JAMMING PROBABILITIES AND THROUGHPUT OF COGNITIVE RADIO COMMUNICATIONS AGAINST A WIDEBAND JAMMER

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ABSTRACT

In this paper we give closed-form analysis results of the jamming probabilities and throughput of cognitive radio transmissions when facing a wideband jammer. We first set up a Markov model of the cognitive radio transmissions which consists of three states: spectrum sensing, channel access, and channel switching. The jamming probabilities of the three states are derived under the assumption of a wideband jammer. The normalized transmission throughput is then derived. This expression is simple enough for us to analyze and optimize some important jamming and anti-jamming parameters for optimal anti-jamming design. Simulations are conducted to verify the analysis results.

Key words: cognitive radio, dynamic spectrum access, jamming, throughput, Markov model

1. INTRODUCTION

Cognitive radio technology provides a flexible radio platform for enhancing the radio transmission performance and for enhancing the spectrum utilization. Some people have focused specifically on the cognitive function of this technique to develop radios that can learn from the environment and thus behave accordingly, which provides another level of adaptivity. On the other hand, many other people have focused on this technology's potential of resolving the critical spectrum shortage problem [1] since cognitive radios can be developed to find and exploit the spectrum white space, i.e., the spectrum resource that is not being used by the primary users. This type of secondary spectrum access is called dynamic spectrum access (DSA). There are many practical systems in developing, such as the IEEE 802.22 devices working in the TV bands [2].

In DSA systems, secondary users have to guarantee no interference to any primary user (PU) who is using this spectrum at this time in this location [2] [3]. Therefore, in a typical setting, the cognitive radios have to periodically sense the spectrum to detect whether the spectrum is white. They have to vacate the channel immediately even when extremely weak PU signal is detected. This unique feature of cognitive radio makes the DSA system quite different from the conventional wireless communication systems. DSA systems have many unique properties that need careful investigation.

We have been focusing on studying the anti-jamming performance of cognitive radio transmissions [4] [5] because the anti-jamming capability of cognitive radios are extremely different from that of conventional radios. While cognitive radios may enjoy better anti-jamming capability because of their flexible physical- and MAC-layer functions, our study shows that they are in fact more susceptible to jamming attacks. This is primarily because of the requirement of vacating channel upon a negative spectrum sensing result, which provides the jammers a low-cost and easy way of conducting jamming. A jammer can drastically increase its jamming capability by using extremely low power signals to jam multiple channels at the same time. The conventional PHY-layer anti-jamming techniques such as spreading may not be effective in dealing with this kind of jamming attacks. The upper-layer anti-jamming techniques such as channel hopping and switching may be too costly. Channel switching among cognitive radios is time-consuming since the spectrum white space channels are time-varying and need to be detected in real time.

In our recent study [5], we have conducted a joint PHY- and MAC-layer study of the anti-jamming performance of cognitive radios. With a Markov model of the cognitive radio functions, we have derived the throughput expression of cognitive radios in face of multiple jammers. Unfortunately, the expressions are mathematically too complex to do any further analysis and system optimization except simulations.

In this paper, we will conduct an analytical study of the jamming probabilities and throughput, and then investigate and optimize some important parameters that are critical for anti-jamming design. For this purpose, we will first simplify our model and the throughput expression into a form that is suitable for further analysis. Then, we will optimize

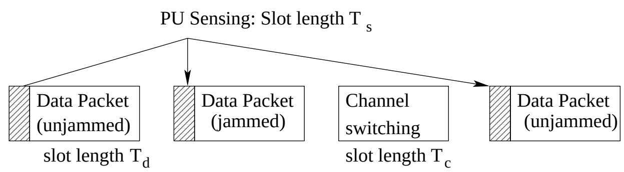

Fig. 1. Illustration of cognitive radio transmissions.

