical curves of the DTD, when $d < 250$ m, the optimal high threshold η_H^* is about 30 dB and the optimal low threshold η_L^* is about -80 dB, which means that the decision mainly depends on η_H^* ; when the S-BS moves away from the M-BS, i.e., $250 \text{ m} < d < 350$ m, the decision depends on both thresholds; when the S-BS is close to the edge of the M-BS's coverage, i.e., $350 \text{ m} < d < 500$ m, the low threshold becomes the dominant threshold. As the S-BS keeps on moving out of the M-BS's coverage, $d > 500$ m, the overlap between the coverages of the S-BS and the M-BS reduces to zero, and then the S-BS may always access the busy band without interfering with the M-UE. Thus, the two thresholds of the DTD become identical and can be any value, which has been omitted in Fig. 2.7. Furthermore, the simulation curves match the theoretical ones very well except for the lower threshold η_L^* in the range $36 \text{ m} < d < 250$ m and the higher threshold η_H^* in the range $350 \text{ m} < d < 500$ m. This is reasonable since the optimal thresholds η_L^* and η_H^* in these ranges approach zero and infinity, respectively. We cannot obtain the theoretical values by conducting the simulation with 10^4 trials.

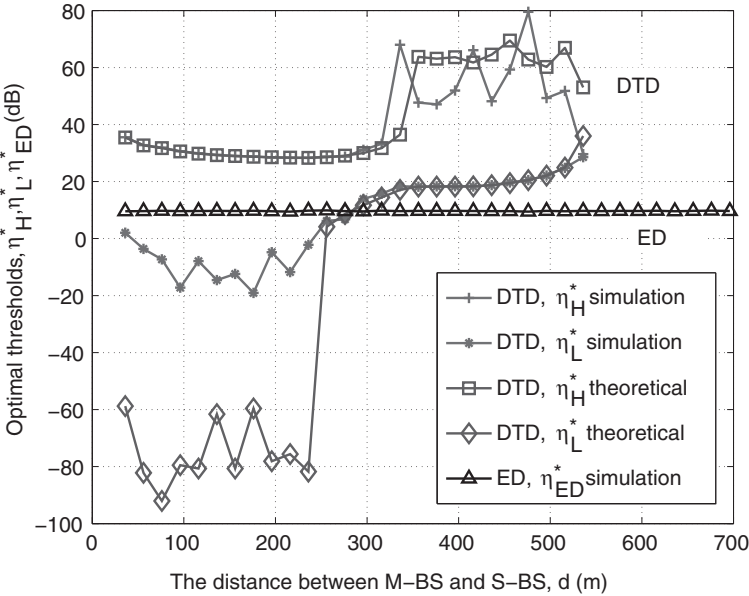


Fig. 2.7 Optimal thresholds of the DTD and the ED

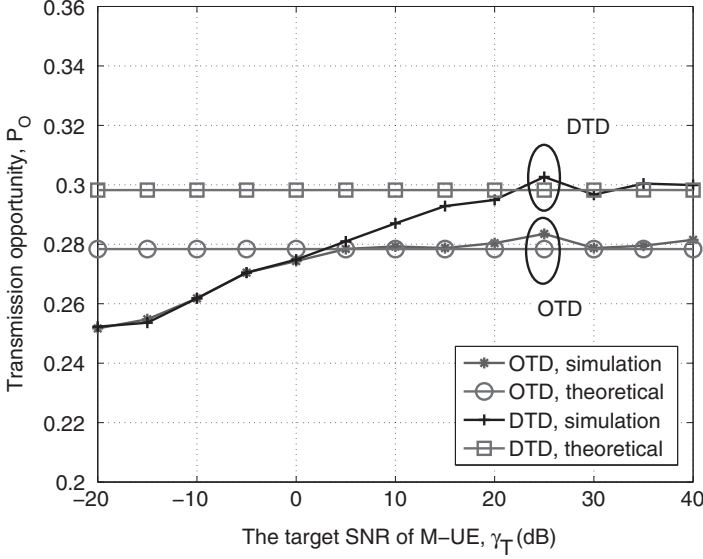


Fig. 2.8 Theoretical and simulation results comparison in the OTD and the DTD

2.5.2 Transmission Opportunities Versus γ_T and r

Figure 2.8 compares the simulation results of the OTD and the DTD with the theoretical ones in terms of the transmission opportunity. Since the largest gap between simulation and theoretical curves in Fig. 2.3 appears at $d \approx 300$ m, we evaluate our theoretical results under the worst case of $d = 300$ m. From the figure, the simulation and theoretical curves of the OTD do not overlap for $\gamma_T < 5$ dB, and these of the DTD do not overlap for $\gamma_T < 15$ dB. The reason is that we omit the noise in our derivation, which is not valid in low SNR regions. Fortunately, such an approximation works well in practice, which covers most target SNR values of the M-UE.

