TRANSMISSION POWER AND CAPACITY OF SECONDARY USERS IN A DYNAMIC SPECTRUM ACCESS NETWORK

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ABSTRACT

In this paper, we analyze the capacity of secondary spectrum access in a broadcasting system consisting of one primary transmitter and multiple primary receivers. At the cost of a small redundancy of the SINR of primary receivers, secondary users can gain a significant capacity when allowed to share the spectrum at the same time with the primary transmitter. The average transmission power and capacity of secondary users are derived, evaluated numerically, and verified by simulating a simple dynamic spectrum access protocol. The results show that the capacity depends on the distance between primary and secondary transmitters as well as the density of primary receivers.

1. INTRODUCTION

On November 2002 the Federal Communications Commission (FCC) published a report [1] for improving the way in which spectrum is managed in the United States. This report states that spectrum access is more of a problem than physical scarcity of the spectrum, mainly because the conventional command-and-control regulations limit the ability of potential spectrum users to obtain such access. Such a report has inspired a rapid increase of research on dynamic spectrum access (DSA).

The idea of DSA has also be investigated in DARPA in the so-called NeXt Generation (XG) program, based on intelligent radios known as cognitive radios (CR) [2]. Similar projects are being conducted in Europe under the name of the DRiVE project [3], which aims to improve the spectrum utilization by analyzing the statistics of spectrum usage in the spatial and temporal domains. All of these projects have the similar objective of utilizing the spectrum more efficiently.

The DSA and CR technologies have both commercial and military applications. An immediate commercial application under developing is the exploitation of some of the less utilized TV spectrum. For military applications the benefits of DSA can be both spectrum efficiency and security. For instance, a subdivision under General Dynamics, the C4 system, has developed a CR called AN/USC-61(c) system for US Navy, which has approximately 750 sub-channels between 2MHz and 2GHz for operation.

In DSA networks, secondary spectrum access can be granted in various ways. One of the ways is for secondary users to utilize the spectrum hole which the primary users do not use during some time period and in some place [4]. This may require an accurate model of the primary users' activity [5]. Another way is to allow the secondary users to utilize the same spectrum at the same time and the same place with the primary users. Obviously, this way may introduce interference to primary users, but can potentially achieve a much higher capacity for secondary users. The secondary transmitters may use an underlay approach for spectrum access, in which they transmit at low enough power so as to guarantee a small enough interference to primary users. An example is the ultra-wideband (UWB) transmission. An alternative approach is overlay, in which secondary transmitters can have larger transmission power. In this case, in order to limit the interference to the primary users, the secondary transmitters either schedule their transmission power so that their interference to primary users is limited to an acceptable level [6], or exploit special coding techniques such as dirty paper coding so that they can use a portion of transmission power to help the primary users while the rest power to transmit their own information [7].

In this paper, we focus on an approach similar to [6] where secondary spectrum access is allowable as long as the interference to primary users is within a certain threshold. This is more practical and may be easier to implement than other approaches considering that most practical primary systems have some redundancy in receiver's signal-to-interference-plus-noise ratio (SINR). For simplification, we consider a broadcast-style transmission from a primary transmitter. Secondary transmitters are allowed to conduct transmission at the same time and the same frequency as the primary transmitter. We then analyze the SINR and derive the secondary transmitters' allowable transmission power as well as capacity. In contrast to [6] that studies fixed users (number and location), we derive the average capacity considering only the density of primary receivers in the network.

The organization of this paper is as follows. In Section 2, we give the system model and outline a simple dynamic spectrum access protocol. Then in Section 3, we analyze the capacity by a geometric method for a single secondary transmitter. Extensions to multiple secondary transmitters are discussed in Section 4. Simulations are conducted in Section 5. Conclusions are then given in Section 6.

