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Performance Analysis of Adaptive Modulation for Cognitive Radios With Opportunistic Access

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***Abstract*—The performance of adaptive modulation for cognitive radio with opportunistic access is analyzed by considering the effects of spectrum sensing and primary user traffic for Nakagami-m fading channels. Both the adaptive continuous rate scheme and the adaptive discrete rate scheme are considered. Numerical results show that spectrum sensing and primary user traffic cause considerable degradation to the bit error rate performance of adaptive modulation in a cognitive radio system with opportunistic access to the licensed channel. They also show that primary user traffic does not affect the link spectral efficiency performance of adaptive modulation, while the spectrum sensing degrades the link spectral efficiency performance.**

I. Introduction

Adaptive modulation is a very effective method of increasing the link spectral efficiency for communications over fading channels [1] - [4]. Conventional modulation uses a fixed constellation size. The data rate increases but the reliability also decreases, when the constellation size increases [5]. Most practical wireless channels suffer from multipath fading, leading to dramatic changes in the channel condition over the time. In this case, the performance of conventional modulation deteriorates. In contrast, adaptive modulation adapts the constellation size of the modulation format to the channel condition. It has been proved in [1] that the average link spectral efficiency can be greatly increased compared to conventional modulation with fixed constellation size. On the other hand, cognitive radio has been proposed as one of the most promising solutions to the problem of "spectrum scarcity" [6]. In the proposed IEEE 802.22 standard [7], cognitive radios adopt a frame structure where the first part of the frame is the overhead used to conduct spectrum sensing and the second part of the frame is used for the actual data transmission.

Applying adaptive modulation to cognitive radio is a natural choice, as together they provide much flexibility. Several issues may arise compared with conventional adaptive modulation in the previous works [1] - [4]. First, although the licensed channel is deemed as unoccupied by spectrum sensing during the first part of the frame, the licensed user of the channel or the primary user may come back at any time in the second part of the frame when the data of the cognitive radios' are being transmitted. Second, there is a possibility that spectrum sensing will make a misdetection such that the licensed channel is deemed unoccupied while the primary user is actually transmitting. There is also a possibility that spectrum sensing will make a false alarm such that the licensed channel is deemed occupied while the primary user is actually absent. In [9], the performance of adaptive modulation in an underlay cognitive radio system was studied. However, the focus was on the optimization of the transmitter rate and power and none of these effects mentioned above were considered. In [10], the effect of the primary user traffic on spectrum sensing was investigated for an interweave cognitive radio system. However, the results in [10] do not consider adaptive data transmission of the cognitive radio.

In this paper, we evaluate the effects of spectrum sensing and the primary use traffic on the performance of adaptive modulation for a cognitive radio system with opportunistic access to the licensed channel that experiences Nakagami-m fading. Both the bit error rate (BER) and the link spectral efficiency (SE) are investigated. In addition to the adaptive continuous rate (ACR) scheme, the more practical adaptive discrete rate (ADR) scheme is also studied. Numerical results show that spectrum sensing and primary user traffic during the data transmission part of the cognitive radio's frame have significant impact on the performance of adaptive modulation, and the degree of impact depends on the SNR of the cognitive radio user, the SNR of the primary user, the channel condition and the primary user traffic intensity.

II. System Model

Consider a cognitive radio system where transmission is performed on a frame-by-frame basis. In each frame, the first part is the overhead that is used for spectrum sensing and training. Define H_0 as the hypothesis that the licensed channel is free and H_1 as the hypothesis that the licensed channel is occupied. For simplicity and also for generality, we do not assume any specific spectrum sensing methods in the paper. Instead, we assume that the probability of false alarm is given by $P_{fa} = Pr\{H_1|H_0\}$ and the probability of misdetection is given by $P_{md} = Pr\{H_0|H_1\}$, from the spectrum sensing. For later use, the *a priori* probabilities of H_0 and H_1 are defined as $Pr\{H_0\}$ and $Pr\{H_1\}$, respectively. The cognitive radio user will proceed to data transmission if the licensed channel is free and is detected free, with a probability of $1 - P_{fa}$, or

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if the licensed channel is occupied but is detected free, with a probability of P_{md}.