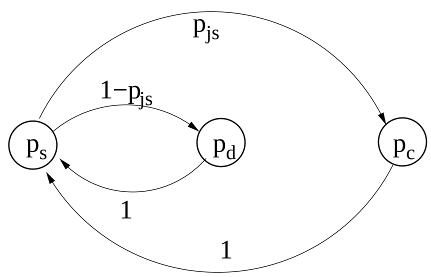

Fig. 2. Markov model for cognitive radio transmission under various jamming probabilities.

the throughput expressions over some important system parameters.

The organization of this paper is as follows. In Section 2, we give the models of the cognitive radio transmission and the jammer. Then in Section 3, we drive the throughput and conduct an analytical study. Simulations are conducted in Section 4. Conclusions are then given in Section 5.

2. COGNITIVE RADIO TRANSMISSION MODEL AND JAMMER MODEL

We consider a simplified cognitive radio transmission model that includes three states: spectrum sensing, data transmission and channel switching, as shown in Fig. 1. The working sequence of a cognitive radio always begins with the spectrum sensing. If the spectrum sensing indicates the channel is available for secondary access, then the cognitive radio transmits a data packet: the model shifts into the data transmission state. If the spectrum sensing indicates the channel is not available (due to either primary user activity or jamming activity), the cognitive radio will conduct channel switching: the model then shifts into the channel switching state. In order to simplify the analysis, we assume that the channel switching is always successful. For data transmission, whether it is being jammed or not, the model always shifts back to the spectrum sensing state. We can use the Markov model in Fig. 2 to model this system.

Let the durations of spectrum sensing slot, data transmission slot, and channel switching slot be T_s, T_d, and T_c, respectively. Usually the spectrum sensing duration T_s is much smaller than both T_d and T_c for high throughput.

We use signal-to-noise-and-interference ratio (SINR) to measure the signal and jamming levels. For the data transmission slot, we assume that the minimum workable SINR is Γ_d. An SINR less than Γ_d means being jammed. For the spectrum sensing slot, we assume that if the SINR is larger than the detection threshold Γ_s, then the cognitive radio will make a decision that the channel is occupied by primary users, and thus not available. We assume that the cognitive radios can not determine whether the signal comes from primary users or jammers. Obviously, Γ_d is usually much larger than Γ_s. For example, a typical Γ_d might be $10 \sim 20$ dB, while a typical Γ_s might be -10dB.

In Fig. 2, we use p_s, p_d and p_c to describe the probabilities of the cognitive radios staying in the spectrum sensing, data transmission and channel switching states, respectively. In addition, p_{js} and p_{jd} are the probabilities that the spectrum sensing and the data transmission are jammed, respectively.

In this paper, we consider a single jammer for simplicity. We assume that the jammer has the same capabilities as a cognitive radio, including spectrum sensing and RF transceiving. The jammer does not know the secret keys the cognitive radios are using for channel selection and communication. Therefore, it does not know the channel used by the cognitive radios, and thus the only way left for the jammer is to randomly select channels to jam. We do not consider the capability that the jammer can smartly detect which channel the cognitive radios are using by observing the activity of each channel.

The jammer model used in this paper is somewhat different from that in [5]. Instead of assuming that the jammer fastly switches channels and uses short jamming pulses, we assume a wideband jammer that can adjust the number of channels it jams simultaneously. The jamming pulse duration is fixed to be T_j that satisfies

$$T_j \geq T_d > T_s. \tag{1}$$

We assume that the jammer's total jamming power be P_J, whereas the cognitive radio's transmission power is P_s. Then the actual jamming power sent to each channel is

$$P_k = \frac{P_J}{k}, \tag{2}$$

if the jammer chooses k channels to jam simultaneously. We assume the maximum number of channels (i.e, the maximum transmission bandwidth) of the jammer be K_J. Then

$$0 \leq k \leq K_J. \tag{3}$$

Conventionally, jamming is successful only if the SINR of the receiver is less than threshold Γ_d. In cognitive radio case, however, jamming may be more easily deployed and more effective by jamming the spectrum sensing slot [5]. As long as the jamming signal emitted to the spectrum sensing slot makes the SINR larger than the sensing threshold Γ_s, the cognitive radios must vacate the channel and take the time-consuming channel switching procedure to negotiate a new one.

