On the Outage Behavior of Interference Temperature Limited CR-MISO Channel

Hyung Yun Kong and Asaduzzaman

Abstract: **This paper investigates the outage behavior of peak interference power limited cognitive radio (CR) networks with multiple transmit antennas. In CR-multi-input single-output (MISO) channel, the total transmit power is distributed over the transmit-antennas. First, we use the orthogonal space-time codes (STC) to achieve the transmit diversity at CR-receiver (rx) and investigate the effect of the power distribution on the interference power received at the primary-receiver (P-rx). Then, we investigate the transmit antenna selection (TAS) scheme in which the CR system selects the best transmit antenna and allocates all the power to the selected best antenna. Two transmit antenna selection strategies are proposed depending on if feedback channel is available or not. We derive the closed form expressions of outage probability and outage capacity of all schemes with arbitrary number of transmit-antennas. We show that the proposed schemes significantly improve the outage capacity over the single antenna systems in Rayleigh fading environment. We also show that TAS based scheme outperforms the STC based scheme when peak interference power constraint is imposed on the P-rx only if a feedback channel from CR-rx to CR-transmitter is available.**

Index Terms: **Cognitive radio (CR), fading channel, interference temperature, outage probability, transmit diversity.**

I. INTRODUCTION

In recent years, the demand of radio spectrum has rapidly increased due to the dramatic growth of wireless applications. In current spectrum management policy, most of the spectrum has already been allocated and it is difficult to find spectrum for the new wireless applications. As a solution of this problem, the concept of cognitive radio (CR) has been proposed in [1]. In cognitive radio networks, the unlicensed CR users access to the frequency bands of a licensed network (primary network) opportunistically by using their cognition capabilities [2]. To do this, CR users must be capable of sensing the spectrum of the primary users. Depending on the spectrum sensing, the CR users can access to the spectrum of a primary network provided that the operation of the primary network is not compromised [3].

In CR networks, the CR users may coexist with the primary users either on non-interference basis or interference tolerant basis. In case of non-interference basis systems, the CR users are allowed to operate in the unused frequency bands, commonly known as spectrum holes or white spaces [2]. Contrarily, interference tolerant basis systems allow CR users to access the frequency band of the primary users provided that the interference power level at the primary-receivers (P-rxes) is kept below some certain threshold [3] and [4]. Such limit on the interference power is commonly known as interference temperature. In such CR systems, the users may not be able to provide the required quality of services (QoS) all the time due to the interference temperature constraint. Consequently, there exists an outage phenomenon and the system operates on a certain outage probability [5]. In order to guarantee a certain quality of service by reducing the outage probability transmit-diversity may be an attractive choice.

It is well known that transmit diversity is an effective way to mitigate the channel fading with total transmit power constraint [6]. In interference limited CR networks, the users may need to operate in low signal-to-noise ratio (SNR) to protect the P-rxes. Hence, the transmit diversity may be the efficient technique to ensure the quality of services of CR users in fading environment. The outage analysis of such interference limited systems with transmit diversity is important to understand the fundamental limits of the system. The outage capacity along with the power allocation problems for interference temperature limited single antenna fading channel have been investigated in [3] and [4]. In this paper, we consider that the CR users access the frequency band of primary users provided that the interference power level at P-rxes is kept below some certain threshold. The CR users use their cognition capabilities to decide the level of transmit power corresponding to the interference temperature. In such scenario, the main objective of a CR transmitter-receiver pair is to maximize the link capacity by maintaining the interference temperature constraint.

To achieve transmit diversity, we consider two types of transmission technique. First, we consider STC based simultaneous transmission. In this case, all the antennas transmit at the same time using orthogonal STC [7]. Next, we consider transmit antenna selection (TAS) based transmission schemes. We propose two antenna selection policies: TAS without feedback and TAS with feedback. There are several works in existing literature that analyzed the performances of multi-input single-output (MISO) systems [6]–[9] under peak transmit power constraint. The capacities and power allocation problem of such systems are analyzed in [6] and [8]. The bit error rate (BER) performance of a non-cognitive radio MISO system has studied in [9]. To the best of our knowledge there is no such work for interference temperature limited MISO systems.

The main focus of this paper is to show the effect of transmit diversity on the interference temperature at the primary-receiver. In case of STC based simultaneous transmission, due to the transmit diversity, the signal received at the P-rx also

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achieves diversity. We show that this effect of multi antenna diversity at the P-rx can be reduced by using single antenna selection technique. We derive the closed form expressions of the outage probability of the transmission schemes. The outage capacities of the schemes are also calculated. We show that the STC and the TAS with feedback can achieve the diversity of order of number of antennas. On the other hand, TAS without feedback does not achieve any diversity but still outperforms the single antenna system. Results show that the TAS based scheme outperforms STC based scheme only if the CR-receiver (CR-rx) selects the antenna and feedback to the CR-transmitter (CR-tx).