2. DSA SYSTEM MODEL

We consider a cellular-like system, where in a cell there is a base station that communicates with multiple mobile users. We denote the base station as primary transmitter T0 and the mobile users as primary receivers. In addition, there are a number of secondary transmitters, which are denoted as T1, T2, etc, and the corresponding secondary receivers. Both the number and the positions of the primary receivers are unknown to the secondary users. As shown in Fig. 1(a), we put the base station T0 in the center of a cell with radius r_0. We let the density of primary receivers be β, which means that on average there are $\pi r_0^2 \beta$ primary receivers.

We consider a slotted transmission protocol with alternating base station transmission slot and primary receivers' transmission slot. For secondary users, we assume that secondary transmitters can only transmit in the base station's transmission slot, i.e., secondary transmitters T1, T2, etc, and the primary transmitter T0 are transmitting at the same time, as shown in Fig. 1 (b). The transmission power of the secondary transmitters should be determined appropriately so that all the primary receivers can still work as if there were no secondary users. In other words, while secondary transmission degrades the primary receivers' SINR, such a degradation should be smaller than certain threshold.

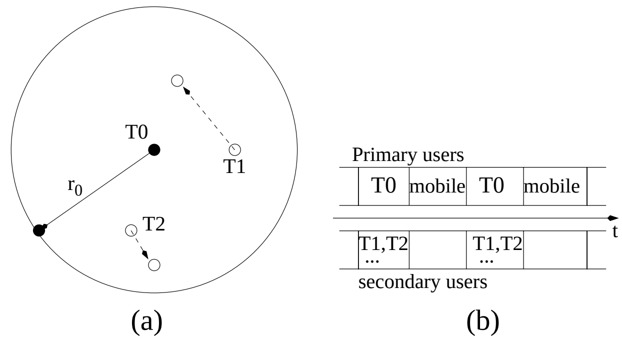


Fig. 1. Secondary spectrum access network. (a) A cell with primary users (base station T0 and its primary receivers), and secondary users (secondary transmitters T1, T2, $\cdots$, and secondary receivers). (b) DSA channel access protocol, where the primary transmitter T0 and the secondary transmitters can transmit at the same slot.

Since the base station T0 may transmit either information targeting a single primary receiver or system management information targeting all the primary receivers, each primary receiver needs to be able to receive reliably any information from the base station. During the primary receivers' transmission slots, mobile users may transmit either information packets or feedback acknowledgement (ACK) packets to T0. The ACK packets indicate primary receivers' SINR, which the secondary users can exploit when determining their transmission power.

As a practice, we assume that the primary system is designed with certain redundancy in SINR, i.e., the worst case SINR of the primary receivers is larger than the minimum required SINR Γ_0 when there is no secondary spectrum access. The redundancy is described by a factor $\Delta\Gamma_0$ as shown below

$$\frac{KP_0 r_0^{-\alpha}}{N} \geq \Gamma_0 + \Delta\Gamma_0, \quad (1)$$

where P_0 is the transmission power of the base station T0, N is the AWGN noise power at the receiver which we assume identical for all the receivers, the parameter α is the path-loss exponent, and K is the constant that includes all other propagation effects such as antenna gains and carrier wavelength. The redundancy $\Delta\Gamma_0$ provides room for secondary spectrum access. In other words, in case of secondary spectrum access, we just need to assure the SINR γ_0 of any primary receiver to satisfy

$$\gamma_0 \geq \Gamma_0. \quad (2)$$

Obviously, the capacity loss due to this extra redundancy is only

$$C_{\text{loss}} = \log_2\left(\frac{1+\Gamma_0+\Delta\Gamma_0}{1+\Gamma_0}\right). \quad (3)$$

A possible practical implementation of this secondary spectrum access scheme is to exploit the acknowledgement information that the primary receivers send to the base station. If there are some primary receivers that can not receive packets successfully due to the increased interference, they send negative ACK (or just do not send positive ACK). The secondary transmitters can thus exploit such information to adjust their transmission power. A simple protocol for the secondary transmitters to adjust their transmission power is outlined below.