As the anti-jamming performance metric, we consider the average throughput R of the cognitive radio transmissions, which can be calculated from the probabilities of the three states in Fig. 2 and the corresponding slot lengths. Note that only the data transmission state with successful (unjammed) data transmission is counted toward the average throughput.

3. JAMMING PROBABILITIES AND THROUGHPUT ANALYSIS

3.1. Jamming probabilities

Consider a cognitive radio communication system, where a pair of cognitive radio transmitter and receiver is conducting transmission at unit throughput. A jammer with the similar channel sensing and transmission capability as a cognitive radio wants to jam the cognitive radio transmissions.

First, we consider the data transmission slot, which has slot length T_d and receiving SINR threshold Γ_d. Because the jamming duration $T_j \geq T_d$, we assume this full slot is either being jammed or free of jamming signal. Therefore, if there is a jamming signal, the cognitive radio's received signal's SINR can be described as

$$\gamma_d = \frac{P_s \alpha_s^2}{P_k \alpha_j^2 + N} \tag{4}$$

where α_s^2 is the Rayleigh flat fading channel (power) coefficient of the cognitive radio, α_j^2 is the Rayleigh flat fading channel (power) coefficient of the jamming signal, N is the power of the additive white Gaussian noise (AWGN). We assume that the channel power coefficients α_s^2, α_j^2 are independent exponential random variables with unit mean. If there is no jamming signal, the SINR is

$$\gamma_d' = \frac{P_s \alpha_s^2}{N}. \tag{5}$$

Assume there are M white space channels available for secondary spectrum access. If the jammer randomly selects a block of k channels to jam, then it has probability k/M of sending a jamming signal to the channel being used by the cognitive radios, and has probability $1-k/M$ of not sending jamming signal to the right channel. Therefore, the probability that the data transmission is jammed can be written as

$$p_{jd} = P[\gamma_d < \Gamma_d] \frac{k}{M} + P[\gamma_d' < \Gamma_d] \left(1 - \frac{k}{M}\right). \tag{6}$$

Note that the transmission outage caused by Rayleigh fading is also counted in the jamming probability.

Proposition 1. Assume independent Rayleigh flat fading channels. The probability that the data transmission is jammed is

$$p_{jd} = 1 - e^{-\frac{N\Gamma_d}{P_s}} \left(1 + \frac{P_J \Gamma_d}{M(P_s + P_k \Gamma_d)}\right). \tag{7}$$

Proof. From (4), we can derive

$$P[\gamma_d < \Gamma_d] = P[P_s \alpha_s^2 - P_k \Gamma_d \alpha_j^2 < N\Gamma_d]. \tag{8}$$

Since α_s^2 and α_j^2 are two independent exponential random variables with unit mean, their joint distribution can be written as

$$f(x, y) = f_{\alpha_s^2}(x) f_{\alpha_j^2}(y) = e^{-x} e^{-y}, \quad \text{for } x \geq 0, y \geq 0. \tag{9}$$

Then the probability (8) can be directly evaluated as

$$\begin{aligned} P[\gamma_d < \Gamma_d] &= \int_0^\infty e^{-y}\, dy \int_0^{\frac{N\Gamma_d}{P_s} + \frac{P_k \Gamma_d}{P_s} y} e^{-x}\, dx \\ &= \int_0^\infty e^{-y} \left[1 - e^{-\frac{N\Gamma_d}{P_s}} e^{-\frac{P_k\Gamma_d}{P_s} y}\right] dy \\ &= 1 - e^{-\frac{N\Gamma_d}{P_s}} \frac{P_s}{P_s + P_k \Gamma_d}. \end{aligned} \tag{10}$$

