Outage Probability of Cognitive Heterogeneous Networks with Multiple Primary Users and Unreliable Backhaul Connections

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Abstract. A cognitive heterogeneous network with unreliable backhaul connections is studied in this paper. In this system, a macro-base station connected to cloud transmits information to multiple small cells via backhaul links. In addition, multiple small cells acting as secondary transmitters send information to a receiver by sharing the same spectrum with multiple primary users. Bernoulli process is adopted to model the backhaul reliability. Selection combining protocol is used at the receiver side to maximize the received signal-to-noise ratio. We investigate the impacts of the number of small-cells, the number of primary users as well as the backhaul reliability on the system performance, i.e., outage probability in Rayleigh fading channels. Closed-form expressions are derived and asymptotic analysis is also provided.

Keywords: Cognitive radio network · Wireless unreliable backhaul
Heterogeneous network · Multiple primary users

1 Introduction

In order to satisfy the increasing data traffic demand, future networks are expected to be more dense and heterogeneous [1]. To cope with increasing demand at the access, millimeter wave band can be exploited [2]. In addition, another approach is heterogeneous networks (HetNets), low power small cells including microcells, picocells, femtocells etc. are deployed within the high power macrocells coverage area to achieve substantial gains in coverage and capacity [3–5]. In HetNets, the conventional wired backhaul provides solid connections between macrocells and small cells. However, when a large number of small cells is needed to cover dense scenarios, the cost for the deployment and maintenance is high. To overcome the disadvantage, wireless backhaul has emerged as a suitable solution. However, wireless backhaul is not as reliable as wired backhaul

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due to wireless channel impairments such as non-line-of-sight (nLOS) propagation and channel fading [6].

Several previous works have studied the impact of unreliable backhaul on system performance [1,6–16]. In [6,10,11,14–16], the impact of unreliable backhaul on cooperative relay systems was investigated. In [11], the outage probability of finite-sized selective relaying systems with unreliable backhaul was studied, and the transmitter-relay pair providing the highest end-to-end signal-to-noise ratio (SNR) was selected for transmission. In the aforementioned studies about unreliable backhaul connections, backhaul reliability has been shown as a key factor for the system performance.

The increasing wireless demands for frequencies have caused the spectrum to be exhausted [17]. In HetNets, frequency sharing is essential to increase the spectral efficiency and system capacity, thus to achieve better system performance. Cognitive radio (CR) technology is considered as a promising solution to solve the spectrum scarcity [18]. In the cognitive radio network (CRN), a secondary user (SU) is allowed to use the spectrum that is prior allocated to a primary user (PU) if the interference caused by SUs to the PUs is within an acceptable tolerance level [19]. In [20], the outage probability of the cognitive radio network has been evaluated and the impact of a single PU on the SU's systems has been studied. In [21], other aspects such as the impact of the PU on the energy harvesting CRN was also studied. However, in the CRN, SUs cooperating with a single PU is not sufficient to exploit the cooperation benefits. Recently, some works have investigated a CRN with multiple PUs, which is more practical and realistic [22,23]. However, all of the research related to CR technology [20,22–26] ignored the impact of unreliable backhaul.

The very recent works [8,9,12] introduced CR technology to HetNets and examined the impact of unreliable backhaul on CRNs. In [8], a single transmitter acting as a small cell was considered in the system. However, in the real scenarios, there can be large number of transmitters rather than a single transmitter. There is likely to be several small cells in HetNets to cooperate and achieve better system performance. Therefore, in this research, we assume a cognitive HetNet system with multiple small cells that can be accounted for more scenarios. To the best of our knowledge, there is no previous research that study backhaul reliability in a CRN with multiple PUs. Therefore, we propose a cognitive heterogeneous network with multiple small cells acting as secondary transmitters and multiple PUs that limit the transmit power of secondary transmitters in the system. Our main contributions are summarized as follows:

- For the first time, we propose a cognitive heterogeneous network with multiple small cell transmitters and primary users. In addition, the reliability of the backhaul is modeled as Bernoulli process [6].
- Selection combining is used to choose the best small cell that has the maximum SNR at the destination. The impacts of backhaul reliability, the number of small cells and primary users on the system performance are examined.

- Closed-form and asymptotic expressions for outage probability are derived. Moreover, numerical results are conducted to verify the system performance using Monte Carlo simulations.

The remainder of the paper is organized as follows. System and channel models are described in Sect. 2. Derivation of the SNR distributions in the proposed system is obtained in Sect. 3. The closed-form expressions for outage probability are carried out in Sect. 4, while numerical results are presented in Sect. 5. Finally, the paper is concluded in Sect. 6.