Figures 2.9, 2.10 and 2.11 give the two optimal access probabilities of the OTD with low target SNRs. Here, we only provide the simulation results, since the theoretical results do not match the simulation ones for $\gamma_T < 5$ dB as we have discussed. From the three figures, when $d < 300$ m, $q_1^* = 1$ and $q_2^* = 0$. But when $d > 300$ m, q_1^* and q_2^* become 0 and 1, respectively, as the target SNR γ_T grows from -20 dB to 0 dB. This is reasonable and can be explained by our theoretical analysis in [12], i.e., if γ_T is large, the optimal access probabilities are $q_1^* = 1$ and $q_2^* = 0$ for $d < 300$ m, and $q_1^* = 0$ and $q_2^* = 1$ for $d > 300$ m. In practice, the target SNR of the M-UE is usually larger than 0 dB, i.e., $\gamma_T > 0$ dB, then the optimal access probabilities of the OTD can be either 0 or 1, which is also confirmed by Fig. 2.6. Therefore, the proposed OTD is easy to be implemented in practical systems.

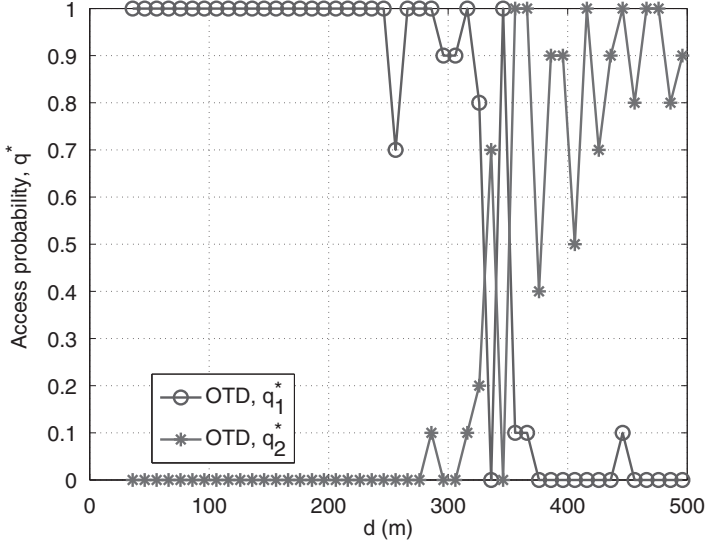


Fig. 2.9 Optimal access probability of the OTD for low target SNR, $\gamma_T = -20$ dB

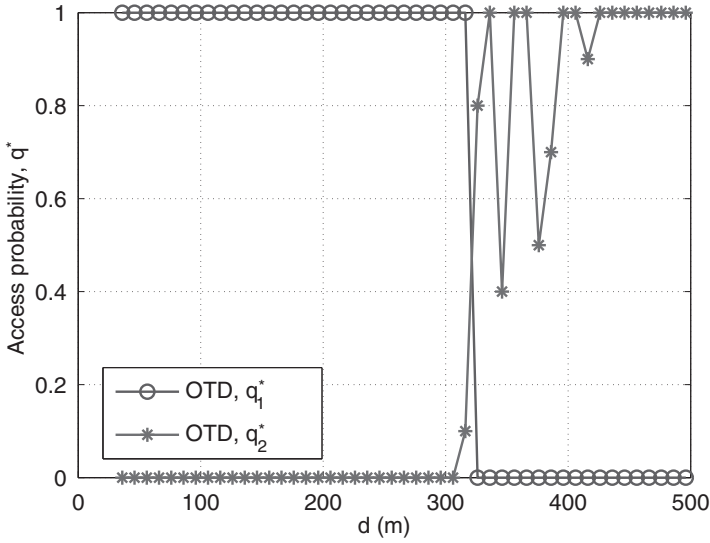


Fig. 2.10 Optimal access probability of the OTD for low target SNR, $\gamma_T = -10$ dB

Figure 2.12 shows the transmission opportunities of the OTD and the DTD for different radii of the small cell, where $\gamma_T = 20$ dB. Here, we only provide the theoretical results for simplicity since the theoretical and simulation results match very well in high target SNR. From the figure, the transmission opportunities of the OTD and the DTD have the same trend for different distances between the S-BS and