It is easy to see that

$$P[\gamma_d' < \Gamma_d] = 1 - e^{-N\Gamma_d / P_s}. \tag{11}$$

Substituting (10) and (11) into (6), using (2)-(3), after some straightforward deductions, we can get (7). □

The SINR and the jamming probability of the spectrum sensing slot are different than those in data transmission slot. The SINR in this case is in fact the interference (or jamming) to noise ratio γ_s. Since the cognitive radios must be extremely sensitive in order to detect even weak primary user signals, we use an extremely small threshold Γ_s, and $\gamma_s \geq \Gamma_s$ means that either there is primary user activity or the jammer successfully disguises primary users to prevent the cognitive radios to use this channel. In our sense, this means that the spectrum sensing slot is jammed.

Since the jamming signal duration $T_j > T_s$, we can assume that the jamming signal either occupy the entire sensing slot, or the sensing slot is free of jamming signal. In case of absence of primary user, when there is jamming signal in this sensing slot, then we have SINR

$$\gamma_s = \frac{P_k \alpha_j^2}{N}. \tag{12}$$

Otherwise, if there is no jamming signal in this sensing slot, then the SINR becomes simply $1/N$. Obviously, we must have $1/N < \Gamma_s$. Therefore, for jamming probability, we just need to consider (12). The probability of having jamming signal in this sensing slot is similarly k/M when the jammer selects k channels to jam simultaneously. The probability that the sensing slot is jammed can then be defined as

$$p_{js} = P[\gamma_s \geq \Gamma_s]\frac{k}{M}. \tag{13}$$

Proposition 3. The probability that a channel sensing slot is jammed is

$$p_{js} = \frac{P_J}{MP_k} e^{-\frac{N\Gamma_s}{P_k}}. \tag{14}$$

Proof. From equation (12) we can derive

$$P[\gamma_s \geq \Gamma_s] = P\left[\alpha_j^2 \geq \frac{N\Gamma_s}{P_k}\right] = e^{-\frac{N\Gamma_s}{P_k}}. \tag{15}$$

Considering (2), we can obtained (14). □

3.2. Average throughput

The jamming probability p_{js} in (14) defines the transitional probability in the Markov model in Fig. 2. According to the steady state property of the Markov model, we can calculate the probabilities of the three states p_s, p_d and p_c by solving the following equation

$$\begin{bmatrix} -1 & 1 & 1 \\ 1-p_{js} & -1 & 0 \\ p_{js} & 0 & -1 \end{bmatrix} \begin{bmatrix} p_s \\ p_d \\ p_c \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix}. \tag{16}$$

Although this equation has infinitely many solutions, it can give us a way to represent p_d and p_c by p_s, i.e.,

$$p_d = (1-p_{js})p_s, \;\; p_c = p_{js}p_s. \tag{17}$$

With the state probabilities, we can define the normalized average throughput of the cognitive radio transmission as

$$R = \frac{p_d(1-p_{jd})T_d}{p_sT_s + p_dT_d + p_cT_c}. \tag{18}$$

From the normalized average throughput definition (18) and the Markov model stead-state equation (17), the throughput under wideband jamming signal P_k is

$$R = \frac{(1-p_{js})(1-p_{jd})T_d}{T_s + (1-p_{js})T_d + p_{js}T_c}. \tag{19}$$

To simplify notation, we let $T_c = T_d$. Then (19) can be changed to

$$R = \frac{e^{-\frac{N\Gamma_d}{P_s}}}{1+\frac{T_s}{T_d}}\left(1 + \frac{\Gamma_d P_J}{MP_s + MP_k\Gamma_d}\right)\left(1 - e^{-\frac{N\Gamma_s}{P_k}}\frac{P_J}{MP_k}\right). \tag{20}$$

3.3. Anti-jamming capability analysis

For the wideband jammer, the major parameter for adjusting jamming attack strength is the jamming signal's bandwidth, which specifically refers to the number of channels $k = P_J/P_k$ that can be jammed at the same time. In contrast, one of the major parameters for the cognitive radio to adjust its anti-jamming capability is the number of white space channels M.