Secondary spectrum access protocol

1. Secondary transmitters begin transmission with a very small transmission power.
2. All primary receivers calculate their received SINR, if the SINR is larger than threshold, then send positive ACK. Otherwise, send negative ACK.
3. If secondary transmitters find negative ACK (or rate of negative ACK) increasing, they reduce transmission power by a half. Otherwise, they increase transmission power by a unit step. The procedures (2)-(3) repeats iteratively.

In Section 5, we will simulate this protocol and evaluate the average capacity of the secondary users.

3. CAPACITY OF A SINGLE SECONDARY TRANSMITTER

In this section, we analyze the capacity of secondary spectrum access when there is only a single secondary transmitter T1 in the cell with a primary transmitter T0 and some primary receivers. Let the distance between T0 and T1 be d (meters), and the primary receivers are distributed uniformly with a density β in the cell of radius r_0.

If there are primary receivers that are close to T1, then the transmission power of T1 has to be small. The transmission power as well as the capacity of T1 depend on the position of the primary receivers. We therefore evaluate the expected transmission power and the expected capacity of T1. For this task, let us first consider a special case, i.e., there is no primary receiver within a circle of radius x around T1. We will derive the allowable transmission power for T1 that makes all primary receivers to satisfy the SINR requirement (2).

If the radius of the circle of T1 is small so that $0 \leq x \leq r_0 - d$, as shown in Fig. 2(a), then the probability that there is no primary receiver in the circle of T1 can be modelled as

$$F(x) = \frac{(\pi x^2 \beta)^0}{0!} e^{-\pi x^2 \beta} = e^{-\pi x^2 \beta} \quad (4)$$

with a Poisson distribution assumption of the primary receivers arriving inside the circle. On the other hand, if the radius x is larger so that $r_0 - d < x \leq r_0 + d$, as shown in Fig. 2(b), then the area of the intersection of the circle of T0 and the circle of T1 is

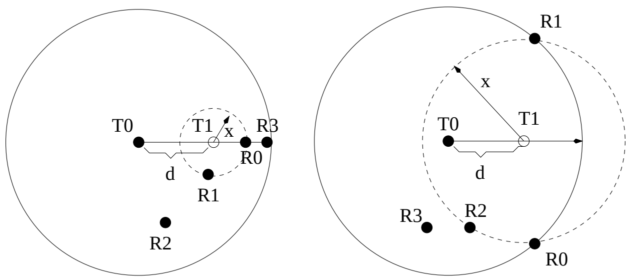
$$A(x) = x^2\eta + r_0^2\phi - 2\sqrt{g(g-r_0)(g-d)(g-x)}, \quad (5)$$

where $g = \frac{r_0+d+x}{2}$, $\eta = \cos^{-1}\left(\frac{d^2+x^2-r_0^2}{2xd}\right)$, $\phi = \cos^{-1}\left(\frac{r_0^2+d^2-x^2}{2r_0 d}\right)$. Note that η and ϕ are described in unit radius. Then similar to (4) the probability that there is no primary receivers in this intersection is

$$F(x) = e^{-A(x)\beta}. \quad (6)$$

This probability becomes 0 for $x \geq r_0 + d$ because the circle of T1 would then include the entire circle of T0.

Therefore, from (4) and (6), the probability that all the primary receivers have at least a distance of x away



(a) (b)

Fig. 2. Circles of primary transmitter T0 and secondary transmitter T1. (a) For $0 \leq x \leq r_0 - d$, primary receiver R0 has the smallest SINR. (b) For $r_0 - d < x \leq r_0 + d$, primary receivers R0 and R1 have the same smallest SINR. Note that all the receivers R0, R1, R2, R3 in this figure refer to primary receivers.

from T1 is

$$F(x) = \begin{cases} e^{-\pi x^2 \beta}, & \text{if } 0 \leq x \leq r_0 - d \\ e^{-A(x)\beta}, & \text{if } r_0 - d < x \leq r_0 - d \\ 0, & \text{otherwise.} \end{cases} \quad (7)$$