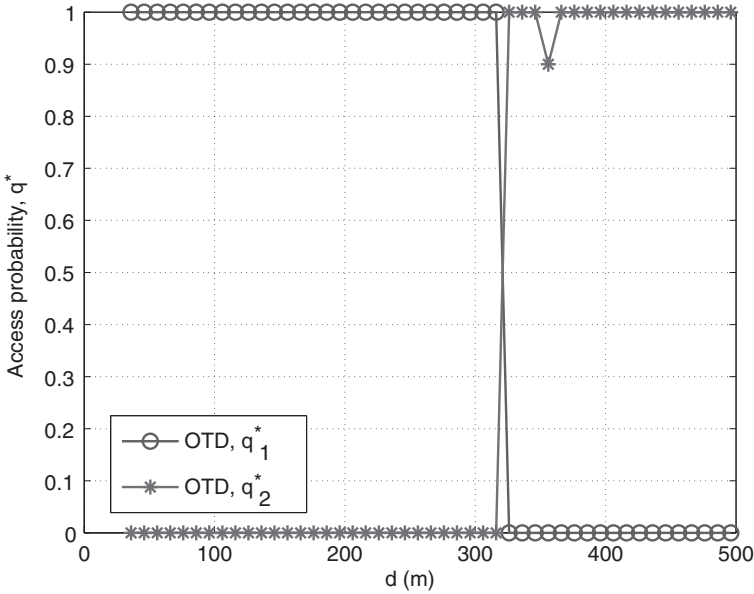


Fig. 2.11 Optimal access probability of the OTD for low target SNRs, $\gamma_r = 0$ dB

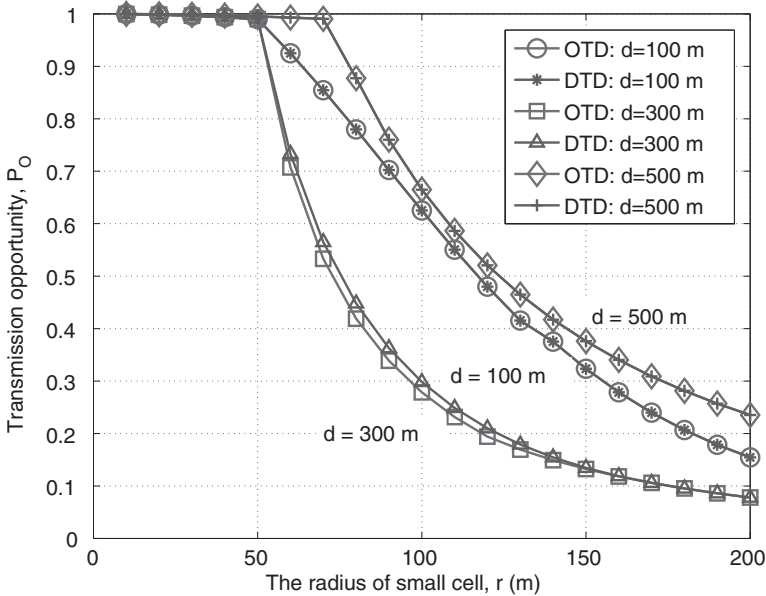


Fig. 2.12 Detection probabilities of the OTD and the DTD versus the radius of small cell

M-BS. Specifically, the transmission opportunity of all curves are equal to 1 for $d < 50$ m and the S-BS may always access the busy band. The reason is that the coverage of the S-BS is so small that the interference to the M-UE can be ignored. But, as the radius r grows, all the transmission opportunities decrease. This is because the large coverage of the S-BS results in high interference probability to the M-UE. To meet the interference probability constraint, the transmission opportunity of the S-BS reduces.

2.5.3 γ_T Unknown to S-BS

In practice, the target SNR of the M-UE varies with different services and may even be unknown to the S-BS. Thus, we assume that the target SNR is uniformly distributed in a reasonable range, e.g., between 5 dB and 20 dB. Then, the CDF of the test statistic in Sect. 2.4 needs to incorporate the distribution of γ_T . Since it is very difficult to obtain the closed-form CDF in this case, we will provide simulation results instead.