If considering just P_k and M, the optimal anti-jamming design of cognitive radios can be casted into the following max-min optimization

$$\max_{M>0} \min_{0 \leq P_k \leq P_J} R \tag{21}$$

The inside $\min$ operation refers to the jammer's strategy to reduce throughput, while the outside $\max$ operation refers to the cognitive radio's strategy to increase throughput.

First, we analyze the jammer's strategy to reduce throughput. We can define an optimization parameter

$$y = \frac{P_k}{P_J} = \frac{1}{k}, \tag{22}$$

and rewrite the throughput (20) as $R(y)$ where

$$R(y) = \frac{e^{-\frac{N\Gamma_d}{P_s}}}{1+\frac{T_s}{T_d}}\left(1 + \frac{\Gamma_d/M}{\frac{P_s}{P_J} + y\Gamma_d}\right)\left(1 - e^{-\frac{N\Gamma_s}{P_J y}}\frac{1}{My}\right). \tag{23}$$

Note that the practical range of y is $1/K_J \leq y \leq 1$. For the convenience of analysis, we assume a continuous y within $[0, \quad 1]$ for the moment. If y is extremely small, such as in the neighborhood of zero, then the item $e^{-\frac{N\Gamma_s}{P_J y}}\frac{1}{My} \approx 0$ can be omitted from $R(y)$. In this case, the derivative

$$\frac{\partial R(y)}{\partial y} \approx -\frac{e^{-\frac{N\Gamma_d}{P_s}}}{1+\frac{T_s}{T_d}}\frac{\Gamma_d^2}{M(P_s/P_J + \Gamma_d y)^2} < 0, \tag{24}$$

which means $R(y)$ is a monotone decreasing function of y when y is extremely small. On the other hand, for other y ranges, because $N\Gamma_s/P_J$ is usually a very small number, we can assume $e^{-N\Gamma_s/(P_J y)} \approx 0$. In this case, we have

$$R(y) \approx \frac{e^{-\frac{N\Gamma_d}{P_s}}}{1+\frac{T_s}{T_d}}\left(1 + \frac{\Gamma_d/M}{\frac{P_s}{P_J} + y\Gamma_d}\right)\left(1 - \frac{1}{My}\right). \tag{25}$$

By taking the derivative of (25) with respect to y, we can easily find that

$$\frac{\partial R(y)}{\partial y} \approx \frac{e^{-\frac{N\Gamma_d}{P_s}}}{1+\frac{T_s}{T_d}}\frac{1}{M}\left(\frac{1}{P_s/(P_J\Gamma_d) + y} + \frac{1}{y}\right) > 0, \tag{26}$$

which means that the throughput $R(y)$ becomes a monotone increasing function for relatively large y. Therefore, the minimum $R(y)$ should happen with some extremely small y values, whereas the maximum throughput happens either when $y = 1$ or $y = 0$. The former means that the jammer just jams one channel at a time, while the latter means there is no jamming signal. Since we are more interested in the jamming case, so the maximum throughput can be written as

$$R_{\max} = \frac{e^{-\frac{N\Gamma_d}{P_s}}}{1+\frac{T_s}{T_d}} \left(1 + \frac{\Gamma_d/M}{\frac{P_s}{P_J} + \Gamma_d}\right) \left(1 - e^{-\frac{N\Gamma_s}{P_J}} \frac{1}{M}\right). \tag{27}$$

The optimal jamming parameter for the minimum throughput is shown below.