The rest of the paper is organized as follows. In Section II, we describe the system and channel models. Section III presents the outage analysis of the transmission schemes. Simulation results and discussions are given in Section IV and, finally we conclude this paper in Section V.

II. SYSTEM MODEL

We consider a spectrum sharing scenario where CR-users coexist with primary-users, and they are using the same frequency band as shown in Fig. 1. Assume that the CR-transmitters are equipped with M antennas. In this work, we focus on the effect of the transmit diversity on CR network with peak interference temperature constraint. Consequently, we assume both P- and CR-rxes are single antenna devices, for simplicity. Therefore, the assumed channel model is a simple MISO channel. We consider flat Rayleigh fading channel with additive white Gaussian noise (AWGN). Let $\mathbf{G} = [g_1, g_2, \cdots, g_M]$ and $\mathbf{H} = [h_1, h_2, \cdots, h_M]$ represent the instantaneous channel power gain from the CR-tx to CR-rx and P-rx, respectively. Assume, the antenna separation of CR-tx is enough to ensure that the entries of $\mathbf{G}$ and $\mathbf{H}$ are uncorrelated. For Rayleigh fading, g_m and h_m, $m \in \{1, 2, \cdots, M\}$ are the exponential random variables with parameter λ_g and λ_h, respectively.

Assume that perfect CSI are available at the CR-rx but not at the transmitter. This can be achieved by transmitting a sequence of pilot symbols from CR-tx. Due to the perfect CSIs at the receivers coherent detection is possible and thus only the channel power gains are of interest. We also assume that the channel power gain of CR-tx to P-rx is known to the CR-tx. The main drawback of interference limited CR system is that, to implement such spectrum sharing system, CR-tx must use some power control technique based on the instantaneous channel power gains with P-rx. Hence, the CR-tx should have perfect knowledge of $\mathbf{H}$. Assume that only the channel power gains, i.e., square amplitude of the channel state information (CSI) is known at the CR-tx but not the phase of the CSIs. The CR-tx can achieve the information about $\mathbf{H}$ through feedback. The feedback may carried out directly by the P-rx [3] or through a band manager [10]. In any case, some sort of cooperation among the primary and CR system is required to realize the considered system model. Throughout this paper, similar to other works on interference limited CR systems [3]–[5], we consider that the entries of $\mathbf{H}$ are perfectly known at the CR-tx. The knowledge about the channel between CR-tx and CR-rx can also be obtained at the CR-tx through feedback. But it is not a must to maintain the interference temperature. In this paper, we consider both cases with and without the knowledge of $\mathbf{G}$ at the CR-tx, in case of TAS scheme with feedback and TAS scheme without feedback, respectively.

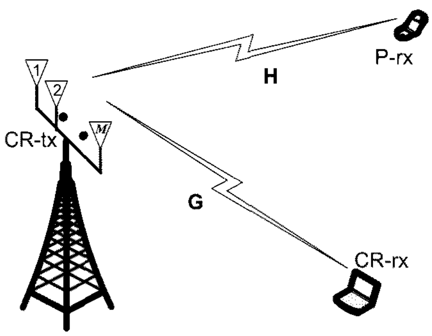


Fig. 1. System model.

We investigate STC based simultaneous transmission and TAS based transmission to achieve diversity at the CR-rx. Assume that a suitable space time block code [7] is used by the transmitter for STC based transmission. In case of TAS based transmission, we propose a single transmit antenna selection procedure. In this case, only the selected best antenna will take part in the transmission. We propose two antenna selection policies: (1) TAS without feedback and (2) TAS with feedback. In case of TAS without feedback, the CR-tx selects the best antenna that minimizes the interference at the P-rx. Contrarily, in case of TAS with feedback, the CR-rx selects the best antenna and informs the decision to the CR-tx through a low rate feedback channel. We assume that the feedback channel is error free.

For the purpose of theoretical analysis and to understand the outage behavior of the MISO-CR system, we consider only one CR-tx and one P-rx. In practical applications, there must be multiple CR and primary users. In case of multiple CR-txes, there should be some channel access protocol to avoid collision which is beyond the scope of our outage analysis. On the other hand, the proposed outage analysis can be implemented on scenarios with multiple P-rxs. In such case, the CR-tx must consider the P-rx which is closest to it in terms of communication distance. Without losing generality, we consider a system model in which only the nearest P-rx is considered to protect from interference constraint.