Notation: $P[\cdot]$ is the probability of occurrence of an event. For a random variable X, $F_X(\cdot)$ denotes its cumulative distribution function (CDF) and $f_X(\cdot)$ denotes the corresponding probability density function (PDF). In addition, $\max(\cdot)$ and $\min(\cdot)$ denote the maximum and minimum of their arguments, respectively.

2 System and Channel Models

We consider a cognitive heterogeneous network consisting of a macro-base station (BS) connected to cloud, K small cells as the secondary transmitters $\{SC_1...SC_k,...SC_K\}$, a secondary receiver ($SU-D$) as the destination and N primary users $\{PU_1...PU_n,...PU_N\}$, as shown in Fig. 1. The BS is connected to K small cells by unreliable wireless backhaul links. The K small cells send information to the destination while using the same spectrum of N primary users. All nodes are supposed to be equipped with a single antenna. Assuming all the

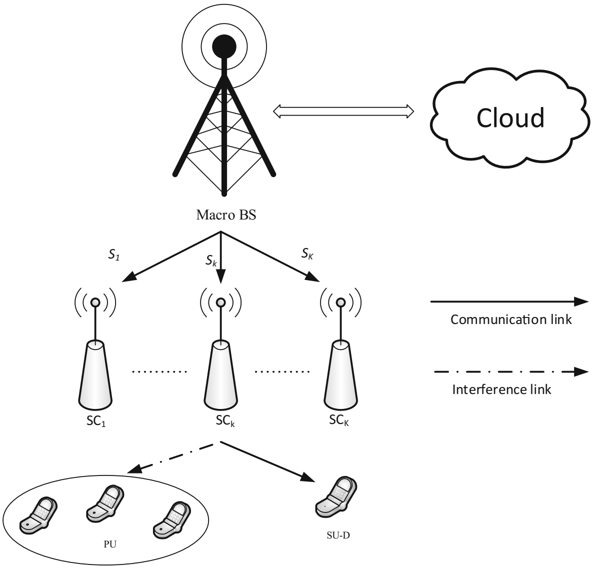

Fig. 1. A cognitive heterogeneous network with multiple primary users and multiple small cells acting as secondary users

channels are Rayleigh fading and are independent and identically distributed, in which the channel power gains are exponential distributed with parameter λ_X for $X = \{\lambda_{kp}, \lambda_{ks}\}$. The link $SC - PU$ follows exponential distribution with parameter λ_{kp}, and the link $SC - SU$ follows exponential distributed with parameter λ_{ks}. In the CRN, the secondary network consists K secondary transmitters and a $SU - D$, they can operate in the same spectrum licensed to PUs as long as they do not cause any harmful interference to PUs. The maximum tolerable interference power at the PU are I_p. Assuming the transmit powers at the secondary transmitters are limited to P_T [20]. In this way, the transmit power at the secondary transmitters can be written as

$$P_k = \min\left(P_T, \frac{I_p}{\max\limits_{i=1,\ldots,N} |h_{\mathsf{kp}_i}|^2}\right), \tag{1}$$

where h_{kp_i}, $i = \{1, \ldots n, \ldots N\}$ donates the channel coefficients of the interference link from SC to PUs. Without considering the backhaul reliability, the instantaneous received SNR of the link SC to $SU - D$ is given as

$$\gamma_{\mathsf{ks}} = \min\left(\gamma_{\mathsf{P}}|h_{\mathsf{ks}}|^2, \frac{\gamma_{\mathsf{I}}}{\max\limits_{i=1,\ldots,N} |h_{\mathsf{kp}_i}|^2}|h_{\mathsf{ks}}|^2\right), \tag{2}$$

where h_{ks} donates the channel coefficients of the interference link from SC to $SU - D$. The average SNR of the primary network is given as $\gamma_{\mathsf{I}} = \frac{I_p}{\sigma_n^2}$, and the average SNR of the secondary networks is given as $\gamma_{\mathsf{P}} = \frac{P_t}{\sigma_n^2}$, where σ_n^2 is the noise variance.

Considering the backhaul reliability, the signal received at the destination $SU - D$ is given as

$$y_{ks} = \sqrt{P_k} h_{\mathsf{ks}} \mathbb{I}_k x + n_{ks}, \tag{3}$$

where P_k is given in (1), n_{ks} is the complex additive white Gaussian noise (AWGN) with zero mean and variance σ, i.e., $z \sim CN(0, \sigma)$.