The second part of each frame is used for data transmission, where adaptive modulation is performed. Assume that there are Q data symbols each with a symbol period of T_s. Similar to [1], consider a multi-level quadrature amplitude modulation (M-QAM) scheme. We use rate adaptation but no power adaptation. The BER of the coherent M-QAM with two-dimensional Gray coding over an additive white Gaussian noise (AWGN) channel can be approximated as [1, eq. (28)]

$$BER(M,\gamma) \approx 0.2e^{-\frac{3\gamma}{2(M-1)}} \qquad (1)$$

where γ is the SNR in the channel and M is the constellation size.

Finally, the primary user traffic is assumed to follow an independent and identically distributed on-off process with "0" representing the case when the primary user is off or the licensed channel is free and "1" representing the case when the primary user is on or the licensed channel is occupied. The holding time of each case is assumed to be exponential with mean parameter λ for "0" and μ for "1". Initially, the licensed channel is busy with probability $p_b = \frac{\mu}{\lambda+\mu}$ and free with probability $p_f = \frac{\lambda}{\lambda+\mu}$. The status transition probability matrix is given by

$$\begin{pmatrix} p_{00} & p_{01} \\ p_{10} & p_{11} \end{pmatrix} = \begin{pmatrix} \frac{\mu+\lambda e^{-(\lambda+\mu)t}}{\lambda+\mu} & \frac{\lambda-\lambda e^{-(\lambda+\mu)t}}{\lambda+\mu} \\ \frac{\mu-\mu e^{-(\lambda+\mu)t}}{\lambda+\mu} & \frac{\lambda+\mu e^{-(\lambda+\mu)t}}{\lambda+\mu} \end{pmatrix} \qquad (2)$$

where each element $p_{s_1 s_2}$ represents the probability that the channel is in s_1 when it was in s_2 exactly t seconds ago, where $s_1, s_2 = 0, 1$. We further assume that the primary user arrives or departs during the data transmission period that has a total time interval of QT_s. The status change of the primary user only happens once during the data transmission, which is the case when the average frame length of the primary user signal is larger than QT_s.

III. Performance Analysis

We start with the conventional adaptive modulation without cognitive transmission. In a Nakagami-m fading channel, γ is a Gamma random variable with parameters m and γ_s/m, where m is the Nakagami m parameter and γ_s represents the average SNR in the channel. The value of m is assumed to be an integer. For the conventional ACR scheme, the average BER in a Nakagami-m fading channel equals the target BER BER_0, and the average link SE in a Nakagami-m fading channel is given by [1, eq. (32)]. For the conventional ADR scheme, the average BER for the conventional ADR scheme is calculated as [1, eq. (35)]. The link SE is given by [1, eq. (33)]. Next, we derive results for adaptive modulation in cognitive radio.

For the ACR scheme, the average BER is derived in the Appendix as

$$\begin{aligned} & < BER >_{CRACR1} \\ = \; & Pr\{H_0\}(1-P_{fa}) \sum_{k_1=1}^{Q-1} Pr\{k_1\} \times BER(k_1)_{CRACR} \\ + \; & Pr\{H_1\}P_{md} \sum_{k_2=1}^{Q-1} Pr\{k_2\} \times BER(k_2)_{CRACR} \qquad (3) \end{aligned}$$

where $BER(k_1)_{CRACR}$, $Pr\{k_1\}$, $BER(k_2)_{CRACR}$ and $Pr\{k_2\}$ are given in the Appendix. On the other hand, the average link SE does not depend on the primary user traffic during the data transmission, as it is determined before data transmission. However, it still depends on spectrum sensing. The average link SE for the ACR scheme in cognitive radio is derived in the Appendix as