The ergodic capacity is the measure of the maximum achievable long-term rate without considering any delay constraint. However, in reality many wireless applications have certain delay constraints. In such environment, delay limited capacity which defines the constant-rate that is achievable in all fading states, is a more appropriate notion. However, the delay limited capacity in Rayleigh fading environment is zero as the transmitter has to spend a huge amount of power for channel states in deep fades to maintain a constant rate. Alternatively, a non zero capacity can be achieved in Rayleigh fading channel by declaring outage when the channel states are in deep fade. Such capacity is known as outage capacity that exist a capacity-versus-outage phenomenon. Hence, outage capacity is an appropriate measure of the channel capacity for slowly varying Rayleigh fading channel [11]. In this paper, we investigate the outage probability and outage capacity of both STC and TAS based schemes while the P-rx is protected by the peak interference power (PIP) constraint, Q.

III. OUTAGE ANALYSIS

The main goal of the CR system is to provide a certain quality of service to its users without hampering the operation of the primary users. This paper is concerned about the interference tolerant based operation where the primary users are protected by a predefined peak interference power. In such scenario, the CR users always look for the transmission opportunity with certain quality of services by maintaining the peak interference constraint. The fundamental measure of the quality of service is the transmission rate in bits/s/Hz. Assume that the CR system needs to maintain a target transmission rate of r bits/s/Hz. The CR system abandons the transmission if the achievable transmission rate is less than the target rate. Such event can be defined as the outage event and the probability of occurring this event is known as the outage probability of the system [11]. Therefore, the outage probability is a good measure of the transmission opportunity of the interference tolerant CR systems.

A. STC Scheme

In this scheme, all the antennas of the CR-tx take part in simultaneous transmission using orthogonal space-time codes. The interference power received at the P-rx due to the transmission of CR-tx can be given as, $\sum_{m=1}^{M} P_m h_m$. The optimal power allocation for single antenna CR network has been investigated in [4]. To allocate optimal power over the antennas, conditioned on the fading coefficients, solution of tedious optimization problem is required. To solve such optimization problem, CR-tx requires the full instantaneous CSI [8]. In this paper, we consider that the instantaneous CSIs are available at the receivers but not at the transmitters. Consequently, optimal power allocation is not possible and equal power allocation to all antennas as, $P_1 = P_2 = \cdots = P_M = P/M$ is considered. The transmit power constraint in terms of the peak interference power, Q can be given as

$$\frac{P}{M}\sum_{m=1}^{M} h_m \leq Q \Rightarrow P \leq \frac{MQ}{h_T} \tag{1}$$

where $h_T = \sum_{m=1}^{M} h_m$. Now the received SNR at the CR-rx can be written as

$$\begin{aligned}\gamma &= \frac{P}{MN_0B}\sum_{m=1}^{M} g_m \\ &= \frac{Q}{N_0B}\frac{g_T}{h_T}\end{aligned} \tag{2}$$

where N_0 is the variance of AWGN, B is the total bandwidth and $g_T = \sum_{m=1}^{M} g_m$. In space time codes, the transmitted symbol from each antenna is different from others. Therefore, the interference at the P-rx is the sum of all interference induced by each transmit antenna. The mutual information between the CR-tx and rx, considering the peak interference power Q at the P-rx, can be given as

$$I = \log_2\left(1 + \frac{Q}{N_0B}\frac{g_T}{h_T}\right). \tag{3}$$

Considering the fact that the transmission is abandoned when the mutual information is less than r bits/s/Hz, the outage probability can be found as

$$\begin{aligned}P_{\text{out}}^{\text{STC}} &= \Pr[I < r] \\ &= \Pr\left[\log_2\left(1 + \frac{Q}{N_0B}\frac{g_T}{h_T}\right) < r\right] \\ &= \Pr\left[\frac{g_T}{h_T} < \alpha\right] \\ &= F_{\frac{g_T}{h_T}}(\alpha)\end{aligned} \tag{4}$$

where $\alpha = (2^r - 1)N_0B/Q$ and $F_{\frac{g_T}{h_T}}(\cdot)$ is the cumulative distribution function (CDF) of the random variable $\frac{g_T}{h_T}$ which is derived in Appendix.

Now, the outage capacity [11], associated with a given outage probability, ϵ, of STC based transmission scheme under the peak interference power constraint can be given as

$$C_{\text{out}}^{\text{STC}}(\epsilon) \;\leq\; B\log\left(1 + \frac{\bar{\alpha}Q}{N_0B}\right)(1-\epsilon) \tag{5}$$

where the value of $\bar{\alpha}$ is the solution of (4) for the target outage probability, ϵ.