In the first hop, the signal is transmitted from BS to the small cells via unreliable backhaul links. The unreliable backhaul links can perform either success or failure transmission. So the reliability backhaul is modeled as Bernoulli process $\mathbb{I}_k$ with success probability s_k where $P(\mathbb{I}_{k^*} = 1) = s_k$ and $P(\mathbb{I}_{k^*} = 0) = 1 - s_k$. This indicates that the probability of the message successfully delivered over its dedicated backhaul is s_k, however, the failure probability is $1 - s_k$. Assume that x is the desired transmitted signal from BS to $SU - D$.

In the second hop, selection combining protocol is used at the destination $SU - D$ in order to select the best small cell that has the maximum SNR to transmit the signal. The small cell SC_{k^*} is selected as

$$k^* = \max_{k=1,\ldots,K} \arg\left(\gamma_{\mathsf{ks}} \mathbb{I}_k\right), \tag{4}$$

In this way, considering the backhaul reliability, the end-to-end SNR at the receiver $SU-D$ can be rewritten as

$$\gamma_{\mathsf{s}} = \min\left(\gamma_{\mathsf{P}}|h_{\mathsf{k}^*\mathsf{s}}|^2, \frac{\gamma_{\mathsf{I}}}{\max\limits_{i=1,\ldots,N}|h_{\mathsf{k}^*\mathsf{p}_i}|^2}|h_{\mathsf{k}^*\mathsf{s}}|^2\right)\mathbb{I}_{k^*}. \tag{5}$$

3 SNR Distributions in Cognitive Heterogeneous Systems

In this section, the distributions of the SNRs are derived, and the system performances are studied based on the derivations in the next section.

From the end-to-end SNR in (5), assume $Y = \max\limits_{i=1,\ldots,N}|h_{\mathsf{kp}_i}|^2$, the CDF and PDF of Y can be given as

$$F_Y(y) = \left[1-\exp(-\lambda y)\right]^N, \tag{6}$$

$$f_Y(y) = \lambda N\sum_{i=0}^{N-1}(-1)^i\binom{N-1}{i}\exp\left[-\lambda(i+1)y\right]. \tag{7}$$

Without considering the impact of backhaul reliability, the CDF of the end-to-end SNR given in (2) can be written as,

$$\begin{aligned}F_{\gamma_{\mathsf{ks}}}(x) = 1 + &\sum_{n=1}^{N}(-1)^n\binom{N}{n}\exp(-\frac{\gamma_{\mathsf{P}}\gamma_{\mathsf{I}}n}{\gamma_{\mathsf{P}}}) - \exp(-\frac{\lambda_{ks}}{\gamma_{\mathsf{P}}}) - \sum_{n=1}^{N}(-1)^n\binom{N}{n}\\ \exp\left(-\frac{\gamma_{\mathsf{P}}\gamma_{\mathsf{I}}n+\lambda_{ks}x}{\gamma_{\mathsf{P}}}\right) &+ N\sum_{i=0}^{N-1}\frac{(-1)^i}{i+1}\binom{N}{i}\exp\left[-\frac{\gamma_{\mathsf{kp}}\gamma_{\mathsf{I}}(i+1)}{\gamma_{\mathsf{P}}}\right] - N\sum_{i=0}^{N-1}(-1)^i\\ \binom{N-1}{i}\frac{\lambda_{kp}}{\frac{\lambda_{ks}x}{\gamma_{\mathsf{I}}}+\lambda_{kp}(i+1)}&\exp\left[\frac{\gamma_{\mathsf{I}}}{\gamma_{\mathsf{P}}}\left(-\frac{\lambda_{ks}x}{\gamma_{\mathsf{I}}}-\lambda_{kp}(i+1)\right)\right]\end{aligned} \tag{8}$$

Proof

$$\begin{aligned}F_{\gamma_{\mathsf{ks}}}(x) &= P\left[\min\left(\gamma_{\mathsf{P}}|h_{\mathsf{ks}}|^2, \frac{\gamma_{\mathsf{I}}}{Y}|h_{\mathsf{ks}}|^2\right)\leq x\right]\\ &= \underbrace{P\left[|h_{\mathsf{ks}}|^2\leq\frac{x}{\gamma_{\mathsf{P}}};\frac{\gamma_{\mathsf{I}}}{Y}\geq\gamma_{\mathsf{P}}\right]}_{J_1} + \underbrace{P\left[\frac{|h_{\mathsf{ks}}|^2}{Y}\leq\frac{x}{\gamma_{\mathsf{I}}};\frac{\gamma_{\mathsf{I}}}{Y}\leq\gamma_{\mathsf{P}}\right]}_{J_2}\end{aligned} \tag{9}$$