Proposition 1. Consider the case that all primary receivers in the circle of T0 are outside of the circle of T1 with radius x. Let the transmission power of T0 and T1 be P_0 and $P_1(x)$, respectively. If the noise power $N \ll KP_1(x)(r_0 + d)^{-\alpha}$, the SINR of the primary receivers satisfy

$$\gamma_0(x) \geq \begin{cases} \frac{KP_0(d+x)^{-\alpha}}{KP_1(x)x^{-\alpha}+N}, & \text{if } 0 \leq x \leq r_0 - d \\ \frac{KP_0 r_0^{-\alpha}}{KP_1(x)x^{-\alpha}+N}, & \text{if } r_0 - d < x \leq r_0 + d. \end{cases} \quad (8)$$

For $0 \leq x \leq r_0 - d$, the equality is achieved by the primary receivers lying in the intersection of the line T0-T1 and the circle of T1. For $r_0 - d < x \leq r_0 + d$, the equality is achieved by the primary receivers lying in the intersections of the circles of T0 and T1.

Proof. We will prove the first part of (8) first by considering the two circles in Fig. 2 (a), where the bigger one is the circle of T0 with radius r_0 while the smaller one is the circle of T1 with radius x. We will show that the primary receiver R0 has the lowest SINR, based on which we can then drive the first equation in (8).

Let us compare R0 with an arbitrary primary receiver R1 on the circle of T1. Since the distance of R0 to T0 is larger than that of R1 to T0, the SINR of R0 is smaller than that of R1. Next, for any other primary receiver R2 within the circle of T0 but out of the circle of T1, if its distance to T0 is the same as a receiver (e.g., R1) on the circle of T1, then its SINR is larger than the latter because its distance to T1 is larger. On the other hand, if its distance is larger or smaller than any receivers on the circle of T1, then it has the same distance to T0 with a receiver on the line of T0-T1, which without loss of generality can be denoted as R3. In this case we can easily see that its SINR is larger than that of R3 because it is farther away from T1.

Then the remaining problem is to show that for all the primary receivers on the line connecting T0 and T1 but outside of the circle of T1, the receiver R0 has the smallest SINR. Without loss of generality, we compare R0 and R3, where the distance from T1 to R3 is $x + \Delta x$. Then the SINR of R0 and R3 are, respectively,

$$\begin{aligned} \gamma_{\text{R0}}(x) &= \frac{KP_0(d+x)^{-\alpha}}{KP_1(x)x^{-\alpha} + N}, \\ \gamma_{\text{R3}}(x+\Delta x) &= \frac{KP_0(d+x+\Delta x)^{-\alpha}}{KP_1(x)(x+\Delta x)^{-\alpha} + N}. \end{aligned}$$

In order to compare $\gamma_{\text{R0}}(x)$ and $\gamma_{\text{R3}}(x + \Delta x)$, we first utilize the assumption that the noise power $N \ll KP_1(x)(x + \Delta x)^{-\alpha}$ so as to be negligible. Then we can remove $N, K, P_0, P_1(x)$, after which the comparison of $\gamma_{\text{R0}}(x) \sim \gamma_{\text{R3}}(x + \Delta x)$ becomes the comparison of

$$\frac{(d+x)^{-\alpha}}{x^{-\alpha}} \sim \frac{(d+x+\Delta x)^{-\alpha}}{(x+\Delta x)^{-\alpha}},$$

which can be simplified to

$$\left(1 + \frac{d}{x}\right)^{-\alpha} \sim \left(1 + \frac{d}{x+\Delta x}\right)^{-\alpha}.$$

Since the left hand side is always less than the right hand side, we have $\gamma_{\text{R0}}(x) < \gamma_{\text{R3}}(x + \Delta x)$.