$$\begin{aligned} & < \frac{R}{W} >_{CRACR1} = Pr\{H_0\}(1-P_{fa}) \frac{e^{\frac{2mK_0}{3\gamma_s}}}{\ln 2} \\ & \sum_{k=0}^{m-1} \left(\frac{2mK_0}{3\gamma_s}\right)^k \Gamma\left(-k, \frac{2mK_0}{3\gamma_s}\right) \qquad (4) \\ - \; & Pr\{H_0\}P_{fa} \frac{e^{\frac{2mK_0}{3\gamma_s}}}{\ln 2} \sum_{k=0}^{m-1} \left(\frac{2mK_0}{3\gamma_s}\right)^k \Gamma\left(-k, \frac{2mK_0}{3\gamma_s}\right) \\ + \; & Pr\{H_1\}P_{md} \frac{e^{\frac{2mK_0(1+\gamma_p)}{3\gamma_s}}}{\ln 2} \sum_{k=0}^{m-1} \left(\frac{2mK_0(1+\gamma_p)}{3\gamma_s}\right)^k \\ & \Gamma\left(-k, \frac{2mK_0(1+\gamma_p)}{3\gamma_s}\right). \end{aligned}$$

where $K_0 = -\ln(5BER_0)$ and $\Gamma(\cdot,\cdot)$ is the complementary incomplete Gamma function defined in [8, eq. (8.350.2)]. Similarly, the average link SE for the ADR scheme in Nakagami-m fading channels is

$$\begin{aligned} < \frac{R}{W} >_{CRADR1} \; = \; & Pr\{H_0\}(1-P_{fa}) \sum_{n=1}^{N} n a_n \\ - \; & Pr\{H_0\}P_{fa} \sum_{n=1}^{N} n a_n \\ + \; & Pr\{H_1\}P_{md} \sum_{n=1}^{N} n b_n \qquad (5) \end{aligned}$$

where $a_n = \frac{\Gamma(m, \frac{mT_n}{\gamma_s}) - \Gamma(m, \frac{mT_{n+1}}{\gamma_s})}{\Gamma(m)}$, $b_n = \frac{\Gamma(m, \frac{mT_n(1+\gamma_p)}{\gamma_s}) - \Gamma(m, \frac{mT_{n+1}(1+\gamma_p)}{\gamma_s})}{\Gamma(m)}$, $T_n = [erfc^{-1}(2BER_0)]^2$ when $n = 1$, $T_n = +\infty$ when $n = N+1$, $T_n = \frac{2}{3}K_0(2^n - 1)$ when $n = 2, 3, \cdots, N$, N is the number of intervals in the ADR scheme that determines the accuracy of the ADR scheme and is different from the constellation size M, and $erfc^{-1}(\cdot)$ is the inverse of the complementary Gaussian error function defined in [8, eq. (8.250.4)], the second term represents the penalty in the average link SE in the case when the licensed channel is free but is detected as busy. Note that the link SE is analyzed in (5) but is not optimized.

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The average BER for the ADR scheme can be derived as

$$\begin{aligned} & < BER >_{CRADR1} \\ = \; & Pr\{H_0\}(1-P_{fa}) \sum_{k_1=1}^{Q-1} Pr\{k_1\} \times BER(k_1)_{CRADR} \\ + \; & Pr\{H_1\} P_{md} \sum_{k_2=1}^{Q-1} Pr\{k_2\} \times BER(k_2)_{CRADR} \end{aligned} \tag{6}$$

where

$$\begin{aligned} & BER(k_1)_{CRADR} = \frac{1}{Q\sum_{n=1}^{N} n a_n} \frac{0.2}{\Gamma(m)} \left(\frac{m}{\gamma_s}\right)^m [k_1 \sum_{n=1}^{N} \\ & \frac{n\Gamma(m, \frac{mT_n}{\gamma_s} + \frac{3T_n}{2(2^n-1)}) - n\Gamma(m, \frac{mT_{n+1}}{\gamma_s} + \frac{3T_{n+1}}{2(2^n-1)})}{(\frac{m}{\gamma_s} + \frac{3}{2(2^n-1)})^m} \\ & +(Q-k_1)\sum_{n=1}^{N} \frac{n\Gamma(m, \frac{mT_n}{\gamma_s} + \frac{3T_n/(1+\gamma_p)}{2(2^n-1)})}{(\frac{m}{\gamma_s} + \frac{3}{2(2^n-1)(1+\gamma_p)})^m}] \\ & -(Q-k_1)\sum_{n=1}^{N} \frac{n\Gamma(m, \frac{mT_{n+1}}{\gamma_s} + \frac{3T_{n+1}/(1+\gamma_p)}{2(2^n-1)})}{(\frac{m}{\gamma_s} + \frac{3}{2(2^n-1)(1+\gamma_p)})^m}] \end{aligned} \tag{7}$$