For the term J_1, because $|h_{\mathsf{ks}}|^2$ and $|h_{\mathsf{kp}_i}|^2$ are independent and $Y = \max\limits_{i=1,\ldots,N}|h_{\mathsf{kp}_i}|^2$, J_1 can be expanded as

$$\begin{aligned}J_1 &= P\left[|h_{\mathsf{ks}}|^2\leq\frac{x}{\gamma_{\mathsf{P}}};Y\leq\frac{\gamma_{\mathsf{I}}}{\gamma_{\mathsf{P}}}\right]\\ &= F_{\gamma_{\mathsf{ks}}}(\frac{x}{\gamma_{\mathsf{P}}})\left[F_{\gamma_{\mathsf{kp}}}(\frac{\gamma_{\mathsf{I}}}{\gamma_{\mathsf{P}}})\right]^N.\end{aligned} \tag{10}$$

For the term J_2, the concept of probability theory is used and with the help of (7), J_2 is expressed as

$$\begin{aligned} J_2 &= P\left[|h_{\mathsf{ks}}|^2 \leq \frac{xY}{\gamma_{\mathsf{I}}}; Y \geq \frac{\gamma_{\mathsf{I}}}{\gamma_{\mathsf{P}}}\right] \\ &= \int_0^{\frac{xY}{\gamma_{\mathsf{I}}}} f_{|h_{\mathsf{ks}}|^2}(y) \int_{\frac{\gamma_{\mathsf{I}}}{\gamma_{\mathsf{P}}}}^{\infty} f_{|h_{\mathsf{kp}_i}|^2}(z) dydz. \end{aligned} \tag{11}$$

The above Eq. (8) is the CDF of SNR without considering the unreliable backhual, we now take into account the backhaul reliability and derive the CDF of the end-to-end SNR given in (5) as follows.

The PDF of $\gamma_{\mathsf{ks}}\mathbb{I}_k$ is modeled by the mixed distribution,

$$f_{\gamma_{\mathsf{ks}}\mathbb{I}_k}(x) = (1-s)\delta(x) + s\frac{\partial F_{\gamma_{\mathsf{ks}}}(x)}{\partial x}, \tag{12}$$

where $\delta(x)$ is the Dirac delta function. According to (12), the CDF of the $\gamma_{\mathsf{ks}}\mathbb{I}_k$ is given as

$$F_{\gamma_{\mathsf{ks}}\mathbb{I}_k}(x) = \int_0^x f_{\gamma_{\mathsf{ks}}\mathbb{I}_k}(x)dx. \tag{13}$$

With the help of [27, Eq. (3.353.2)], the CDF is expressed as

$$\begin{aligned} F_{\gamma_{\mathsf{ks}}\mathbb{I}_k}(x) &= 1 - s\exp\left(-\frac{\lambda_{ks}x}{\gamma_{\mathsf{P}}}\right) - s\sum_{n=1}^{N}(-1)^n\binom{N}{n}\exp\left(-\frac{\lambda_{kp}\gamma_{\mathsf{I}}n + \lambda_{ks}x}{\gamma_{\mathsf{P}}}\right) \\ &+ s\sum_{n=1}^{N}(-1)^n\binom{N}{n}\exp\left(-\frac{\lambda_{kp}\gamma_{\mathsf{I}}n}{\gamma_{\mathsf{P}}}\right) + sN\sum_{i=0}^{N-1}\frac{(-1)^i}{i+1}\binom{N-1}{i}\exp\left[-\frac{\gamma_{\mathsf{I}}\lambda_{kp}(i+1)}{\gamma_{\mathsf{P}}}\right] \\ &- sN\sum_{i=0}^{N-1}(-1)^i\binom{N-1}{i}\frac{\lambda_{kp}}{\frac{x\lambda_{ks}}{\gamma_{\mathsf{I}}} + \lambda_{kp}(i+1)}\exp\left[-\frac{\gamma_{\mathsf{I}}\lambda_{kp}(i+1) + \lambda_{ks}x}{\gamma_{\mathsf{P}}}\right]. \end{aligned} \tag{14}$$