B. TAS Scheme without Feedback

In this subsection, we propose a transmit antenna selection scheme for interference limited MISO channel without any feedback from the CR-rx. Among the M transmit-antennas, CR-tx selects the best antenna and all the power that satisfies the PIP constraint is allocated to the best antenna. The CR-tx only knows channel power gains with the P-rx, $\mathbf{H}$. With this knowledge, the best antenna is the antenna that causes less interference to the P-rx. Therefore, the selection criterion is to select the antenna that has minimum channel power gain with P-rx. The transmit antenna selection criterion without feedback can be written as

$$m^* = \arg \min_{m\in\{1,2,\cdots,M\}} (h_m). \tag{6}$$

The interference power received at the P-rx due to the transmission of the antenna-m can be given as, Ph_m. The power allocation to antenna m, considering PIP constraint, can be given as, $P = \frac{Q}{h_m}$. The mutual information between the any antenna-m and CR-rx, considering the peak interference power Q at the P-rx, can be written as

$$I_m = \log_2\left(1 + \frac{Q}{N_0B}\frac{g_m}{h_m}\right). \tag{7}$$

Logarithm is a monotonically increasing function with any positive argument. Therefore, minimizing h_m is equivalent to maximizing I_m conditioned on g_m. In this scheme, the outage of the CR system occurs if the end-to-end mutual information through the best antenna is less than r bits/s/Hz. The probability that the end-to-end mutual information through the best antenna is less than r bits/s/Hz, conditioned on g_m, can be given as

$$\begin{aligned} P_{\text{out}}^{\text{TAS1}}(g_m) &= \Pr\left[\max\{I_m\} < r \,|g_m\right] \\ &= \prod_{m=1}^{M} \Pr\left[I_m < r \,|g_m\right] \\ &= \prod_{m=1}^{M} \Pr\left[\log_2\left(1+\frac{Q}{N_0 B}\frac{g_m}{h_m}\right) < r \,\middle|\, g_m\right] \\ &= \prod_{m=1}^{M} \Pr\left[h_m \geq \frac{g_m}{\alpha} \,\middle|\, g_m\right] \\ &= \prod_{m=1}^{M} \left\{1 - \Pr\left[h_m < \frac{g_m}{\alpha} \,\middle|\, g_m\right]\right\} \\ &= \left\{1 - F_{h_m}\left(\frac{g_m}{\alpha}\right)\right\}^M \\ &= \exp\left[-M\lambda_h \frac{g_m}{\alpha}\right] \end{aligned} \tag{8}$$

where the superscript 'TAS1' represents the TAS scheme without feedback and $F_x(\cdot)$ represents the CDF of x. The last equality of (8) is obtained by considering that h_m is an exponential random variable.

The unconditional outage probability of this scheme can be obtained by integrating over the PDF of g_m as

$$\begin{aligned} P_{\text{out}}^{\text{TAS1}} &= \int_{x=0}^{\infty} \exp\left[-M\lambda_h \frac{x}{\alpha}\right] \lambda_g \exp\left[-\lambda_g x\right] dx \\ &= \frac{\lambda_g \alpha}{\lambda_h M + \lambda_g \alpha}. \end{aligned} \tag{9}$$

Finally, the outage capacity of TAS based transmission scheme without feedback under the peak interference power constraint can be given as

$$C_{\text{out}}^{\text{TAS1}}(\epsilon) = B \log\left(1 + \frac{\tilde{\alpha} Q}{N_0 B}\right)(1-\epsilon) \tag{10}$$

where the value of $\tilde{\alpha}$ is the solution of (9) for the target outage probability, ϵ.

C. TAS Scheme with Feedback

The transmit antenna selection strategies in peak transmit power limited MISO communication system with low rate feedback have been investigated in [9]. In this paper, we consider the similar antenna selection strategy considering peak interference power constraint at a third party receiver (P-rx). In case of TAS scheme with feedback, the CR-rx selects the best transmit antenna. The selection criterion considered for the antenna selection is the mutual information. The mutual information between antenna-m and CR-rx is defined in (7). The antenna that maximizes the mutual information is selected as best antenna. The transmit antenna selection criterion can be written as

$$m^* = \arg \max_{m \in \{1,2,\cdots,M\}} (I_m). \tag{11}$$

The mutual information between antenna-m and CR-rx (I_m) is a function of both g_m and h_m. Only h_m is known at the CR-tx. Hence, CR-tx cannot calculate the I_m, and consequently cannot select the best antenna that maximizes the mutual information. On the other hand, CR-rx can measure g_m from the pilot symbols and h_m is included in the transmit power of the pilot symbols. Therefore, it is possible to calculate the I_m at the CR-rx. The CR-rx selects the best antenna that satisfies the condition of (11) and feeds back the index of the best antenna to the CR-tx.