Therefore, we have shown that the primary receiver R0 has always the smallest SINR, which can be found as the first equation of (8). For the case of $r_0 - d < x \leq r_0 + d$, by referring to Fig. 2(b), we can prove the second equation of (8) similarly. □

From Proposition 1, we see that for a single secondary transmitter T1, we just need to set its transmission power to guarantee R0 to satisfy the required

SINR. Specifically, for $0 \le x \le r_0 - d$, from (8) and (2) we need to satisfy

$$\frac{KP_0(d+x)^{-\alpha}}{KP_1(x)x^{-\alpha}+N} \ge \Gamma_0, \tag{9}$$

which means T1 should have a transmission power

$$P_1(x) \le x^{\alpha}\left[\frac{P_0(d+x)^{-\alpha}}{\Gamma_0} - \frac{N}{K}\right]. \tag{10}$$

Note that $P_1(x)$ is a function of radius x. On the other hand, for $r_0 - d < x \le r_0 + d$, we need to satisfy

$$\frac{KP_0 r_0^{-\alpha}}{KP_1(x)x^{-\alpha}+N} \ge \Gamma_0. \tag{11}$$

Therefore, from (8), the maximum transmission power $P_1(x)$ of T1 is

$$P_1(x) = \begin{cases} x^{\alpha}\left[\frac{P_0(d+x)^{-\alpha}}{\Gamma_0} - \frac{N}{K}\right], & 0 \le x \le r_0 - d \\ x^{\alpha}\left[\frac{P_0 r_0^{-\alpha}}{\Gamma_0} - \frac{N}{K}\right], & r_0 - d < x \le r_0 + d \end{cases} \tag{12}$$

Note that we do not need to consider $x > r_0 + d$ since it does not happen.

The average transmission power of the secondary transmitter T1 can thus be obtained by evaluating the expectation of transmission power $P_1(x)$ over the probability $f(x)$,

$$P_1 = E[P_1(x)] = \int_{r_0+d}^{0} P_1(x)F'(x)dx, \tag{13}$$

where $F'(x) = dF(x)/dx$ is equivalent to a probability density function.

Therefore, if the distance of a secondary transmitter T1 to a primary transmitter T0 is known, then the average transmission power of T1 can be determined from (13). Note the expectation is conducted by considering all possible primary receiver locations.

With either (12) or (13), we can analyze the SINR of the secondary receivers and the associated transmission capacity. Consider a secondary receiver Rx inside the circle of T0 that has a position (r, θ), where $r \in [0, r_0]$ denotes the distance between T0 and Rx, and $\theta \in [0, 2\pi)$ denotes the angle, as shown in Fig. 3.

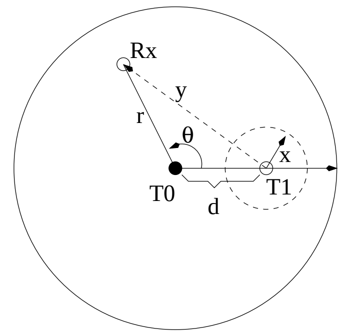


Fig. 3. SINR analysis for the secondary receiver Rx with a position (r, θ).

The distance between the secondary transmitter T1 and the secondary receiver Rx is

$$y = \sqrt{r^2 + d^2 - 2rd\cos\theta} \tag{14}$$

Therefore, with the transmission power $P_1(x)$ in (12), the SINR of Rx is

$$\gamma_1(x, r, \theta) = \frac{KP_1(x)y^{-\alpha}}{KP_0 r^{-\alpha} + N}. \tag{15}$$

The capacity of this transmission is thus

$$C(x, r, \theta) = \log_2\left[1 + \gamma_1(x, r, \theta)\right]. \tag{16}$$

The average capacity for this secondary transmission pair is thus

$$C(r, \theta) = E[C(x, r, \theta)] = \int_{r_0+d}^{0} C(x, r, \theta)F'(x)dx. \tag{17}$$

Due to the complexity of the expressions (13) and (17), we have to resort to numerical evaluation to analyze P_1 or $C(r, \theta)$, which is shown in Section 5.