$$\begin{aligned} & BER(k_2)_{CRADR} = \frac{1}{Q\sum_{n=1}^{N} n b_n} \frac{0.2}{\Gamma(m)} \left(\frac{m}{\gamma_s}\right)^m \quad (8) \\ & [k_2 \sum_{n=1}^{N} \frac{n\Gamma(m, \frac{mT_n(1+\gamma_p)}{\gamma_s} + \frac{3T_n}{2(2^n-1)})}{(\frac{m}{\gamma_s} + \frac{3}{2(2^n-1)(1+\gamma_p)})^m} + (Q-k_2) \\ - \; & k_2 \sum_{n=1}^{N} \frac{n\Gamma(m, \frac{mT_{n+1}(1+\gamma_p)}{\gamma_s} + \frac{3T_{n+1}}{2(2^n-1)})}{(\frac{m}{\gamma_s} + \frac{3}{2(2^n-1)(1+\gamma_p)})^m} \\ + \; & (Q-k_2)\sum_{n=1}^{N} \frac{n\Gamma(m, \frac{mT_n(1+\gamma_p)}{\gamma_s} + \frac{3T_n(1+\gamma_p)}{2(2^n-1)})}{(\frac{m}{\gamma_s} + \frac{3}{2(2^n-1)})^m} \\ - \; & (Q-k_2)\sum_{n=1}^{N} \frac{n\Gamma(m, \frac{mT_{n+1}(1+\gamma_p)}{\gamma_s} + \frac{3T_{n+1}(1+\gamma_p)}{2(2^n-1)})}{(\frac{m}{\gamma_s} + \frac{3}{2(2^n-1)})^m}] \end{aligned}$$

with all the symbols being the same as defined before.

IV. Numerical Results and Discussion

In this section, numerical examples are presented to examine the effects of spectrum sensing and the primary user traffic on adaptive modulation in cognitive radio systems. In the examination, we set $Pr\{H_0\} = 0.7$ and $Pr\{H_1\} = 0.3$, as most target bands of cognitive radios have a larger vacant probability than an occupied probability. Also, $P_{fa} = 0.1$ and $P_{md} = 0.1$. The target BER is set to $BER_0 = 10^{-5}$. Assume that $Q = 10$.

Fig. 1 compares the BER performances of the conventional adaptive modulation with the BER performances of adaptive modulation for cognitive radio in a Nakagami-m fading channel with $m = 2$, $\gamma_p = 0\ dB$ and $\lambda = \mu = \frac{1}{100T_s}$. Several observations can be made. First, spectrum sensing and the primary user traffic degrade the BER performance of adaptive modulation. For example, the BER of the ACR scheme for the conventional adaptive modulation is at the target value 10^{-5},

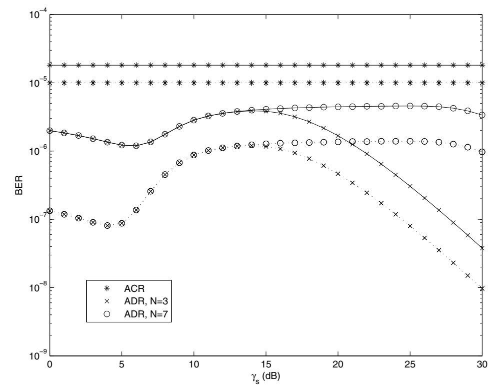

Fig. 1. Comparison of the BER for conventional adaptive modulation (dotted lines) and the BER for adaptive modulation for cognitive radio (solid lines) in Nakagami-m fading channels ($m = 2$) with $\gamma_p = 0\ dB$ and $\lambda = \mu = \frac{1}{100T_s}$.