In this scheme, the outage of the CR system occurs if the end-to-end mutual information through the best antenna is less than r bits/s/Hz. The probability that the end-to-end mutual information between antenna-m and CR-rx is less than r bits/s/Hz can be calculated as

$$\begin{aligned} \Pr\left[I_m < r\right] &= \Pr\left[\log_2\left(1+\frac{Q}{N_0 B}\frac{g_m}{h_m}\right) < r\right] \\ &= \Pr\left[\frac{g_m}{h_m} < \alpha\right] \\ &= F_{\frac{g_m}{h_m}}(\alpha) \end{aligned} \tag{12}$$

where $F_{\frac{g_m}{h_m}}(\cdot)$ is the CDF of the rv $\frac{g_m}{h_m}$ which is derived in Appendix.

The CR system is in outage when the end-to-end mutual information through the best-antenna is less than r bits/s/Hz. Therefore, the outage probability of TAS scheme with feedback (TAS2) can be obtain as

$$\begin{aligned} P_{\text{out}}^{\text{TAS2}} &= \Pr\left[\max_{m \in \{1,2,\cdots,M\}} (\mathrm{I}_m) < r\right] \\ &= \prod_{m=1}^{M} \left[F_{\frac{g_m}{h_m}}(\alpha)\right] \end{aligned} \tag{13}$$

The last equality is obtained by considering that the random variables g_m and h_m are identically independent. Finally, the outage capacity of TAS based transmission with feedback under the peak interference power constraint can be given as

$$C_{out}^{TAS2}(\epsilon) = B \log\left(1 + \frac{\hat{\alpha} Q}{N_0 B}\right)(1-\epsilon) \tag{14}$$

where the value of $\hat{\alpha}$ is the solution of (13) for the target outage probability, ϵ.

IV. RESULTS AND DISCUSSIONS

In this section, we provide some numerical and simulation results of the outage probabilities and capacities of the proposed transmission schemes that are developed in the previous section. For all cases, we consider $N_0 B = 1$. Figs. 2–4 show the outage probability of the transmission schemes against peak interference power constraint (Q in dB) with different number of antennas (M). $M = 1$ indicates the conventional single-input single-output (SISO) system which is taken as the reference of the outage performance. For these figures, we assume, $\lambda_h = 0.5$, $\lambda_g = 2$ and $r = 1$ bits/s/Hz. In Figs. 2–4, the analytical (a) outage probabilities of the transmission schemes, developed in Section III, are also verified with simulation (s) results. In all cases, the simulation and numerical results match very well.

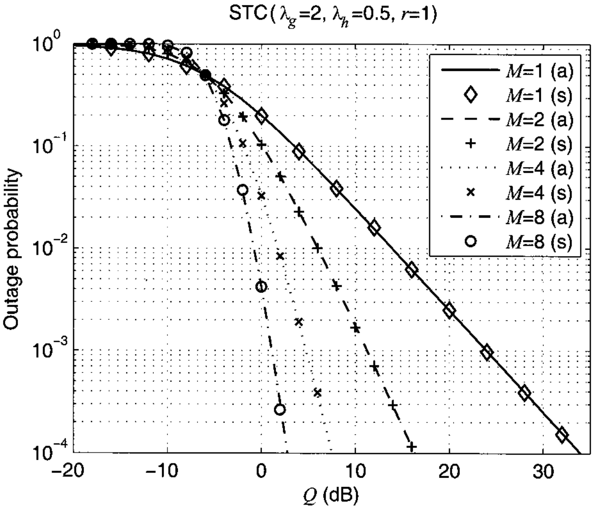


Fig. 2. Outage probability of STC based scheme for different number of antennas.

The outage probability of STC based transmission scheme is shown in Fig 2. It clearly indicates the improvement of outage performance as the number of transmit-antennas increases at the high PIP region. Importantly, in the low values of Q (less than -5 dB) MISO system ($M > 1$) with STC based transmission is worse than the SISO system ($M = 1$). The slope of the outage probabilities at high interference temperature increases as the number of transmit-antennas increases. The high PIP slope for different number of antennas indicates that the STC based transmission scheme achieves full diversity of the order of the number of transmit antennas. Obviously, the source of this diversity gain is the complex orthogonal space-time processing.