Figure 2.13 compares the performance of the OTD, the DTD, and the ED, where γ_T is uniformly distributed between 5 dB and 20 dB. From the figure, the proposed

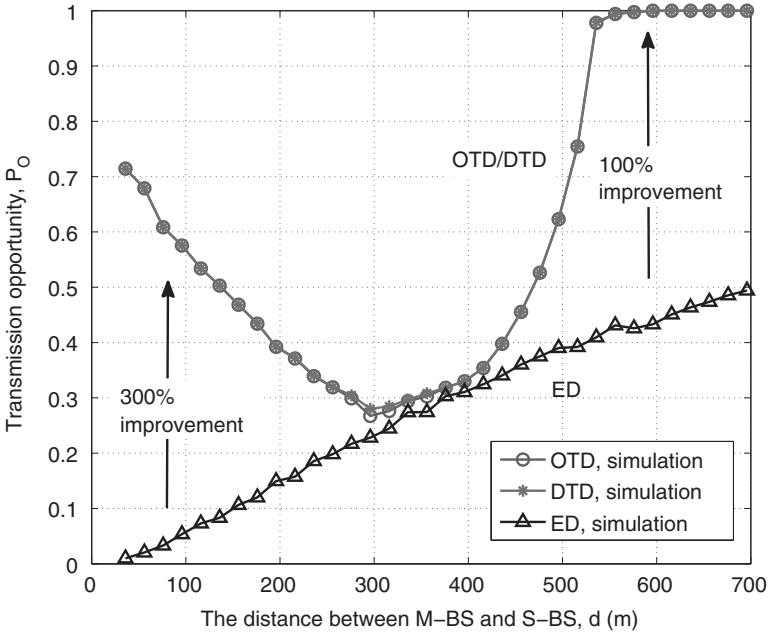


Fig. 2.13 Transmission opportunities of the OTD, the DTD, and the ED (the target SNR of M-UE is unknown to S-BS)

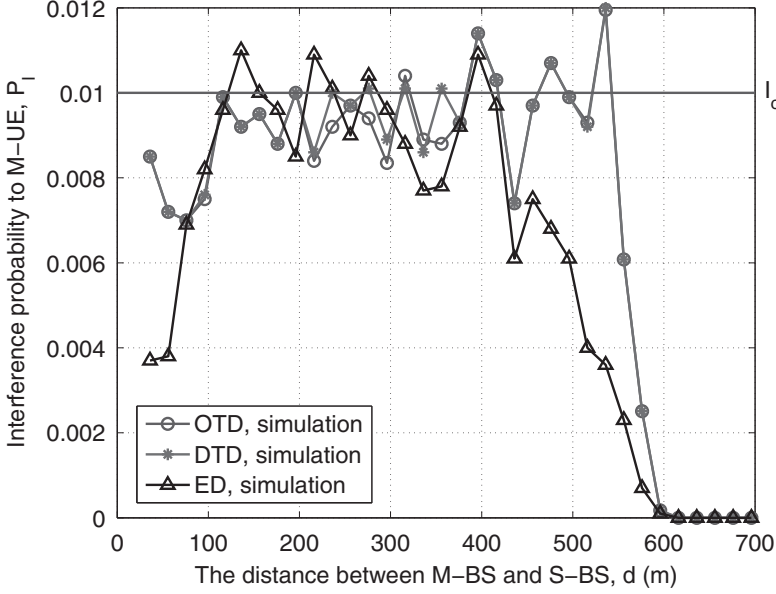


Fig. 2.14 Interference probabilities of the OTD, the DTD, and the ED (the target SNR of M-UE is unknown to S-BS)

the OTD and the DTD obtain almost the same performance. They achieve about 100 % to 300 % more transmission opportunities in average than the conventional ED. Figure 2.14 provides the corresponding interference probabilities of the OTD, the DTD, and the ED. From the figure, the three methods have similar interference to the M-UE, i.e., the interference probabilities are around 0.01 for $d < 500$ m, and approach 0 for $d > 500$ m.

2.5.4 The Case of Shadowing

In this subsection, we provide the performance of the three detectors in the case of shadowing, i.e., path-loss, shadowing, and multi-path fading are all considered. In particular, the shadowing coefficient follows log-normal distribution with the standard variation of 12 dB (We actually provide the worst case performance since the standard variation of shadowing is usually between 4 dB and 12 dB [10]). All simulation parameters except $K = 16$ are the same as those in Figs. 2.13 and 2.14. Here, the reason that the number of samples K is set to 16 is to let the ED has similar interference probability with the OTD and the DTD. This is because the OTD and the DTD are designed under the interference probability constraint. When we consider shadowing, they can automatically adjust the thresholds to reach the preset interference probability $I_c = 0.01$. However, the ED is designed under the