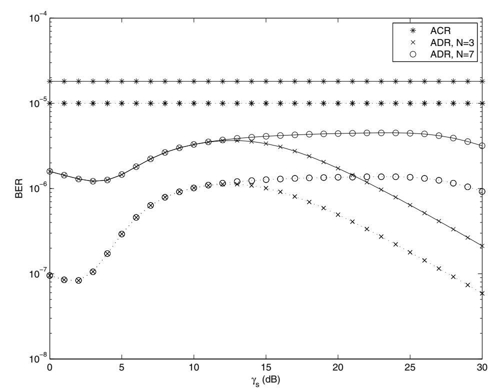

Fig. 2. Comparison of the BER for conventional adaptive modulation (dotted lines) and the BER for adaptive modulation for cognitive radio (solid lines) in Rayleigh fading channels ($m = 1$) with $\gamma_p = 0\ dB$ and $\lambda = \mu = \frac{1}{100T_s}$.

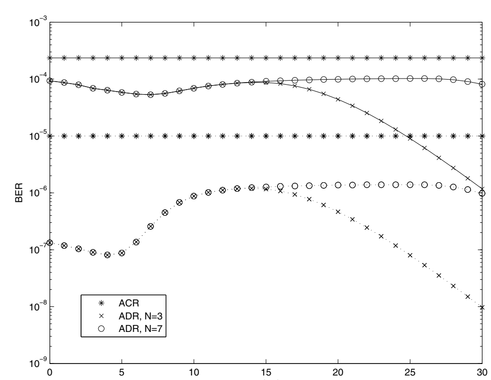

Fig. 3. Comparison of the BER for conventional adaptive modulation (dotted lines) and the BER for adaptive modulation for cognitive radio (solid lines) in Nakagami-m fading channels ($m = 2$) with $\gamma_p = 5\ dB$ and $\lambda = \mu = \frac{1}{100T_s}$.

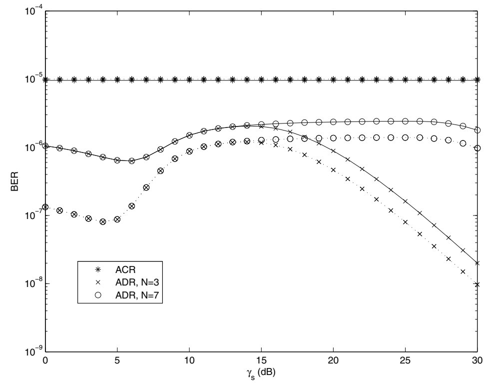

Fig. 4. Comparison of the BER for conventional adaptive modulation (dotted lines) and the BER for adaptive modulation for cognitive radio (solid lines) in Nakagami-m fading channels ($m = 2$) with $\gamma_p = 0\ dB$ and $\lambda = \mu = \frac{1}{200T_s}$.

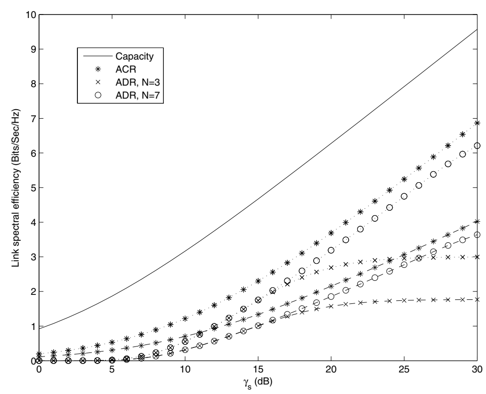

Fig. 5. Comparison of the link SE for conventional adaptive modulation (dotted lines) and the link SE for adaptive modulation for cognitive radio (dashed lines) in Nakagami-m fading channels ($m = 2$) with $\gamma_p = 0\ dB$.