The outage probability of the TAS scheme without feedback for different number of antennas is shown in Fig. 3. The outage probability of this scheme decreases as the number for antenna increases but the slope of the outage curves are the same for all M over the whole range of Q. This indicates that the TAS scheme without feedback achieves some power gain but not the diversity gain. This scheme selects the antenna that has minimum channel power gain with the P-rx. The allowable transmit power that satisfies the PIP constraint is inversely proportional to the channel power gain with the P-rx. Therefore, this antenna selection policy maximizes the transmit power. The channel power gain between CR-tx and rx is not considered in TAS scheme without feedback. Hence, this scheme does not achieve any diversity gain.

The TAS based transmission scheme with feedback, on the other hand, utilizes both the channel power gains from CR-tx to P-rx and CR-tx to CR-rx. Consequently, this scheme achieves both transmit power gain and diversity gain. As shown in Fig. 4, similar to STC based scheme, the high PIP slope of the outage curves increases as the number of antennas increases. The diversity gain achieved by the TAS based transmission scheme with feedback is in fact selection diversity. It is important to note here that the outage performance of MISO system for both TAS based transmission scheme is better than the SISO system over the whole range of PIP constraint, Q. Due to the transmit power gain achieved by both the TAS based schemes, the outage performance of MISO systems is better than SISO systems even at very low PIP as shown in Figs. 3 and 4.

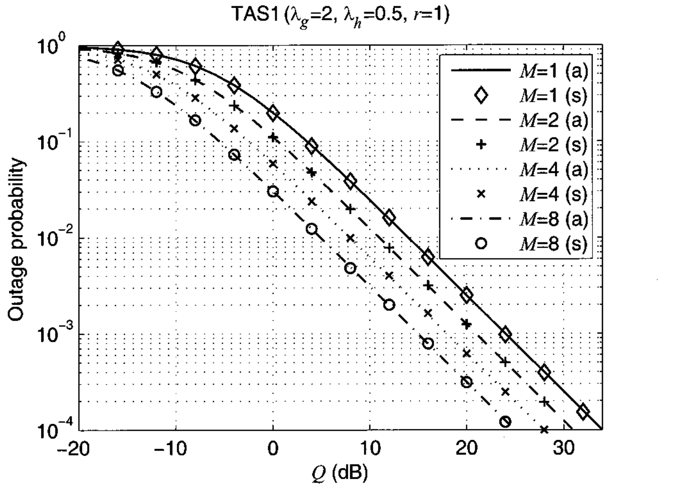


Fig. 3. Outage probability of TAS based scheme without feedback for different number of antennas.

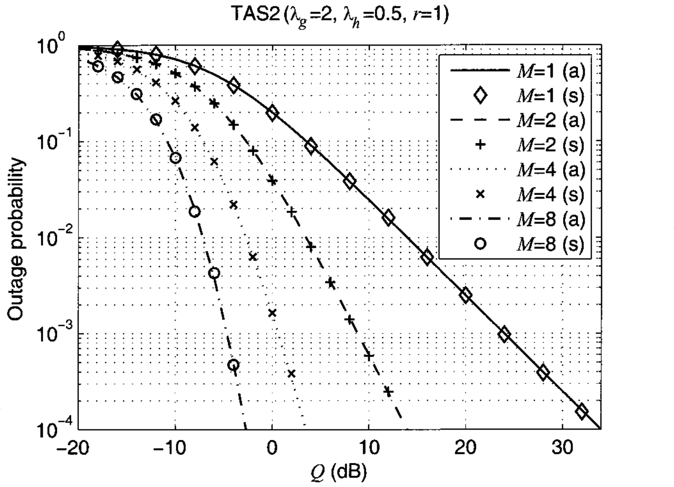


Fig. 4. Outage probability of TAS based scheme with feedback for different number of antennas.

Fig. 5 shows the comparison of the transmission schemes, in terms of outage probability, for $M = 4$. The STC based scheme and TAS based scheme with feedback achieve same diversity order as the slope of the outage probabilities at high interference temperature is the same for both. The TAS based scheme without feedback does not achieve diversity but it performs better than the STC based transmission at the low range of PIP. Among the transmission schemes, TAS based transmission scheme with feedback outperforms the other two schemes at the cost of the overhead required for feedback. The STC based scheme does not require any feedback but it requires complex space-time processing to achieve diversity. The simplest scheme, in terms of implementation complexity, is the TAS scheme without feedback that achieves only power gain. This scheme is very effective at very low PIP region but not at the medium and high PIP region as shown in Fig. 5.