Instead of calculating the capacity for a fixed secondary receiver, we can also derive the range of the capacity over all possible locations of the secondary receiver. Again this can be conducted by using either $P_1(x)$ in (12) or P_1 in (13). We consider the latter for simplicity.

Proposition 2. If the transmission power of primary and secondary transmitters be P_0 and P_1, respectively. For secondary transmission distance y (i.e., the distance between Rx and T1), the secondary receiver's SINR $\gamma_1(y)$ is within the range

$$\frac{KP_1 y^{-\alpha}}{KP_0|d-y|^{-\alpha} + N} \le \gamma_1(y) \le \frac{KP_1 y^{-\alpha}}{KP_0 z^{-\alpha} + N}, \tag{18}$$

where $z = \min\{d + y, r_0\}$. The corresponding transmission capacity $C_1(y)$ is thus

$$\log_2 \left[1 + \frac{KP_1 y^{-\alpha}}{KP_0 |d-y|^{-\alpha} + N}\right] \le C_1(y) \le \log_2 \left[1 + \frac{KP_1 y^{-\alpha}}{KP_0 z^{-\alpha} + N}\right]. \qquad (19)$$

Proof. Let us borrow Fig. 3, but redefine the circle of T1 as the circle that the secondary receiver lies on, which means a secondary transmission distance x. For all secondary receivers that have the same distance x to T1, we can readily see that if $0 \le x \le r_0 - d$, then the secondary receiver with distance $d + x$ to T0 has the highest SINR, while the one with distance $d - x$ to T0 has the lowest SINR. Note that these two receivers are in the intersections of the line T0-T1 and the circle of T1. The SINR $\gamma_1(x)$ in this case is within the range

$$\frac{KP_1 x^{-\alpha}}{KP_0 (d-x)^{-\alpha} + N} \le \gamma_1(x) \le \frac{KP_1 x^{-\alpha}}{KP_0 (d+x)^{-\alpha} + N}.$$

Similarly, if we consider the other case $r_0 - d < x \le r_0 + d$, then the secondary receiver with the highest SINR has a distance of r_0 to T0, while the one with the smallest SINR has a distance of $|x - d|$ to T0. The expressions (18) and (19) are thus available. □

From (18) and (19), we can see that the worst case capacity of secondary transmissions can be very small if the secondary receiver is closer to T0 than T1. On the other hand, when the secondary receiver is closer to T1 than T0, especially when the secondary transmission distance y is small, the capacity can be very large, much larger than the capacity loss C_{loss} defined in (3). This justifies the gain of secondary spectrum access.

4. CAPACITY OF MULTIPLE SECONDARY TRANSMITTERS

When there are multiple secondary transmitters, the optimal transmission power and capacity of each secondary transmitter are difficult to analyze. One of the simple but suboptimal ways is to let each secondary transmitter utilize an equal portion of the overall capacity. Note that this may be justified by the fact that each secondary transmitter may not know other secondary transmitters.

Let a maximum of M secondary transmitters be allowed to access the same spectrum simultaneous. We need to make sure that the primary receivers' SINR satisfy

$$\frac{KP_0 b_0^{-\alpha}}{K \sum_{i=1}^{M} P_i b_i^{-\alpha} + N} \ge \Gamma_0, \qquad (20)$$

where b_i are the distances of a primary receiver to the transmitters. Therefore the transmission power needs to satisfy

$$\sum_{i=1}^{M} P_i b_i^{-\alpha} \le \frac{P_0 b^{-\alpha}}{\Gamma_0} - \frac{N}{K} \triangleq Q_b. \qquad (21)$$

Since Q_b can be looked as the interference created by the M secondary transmitters, as a simplification, we let each transmitter create only $1/M$ of the interference. Therefore, we consider

$$P_i b_i^{-\alpha} \le \frac{Q_b}{M} \qquad (22)$$

for each secondary transmitter.