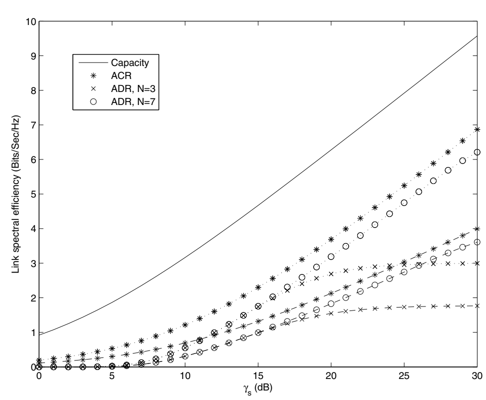

Fig. 6. Comparison of the link SE for conventional adaptive modulation (dotted lines) and the link SE for adaptive modulation for cognitive radio (dashed lines) in Nakagami-m fading channels ($m = 2$) with $\gamma_p = 5\ dB$.

while the BER of the ACR scheme for adaptive modulation in cognitive radio is increased to 1.5×10^{-5}. Second, one sees that the curve for adaptive modulation in cognitive radio has the same trend as the curve for conventional adaptive modulation. For example, the BER of the ACR scheme for adaptive modulation in cognitive radio is still a constant, and the BER curve with larger value of N is still flatter than that with smaller value of N for the ADR scheme at high values of γ_s. The BER does not monotonically decrease with γ_s when γ_s is less than 10 dB, due to the approximation error and the uneven division in the choices of the thresholds T_1 to T_N. Third, the ADR curves for adaptive modulation in cognitive radio are closer to the target BER than the ADR curves for the conventional adaptive modulation. This implies that the ADR scheme in cognitive radio is more likely to meet the target BER than the conventional ADR.

Fig. 2 has the same system settings as Fig. 1, except that it uses $m = 1$. In this case, the BER performance of the ACR scheme in cognitive radio is almost identical to that in Fig. 1 when $m = 2$, while the BER performance of the ADR scheme in cognitive radio is worse than that in Fig. 1 when $m = 2$. This suggests that harsh channel condition degrades the BER performance further, which agrees with intuition. One also sees that the performance difference between conventional adaptive modulation and adaptive modulation in cognitive radio increases when m decreases by comparing Figs. 1 and 2. Fig. 3 has the same system settings as Fig. 1, except that it uses $\gamma_p = 5\ dB$. When the SNR of the primary user increases from 0 dB in Fig. 1 to 5 dB in Fig. 3, the BER of adaptive modulation in cognitive radio increases, as expected, as more interference will result in worse cognitive radio performance. One also sees that most BERs in adaptive modulation for cognitive radio are larger than the target BER $BER_0 = 10^{-5}$, compared with the conventional adaptive modulation. Fig. 4 has the same system settings as Fig. 1, except that the primary user traffic intensity is changed to $\lambda = \mu = \frac{1}{200T_s}$. This means that the primary user traffic is low. One sees that the performance difference between the conventional adaptive modulation and the adaptive modulation in cognitive radio reduces when the primary user traffic intensity decreases. This is expected, as the chance of having a mismatch between the channel condition used to choose the constellation size and the channel condition the actual data transmission experiences is reduced when the primary user is less active. Note that in all the cases, the trends of the curves are reserved.

Figs. 5 and 6 compare the link SE performances of the conventional adaptive modulation with the link SE performances of adaptive modulation for cognitive radio for different system parameters. From Fig. 5, the link SE for adaptive modulation in cognitive radio is smaller than the link SE for conventional adaptive modulation. The SE loss increases when γ_s increases. Therefore, spectrum sensing degrades the SE performance too. Similar to the conventional adaptive modulation, the ACR scheme in cognitive radio has a larger SE than the ADR scheme in cognitive radio. Comparing Fig. 5 with Fig. 6, one sees that the link SE of adaptive modulation for cognitive radio is insensitive to the SNR of the primary user in this case, as the link SE of adaptive modulation for cognitive radio in Fig. 5 is graphically indistinguishable to that in Fig. 6.