Proposition 3. The jammer can use the (approximately) optimal jamming parameter

$$y_o = \max\left\{\frac{1}{K_J},\ \frac{N\Gamma_s}{P_J}\right\} \tag{28}$$

for the minimum throughput

$$R_{\min} = \frac{e^{-\frac{N\Gamma_d}{P_s}}}{1+\frac{T_s}{T_d}} \left(1 + \frac{\Gamma_d/M}{\frac{P_s}{P_J} + y_o\Gamma_d}\right) \left(1 - e^{-\frac{N\Gamma_s}{P_J y_o}} \frac{1}{My_o}\right). \tag{29}$$

Proof. From (23) we can take the derivative $\partial R(y)/\partial y$ and let it be zero to find the optimal y. After some straightforward deductions we have

$$\left(1 - \frac{1}{My}e^{-\frac{N\Gamma_s}{P_J y}}\right) \frac{\Gamma_d^2}{M(P_s/P_J + \Gamma_d y)^2} - \left(1 + \frac{\Gamma_d/M}{P_s/P_J + \Gamma_d y}\right) e^{-\frac{N\Gamma_s}{P_J y}} \frac{1}{My^2} \left(1 - \frac{N\Gamma_s}{P_J y}\right) = 0 \tag{30}$$

Unfortunately, (30) is too complex to find a closed-form solution to y. Therefore, as an approximation, we can consider the major items in (30). Because the minimum $R(y)$ happens when y is extremely small, we can consider only those items in (30) involving $O(y^{-2})$ and $O(y^{-3})$. Then (30) can be approximately simplified to

$$\left(1 + \frac{\Gamma_d/M}{P_s/P_J + \Gamma_d y}\right) e^{-\frac{N\Gamma_s}{P_J y}} \frac{1}{My^2} \left(1 - \frac{N\Gamma_s}{P_J y}\right) = 0 \tag{31}$$

which directly gives solution

$$y = \frac{N\Gamma_s}{P_J}. \tag{32}$$

Because the value in (32) may be too small, considering the practical limit of the wideband jammer K_J in (3) and the monotone increasing property of $R(y)$ for not extremely small y, we can derive (28). The throughput equation (29) can be directly obtained by applying y_o into (23). □

If the M and the jamming bandwidth are large enough so that $y_o = N\Gamma_s/P_J$, then the minimum throughput becomes

$$\begin{aligned} R_{\min} &= \frac{e^{-\frac{N\Gamma_d}{P_s}}}{1+\frac{T_s}{T_d}} \left(1 + \frac{P_J/M}{P_J\Gamma_d + N\Gamma_s}\right) \left(1 - \frac{e^{-1}P_J}{MN\Gamma_s}\right) \\ &\leq \frac{e^{-\frac{N\Gamma_d}{P_s}}}{1+\frac{T_s}{T_d}} \left(1 - \frac{P_J^2}{M^2N^2\Gamma_s^2}\right). \end{aligned} \tag{33}$$

On the other hand, if M is relatively small so the jammer can jam all the channels with $y = 1/M$, then the throughput becomes

$$R_{\min} = \frac{e^{-\frac{N\Gamma_d}{P_s}}}{1+\frac{T_s}{T_d}} \left(1 + \frac{\Gamma_d}{M\frac{P_s}{P_J} + \Gamma_d}\right) \left(1 - e^{-\frac{MN\Gamma_s}{P_J}}\right). \tag{34}$$

Considering the fact that P_J/N is usually large (e.g., 20 dB), while Γ_s is usually small (e.g., -10 dB), all the throughput expressions indicate that the minimum throughput is fairly small. In other words, in order to make the throughput not so small (e.g., 0.5), it can be easily seen that the M should be extremely large (e.g., several hundred). This makes it a very challenging task for anti-jamming cognitive radio design.

As to the anti-jamming parameter optimization, the cognitive radios must reduce the length of spectrum sensing slot T_s to increase the throughput. They can also increase the spectrum sensing threshold Γ_s to increase the throughput, but this may bring more interference to primary users. The most effective approach might be to increase the number of usable channels M. It is easy to verify that $\partial R_{\min}/\partial M > 0$, which means that it always increases throughput by using larger M. In the extreme case, we have

$$\lim_{M\to\infty} R_{\min}(M) = \frac{e^{-\frac{N\Gamma_d}{P_s}}}{1+\frac{T_s}{T_d}}. \tag{35}$$

which equals to the jamming-free throughput. Unfortunately, from (33) we can see that the throughput increases only with respect to $O(1 - 1/M^2)$, which means larger M only brings smaller throughput increase, or the throughput increase tends to saturate at large M.