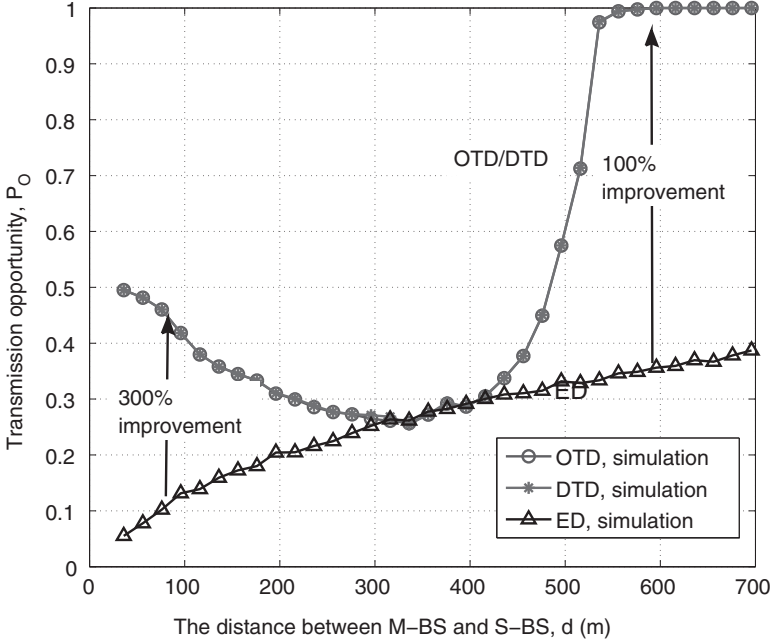


Fig. 2.15 Transmission opportunities of the OTD, the DTD, and the ED in the case of shadowing (the target SNR of M-UE is unknown to S-BS)

false alarm probability. When we consider shadowing, the ED does not change the threshold, which raises the interference probability. Thus, we adjust the number of samples K to raise the threshold and make the ED have similar interference probability with the OTD and the DTD. This allows us to make a comparison of different detectors in terms of the transmission opportunity.

Figure 2.15 provides the transmission opportunities of the three detectors. From the figure, we observe the same trend as in Fig. 2.13, but with only slight performance loss at all detectors. Figure 2.16 shows the corresponding interference probabilities of all three detectors. From the figure, we observe almost the same curves as in Fig. 2.14. Therefore, in the case of shadowing, the proposed OTD and DTD can still achieve about 100 % to 300 % more transmission opportunities in average than the conventional ED.

2.6 Summary

In this chapter, a region-based spectrum sensing method was proposed to enable a cognitive small cell to identify the location of an active user that is being served by a macro cell. Then, the small cell may access the busy band if the active

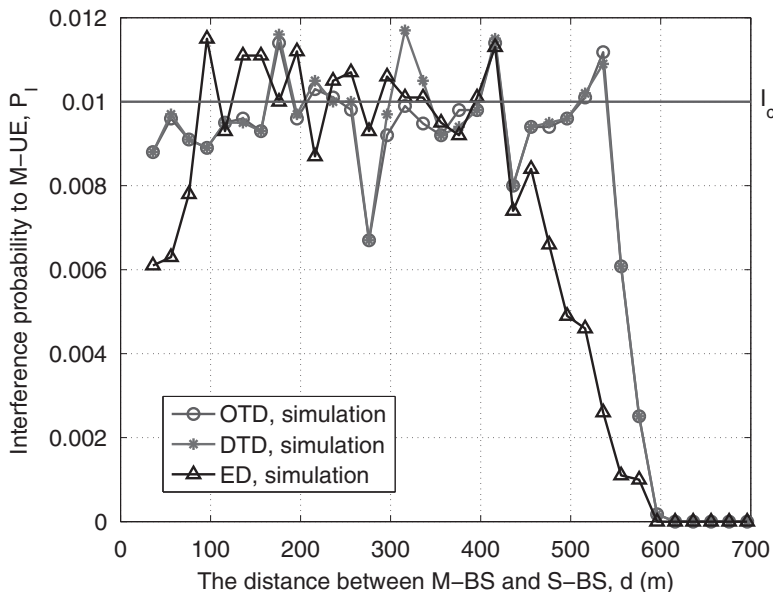


Fig. 2.16 Interference probabilities of the OTD, the DTD, and the ED in the case of shadowing (the target SNR of M-UE is unknown to S-BS)

user is outside the coverage of the small cell, and achieve more transmission opportunities. We suggested that the small cells detect the active user by using the received energy from the macro cell as the test statistic. Then we designed two detectors with one and two thresholds, called OTD and DTD, respectively. Meanwhile, as the conventional energy detector, neither the OTD nor the DTD requires any prior information of the macro cell's signal. Our results indicated that under the same interference probability to the active user, the proposed OTD and DTD achieve about 100 % to 300 % more transmission opportunities in average than the conventional energy detector. This is because our region-based detectors exploit the active user's location information, which is carried by the power of the macro cell's signal for guaranteed services with target SNR requirement. Therefore, the proposed OTD and DTD are suitable for the macro cell with guaranteed services in future wireless communication systems.

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