The outage capacities (bits/s/Hz) of (5), (10), and (14) for different number of transmit-antennas are plotted against the peak interference power constraint in Fig. 6. For this figure, we consider $\lambda_h = \lambda_g = 1$ and $\epsilon = 0.001$. Fig. 6 clearly indicates

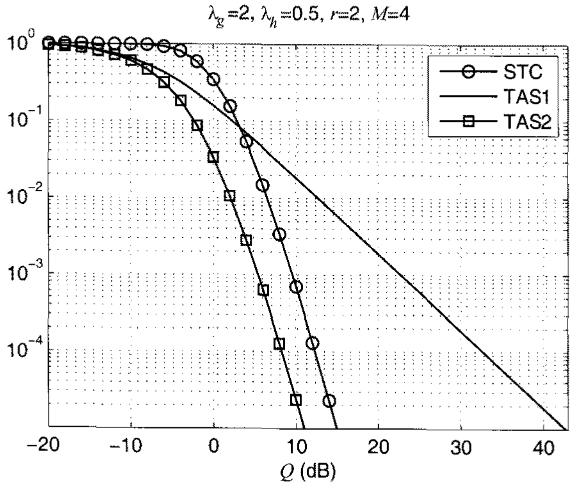


Fig. 5. Comparison of outage probabilities of different transmission schemes for $M = 4$.

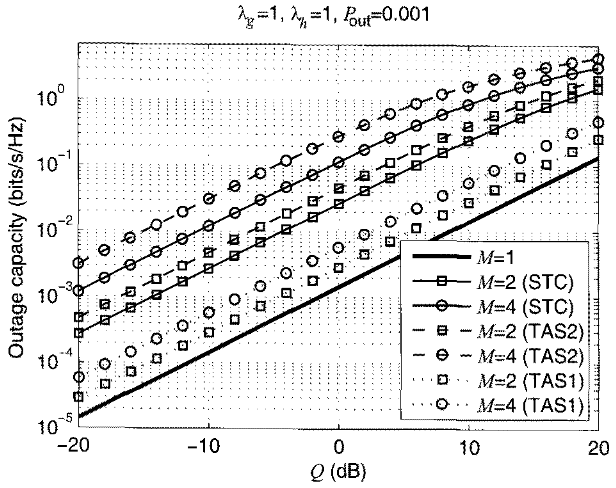


Fig. 6. Comparison of outage capacities of different transmission schemes for $P_{\text{out}} = 0.001$.

that the outage capacity improves as the number of antennas increases for all three schemes. Expectedly, the TAS based scheme with feedback achieves the maximum outage capacity than other two schemes. The capacity gap between TAS with feedback and STC based scheme increases as the number of antennas increase as shown in the figure.

V. CONCLUSION

In this paper, we investigated the information theoretic limits of the interference temperature limited MISO-CR channel. In a CR-tx and rx pair with multiple antennas at transmitter side, the allowable transmit power is distributed over the transmit-antennas to achieve diversity at the receiver. We investigated the effect of this power distribution when peak interference power constraint is imposed to protect the P-rx. We proposed three transmission schemes based on space time coding and transmit antenna selection. The outage probability and the outage capacity of such systems are derived. We showed that the transmit diversity significantly improves the outage capacity under the peak interference temperature. Numerical as well as simulation results are given to support the arguments. For STC based scheme, we investigated the orthogonal space-time code that gives upper bounds of the performance. In this paper, we also assumed that the channel power gains among antennas are uncorrelated. Performance losses due to the loss of orthogonality and due to the antenna correlation are interesting topics for future research. In this paper, we consider peak interference power constraint on the P-rx. Similar analysis with average interference constraint would be a good topic for further research.

APPENDIX

A. PDF and CDF of g_m/h_m

If g_m and h_m are rvs of exponential distribution with parameter λ_g and λ_h respectively then the PDF and CDF of g_m/h_m can be given using [12, (6-60)] as

$$f_{\frac{g_m}{h_m}}(z) = \int\limits_{y=0}^{\infty} y f_{g_m}(yz) f_{h_m}(y)dy = \frac{\lambda_g\lambda_h}{(z\lambda_g+\lambda_h)^2}, \quad (15)$$

$$F_{\frac{g_m}{h_m}}(z) = \int\limits_{0}^{z} f_{\frac{g_m}{h_m}}(z)dz = \frac{z\lambda_g}{z\lambda_g+\lambda_h}. \quad (16)$$