4. SIMULATIONS

In this section, we use simulations to verify the analysis results derived in Section 3. We used the following parameters in the simulations: $M = 100$, $K_J = 100$, $T_d = 5$, $T_c = 5$, $T_s = 0.25$, $\Gamma_d = 10$dB, $\Gamma_c = 10$ dB, $\Gamma_s = -10$ dB, $P_s = P_J = -80$ dBm, $N = -100$ dBm.

First, we use simulations to verify that the analysis results of the throughput R fits the simulated results. For this purpose, we used Monte-Carlo simulations to simulate the cognitive radio transmissions and the jammer, with channel coefficients and white space channel selection randomly generated. For the jammer, we evaluate the jamming signal bandwidth y from 0 (jamming-free) up to 0.1. For the theoretical results, we used equations (19) to calculate R.

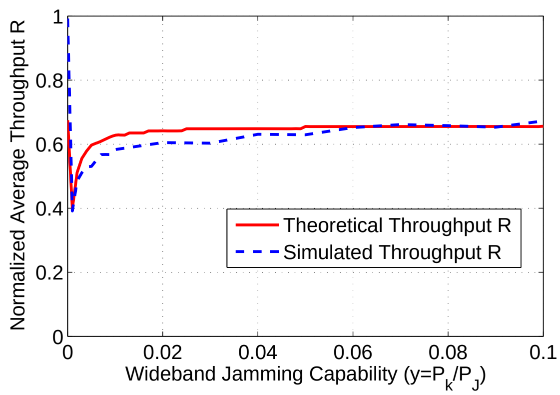

Fig. 3. Comparison of simulation results to the theoretical analysis results of the average throughput.

The simulation results are shown in Fig. 3. From the results, we can see that the theoretical analysis results fit well to the simulated results, which demonstrates the validity of the modelling and analysis. It clearly shows that the throughput reduces with y when y is extremely small, but increases with y when y becomes larger.

Next, we evaluate the anti-jamming performance of cognitive radios when they can hop among more white space channels. For the total number of channels M from 1 to 300, we calculate the theoretical throughput under two different jamming conditions. The results are shown in Fig. 4. From the figure, we can see that while increasing the channel number M can drastically increase the anti-jamming capability, such a benefit tends to saturate after tens of channels have been used.

5. CONCLUSIONS

In this paper, with a simplified Markov model of the cognitive radio transmissions and a simplified jamming model, a simple closed-form expression of cognitive radio throughput is obtained. Then the optimal jamming parameter, i.e., jamming bandwidth (in terms of number of jammed channels), are derived, which gives various approximate minimum throughput expressions. Some anti-jamming parameter optimization is also discussed, in particular the number of white space channels. We have verified the analysis results by simulations. The results indicate that the cognitive radios are extremely susceptible to smart jammers which try to jam the spectrum sensing procedure.

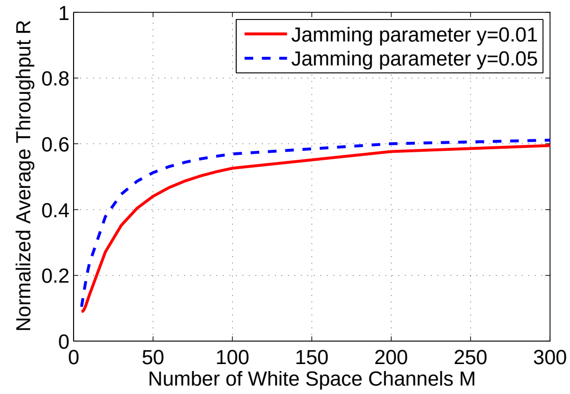

Fig. 4. Average throughput as function of number of white space channels, under various jamming conditions.

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