V. Conclusion

The effects of spectrum sensing and primary user traffic on the performance of adaptive modulation for cognitive radio systems with opportunistic access have been evaluated. Both ACR and ADR schemes have been considered. The evaluation has shown that the BER performance of adaptive modulation is degraded due to spectrum sensing and primary user traffic and that the degradation is considerable in most cases. Future works include extension of this work to hybrid automatic repeat request schemes.

Appendix
Derivations of (3) and (4)

When the primary user arrives at the k_1-th symbol in the data transmission with $1 \leq k_1 \leq Q-1$, this implies that the primary user is absent during the first part of the frame as well as in the first k_1 symbols of the second part of the frame, while it is present during the last $Q-k_1$ symbols in the second part of the frame. In this case, the average BER when the primary user arrives at the k_1-th symbol is given by

$$BER(k_1)_{CRACR} = \frac{k_1}{Q} \times BER_0 + \frac{Q-k_1}{Q} \times 0.2(5BER_0)^{\frac{1}{1+\gamma_p}} \tag{9}$$

and the probability that the primary user arrives at the k_1-th symbol is given by

$$Pr\{k_1\} = p_f p_{00}^{k_1} p_{01} p_{11}^{Q-k_1} \tag{10}$$

where $\frac{\gamma}{1+\gamma_p}$ is the SNR when the primary user is present, γ_p is the SNR of the primary user signal or the interference-to-noise ratio (INR) from the cognitive radio's perspective.

When the primary user leaves at the k_2-th symbol in the data transmission with $1 \leq k_2 \leq Q-1$, this implies that the primary user is present during the first part of the frame as well as in the first k_2 symbols of the second part of the frame, while it is absent during the last $Q-k_2$ symbols in the second part of the frame. In this case, the average BER when the primary user departs at the k_2-th symbol is given by

$$BER(k_2)_{CRACR} = \frac{k_2}{Q} \times BER_0 + \frac{Q-k_2}{Q} \times 0.2(5BER_0)^{1+\gamma_p} \tag{11}$$

and the probability that the primary user leaves at the k_2-th symbol is given by

$$Pr\{k_2\} = p_b p_{11}^{k_2} p_{10} p_{00}^{Q-k_2}. \tag{12}$$

Using (9), (10), (11) and (12), the average BER for the ACR scheme in cognitive radio systems when the primary user randomly leaves or comes during the data transmission period is derived as (3).

When the primary user randomly arrives in the data transmission period, the link SE is given by

$$\frac{R}{W}_{CRACR1} = \log_2\left(1 + \frac{3\gamma}{2K_0}\right) \tag{13}$$

which is a function of γ. By averaging (13) over the Gamma distribution of γ, the average link SE in a Nakagami-m fading channel is given by

$$\frac{e^{\frac{2mK_0}{3\gamma_s}}}{\ln 2} \sum_{k=0}^{m-1} \left(\frac{2mK_0}{3\gamma_s}\right)^k \Gamma\left(-k, \frac{2mK_0}{3\gamma_s}\right). \tag{14}$$

When the primary user randomly leaves in the data transmission period, the instantaneous link SE is given by

$$\frac{R}{W}_{CRACR2} = \log_2\left(1 + \frac{3\gamma}{2K_0(1+\gamma_p)}\right) \tag{15}$$

and the average link SE can be derived by averaging (15) over the Gamma distribution of γ as

$$\frac{e^{\frac{2mK_0(1+\gamma_p)}{3\gamma_s}}}{\ln 2} \sum_{k=0}^{m-1} \left(\frac{2mK_0(1+\gamma_p)}{3\gamma_s}\right)^k \Gamma\left(-k, \frac{2mK_0(1+\gamma_p)}{3\gamma_s}\right) \tag{16}$$

where the SNR of the primary user has been taken into account. Putting these cases together, the average link SE for the ACR scheme in cognitive radio is given by (4).

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