B. PDF and CDF of g_T/h_T

For Rayleigh fading, random variables, g_m and h_m, for all m, are the exponential random variables with parameter λ_g and λ_h, respectively. Hence, g_T and h_T are the random variables with chi-square distribution with $2M$ degree of freedom. The PDF of g_T and h_T can be written as [13, (9.5)]

$$f_{g_T}(x)\frac{\lambda_g}{(M-1)!}x^{M-1}e^{-\lambda_g x}, \quad (17)$$

$$f_{h_T}(y)\frac{\lambda_h}{(M-1)!}y^{M-1}e^{-\lambda_h y}. \quad (18)$$

The PDF of the random variable g_T/h_T can be written as [12, 6-60]

$$\begin{aligned} f_{\frac{g_T}{h_T}}(z) &= \int\limits_{y=0}^{\infty} y f_{g_T}(yz) f_{h_T}(y)dy \\ &= \frac{\lambda_g\lambda_h}{\{(M-1)!\}^2}\int\limits_{y=0}^{\infty} y^{2M-1}z^{M-1}e^{-(\lambda_g z+\lambda_h)y}dy \\ &= \frac{\lambda_g\lambda_h\Gamma(2M)}{\{(M-1)!\}^2}z^{M-1}(\lambda_g z+\lambda_h)^{-2M}. \quad (19) \end{aligned}$$

Now, the CDF of $\frac{g_T}{h_T}$ can be given as

$$\begin{aligned} F_{\frac{g_T}{h_T}}(z) &= \int\limits_{0}^{z} f_{\frac{g_T}{h_T}}(z)dz \\ &= \frac{\lambda_g\lambda_h\Gamma(2M)}{\{(M-1)!\}^2}\frac{z^M}{M\lambda_h^{2M}} \\ &\quad\cdot {}_2F_1(M,2M;M+1;-\lambda_g z/\lambda_h) \quad (20) \end{aligned}$$

where $\Gamma(\cdot)$ is the gamma function and ${}_2F_1(\cdot,\cdot;\cdot;\cdot)$ is the Gaussian hypergeometric function [14].

REFERENCES

[1] J. Mitola III and G. Q. Maguire, Jr., "Cognitive radio: Making sofrware radios more personal," *IEEE Pers. Commun.*, vol. 6, pp. 13–18, Aug. 1999.

[2] N. Devroye, M. Vu, and V. Tarokh, "Cognitive radio networks," *IEEE Signal Process. Mag.*, vol. 25, pp. 12–23, Nov. 2008.

[3] A. Ghasemi and E. S. Sousa, "Fundamental limits of spectrum-sharing in fading environments," *IEEE Trans. Wireless Commun.*, vol. 6, pp. 649–658, Feb. 2007.

[4] X. Kang, Y.-C. Liang, A. Nallanathan, H. K. Garg, and R. Zhang, "Optimal power allocation for fading channels in cognitive radio networks: Ergodic capacity and outage capacity," *IEEE Trans. Wireless Commun.*, vol. 8, pp. 940–950, Feb. 2009.

[5] L. Musavian and S. Aissa, "Ergodic and outage capacities of spectrum-sharing systems in fading channels," in *Proc. IEEE GLOBECOM*, 2007, pp. 3327–3331.

[6] A. Goldsmith, S. A. Jafar, N. Jindal, and S. Vishwanath, "Capacity limits of MIMO channels," *IEEE J. Sel. Areas Commun.*, vol. 21, pp. 684–702, June 2003.

[7] V. Tarokh, N. Seshadri, and A. R. Calderbank, "Space-time codes for high data rate wireless communication: performance criterion and code construction," *IEEE Trans. Inf. Theory*, vol. 44, pp. 744–756, Mar. 1998.

[8] G. Caire, G. Taricco, and E. Biglieri, "Optimum power control over fading channels," *IEEE Trans. Inf. Theory*, vol. 45, pp. 1468–1489, July 1999.

[9] L. Li, S. A. Vorobyov, and A. B. Gershman, "Transmit antenna selection based strategies in MISO communication systems with low-rate channel state feedback," *IEEE Trans. Wireless Commun.*, vol. 8, pp. 1660–1666, Apr. 2009.

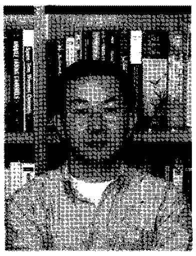
[10] J. M. Peha, "Approaches to spectrum sharing," *IEEE Commun. Mag.*, vol. 43, no. 2, pp. 10–12, 2005.

[11] A. Goldsmith, *Wireless Communications*, Cambridge; New York: Cambridge University Press, 2005.

[12] A. Papoulis and S. U. Pillai, *Probability, Random Variables, and Stochastic Processes.* Boston: McGraw-Hill, 4th ed., 2002.

[13] M. K. Simon and M.-S. Alouini, *Digital Communication over Fading Channels*, Hoboken, N.J.: John Wiley & Sons, 2nd ed., 2005.

[14] I. S. Gradshteyn, I. M. Ryzhik, A. Jeffrey, and D. Zwillinger, *Table of Integrals, Series and Products.* Amsterdam; Boston: Elsevier, 7th ed., 2007.



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