Based on such approximation, the technique used in Section 3 can be applied to determine the transmission power and capacity of each secondary transmitter. Specifically, the transmission power of the i^{th} secondary transmitter, $i = 1, \cdots, M$, as a function of x becomes similar to (10)-(12),

$$P_i(x) = \begin{cases} \frac{x^\alpha}{M}\left[\frac{P_0(d_i+x)^{-\alpha}}{\Gamma_0} - \frac{N}{K}\right], & 0 \le x \le r_0 - d_i \\ \frac{x^\alpha}{M}\left[\frac{P_0 r_0^{-\alpha}}{\Gamma_0} - \frac{N}{K}\right], & r_0 - d_i < x \le r_0 + d_i \end{cases} \qquad (23)$$

where d_i is the distance between T0 and the i^{th} secondary transmitter. The average transmission power is thus

$$P_i = \int_{r_0+d_i}^{0} P_i(x) F'(x) dx. \qquad (24)$$

Then, considering the secondary receivers, the SINR and the associated capacity can be calculated in a similar manner as Section 3.

As an alternative but more complex approach, we can take (21) as a constraint and maximize the total transmission power

$$\begin{array}{ll} \max & \sum_i P_i \\ \text{s.t.} & \sum_i P_i b_i^{-\alpha} \le Q_b. \end{array} \qquad (25)$$

Furthermore, if all the primary and secondary users are known, then the optimization (25) can be adapted toward optimizing the total secondary capacity instead of the total transmission power.

5. SIMULATIONS

In this section, we evaluate by Monte Carlo simulations the capacity of secondary users according to Section 3, and implement the simulation of the protocol in Section 2. The former gives us the average capacity ideally, whereas the latter gives us capacity achievable in a simple protocol.

We assume the transmission power of T0 be 100 watts, the AWGN noise power be $N = 5 \times 10^{-10}$ watts. The gains of the transmission antenna and the receiving antenna are all 1. Thus, we have effective primary transmission range $r_0 \approx 1000$ meters. We set the path loss exponent as $\alpha = 3$ to simulate an urban cellular radio environment.

For the simulation of the protocol in Section 2, we generated primary receivers at random positions with random moving speeds. We placed one secondary receiver with a distance of 50 meters from T1. $\Gamma_0 = 20$ dB is the primary receiver's threshold SINR. The power P_1 was initialized to be small. After the simulation, we calculated the average power and used it to calculate the capacity.

The results are shown in Fig. 4, from which we can see that secondary spectrum access can provide a significant capacity, especially when the density of the primary receivers is small enough. The simple protocol in Section 2 can also give significant capacity, although not as large as predicted by theoretical analysis. Capacity increases when the density β decreases, or when the distance d increases. Especially, when d increases, although the transmission power P_1 decreases, the capacity still increases because the secondary receiver's SINR increases.

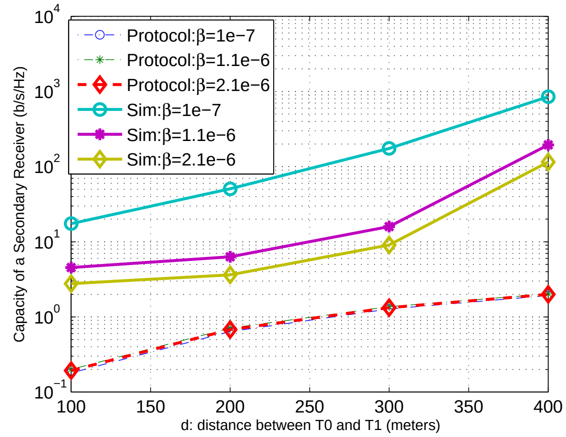


Fig. 4. Monte Carlo simulation results of the capacity of secondary spectrum access.

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