According to (4), k is selected when $\gamma_{\mathsf{ks}}\mathbb{I}_k$ achieves the maximum value, since for all random variables $\gamma_{\mathsf{ks}}\mathbb{I}_k$ are independent and identically distributed. The CDF of SNR γ_{s} can be written as

$$
\begin{aligned}
&F_{\gamma_{\mathsf{s}}}(x) = F^{K}_{\gamma_{\mathsf{ks}}\mathbb{I}_k}(x) \\
&= 1 - \sum_{k=1}^{K}(-1)^k \binom{K}{k} s^k \sum_{j=0}^{k}\binom{k}{j} \sum_{m=0}^{k-j}\binom{k-j}{m} \exp\left[-\frac{\lambda_{ks}x(k-j-m)}{\gamma_{\mathsf{P}}}\right] \\
&\sum_{p=0}^{m}(-1)^p\binom{m}{p}\exp\left(-\frac{\lambda_{ks}xp}{\gamma_{\mathsf{P}}}\right)\sum_{a_1,\dots a_N}^{m}\binom{m}{a_1\dots a_N}\prod_{t=1}^{N}\left[\binom{N}{t}\right]^{a_t}(-1)^{ta_t} \\
&\exp\left(-\frac{\lambda_{kp}\gamma_{\mathsf{I}}ta_t}{\gamma_{\mathsf{P}}}\right)\sum_{q=0}^{k}(N)^q\binom{k}{q}\exp\left(-\frac{\lambda_{ks}xq}{\gamma_{\mathsf{P}}}\right)\sum_{b_0,\dots b_{N-1}}^{q}\binom{q}{b_0\dots b_{N-1}}\prod_{r=0}^{N-1} \\
&\left[\binom{N-1}{r}\right]^{b_r}(-1)^{rb_r}\exp\left[-\frac{\lambda_{kp}\gamma_{\mathsf{I}}(r+1)b_r}{\gamma_{\mathsf{P}}}\right]\left[\frac{\lambda_{kp}}{\frac{\lambda_{ks}x}{\gamma_{\mathsf{I}}}+\lambda_{kp}(r+1)}\right]^{b_r}(-N)^{k-q} \\
&\sum_{c_0,\dots c_{N-1}}^{k-q}\binom{k-q}{c_0\dots c_{N-1}}\prod_{d=0}^{N-1}\left[\binom{N-1}{d}\right]^{c_d}\frac{(-1)^{c_d d}}{d+1}\exp\left[-\frac{\lambda_{kp}\gamma_{\mathsf{I}}(d+1)c_d}{\gamma_{\mathsf{P}}}\right].
\end{aligned}
\tag{15}
$$

4 Performance Analysis of the Proposed System

This section studies the performance of outage probability utilizing the SNR distributions obtained in the previous section. Closed-form expressions are derived and asymptotic calculation is also provided to evaluate the system performance.

4.1 Outage Probability Analysis

The outage probability is defined as the probability that the SNR falls below a certain threshold γ_{th},

$$
P_{out}(\gamma_{\mathsf{th}}) = P(\gamma_{\mathsf{s}} \le \gamma_{\mathsf{th}}) = F_{\gamma_{\mathsf{s}}}(\gamma_{\mathsf{th}}). \tag{16}
$$

The outage probability closed-form expressions of the proposed system,

$$
\begin{aligned}
&P_{\gamma_{\mathsf{s}}}(\gamma_{\mathsf{th}}) = 1 - \sum_{k=1}^{K}(-1)^k \binom{K}{k} s^k \sum_{j=0}^{k}\binom{k}{j} \sum_{m=0}^{k-j}\binom{k-j}{m} \exp\left[-\frac{\lambda_{ks}\gamma_{\mathsf{th}}(k-j-m)}{\gamma_{\mathsf{P}}}\right] \\
&\sum_{p=0}^{m}(-1)^p\binom{m}{p}\exp\left(-\frac{\lambda_{ks}\gamma_{\mathsf{th}}p}{\gamma_{\mathsf{P}}}\right)\sum_{a_1,\dots a_N}^{m}\binom{m}{a_1\dots a_N}\prod_{t=1}^{N}\left[\binom{N}{t}\right]^{a_t}(-1)^{ta_t}\exp\left(-\frac{\lambda_{kp}\gamma_{\mathsf{I}}ta_t}{\gamma_{\mathsf{P}}}\right) \\
&\sum_{q=0}^{k}(N)^q\binom{k}{q}\exp\left(-\frac{\lambda_{ks}\gamma_{\mathsf{th}}q}{\gamma_{\mathsf{P}}}\right)\sum_{b_0,\dots b_{N-1}}^{q}\binom{q}{b_0\dots b_{N-1}}\prod_{r=0}^{N-1}\left[\binom{N-1}{r}\right]^{b_r}(-1)^{rb_r} \\
&\exp\left[-\frac{\lambda_{kp}\gamma_{\mathsf{I}}(r+1)b_r}{\gamma_{\mathsf{P}}}\right]\left[\frac{\lambda_{kp}}{\frac{\lambda_{ks}\gamma_{\mathsf{th}}}{\gamma_{\mathsf{I}}}+\lambda_{kp}(r+1)}\right]^{b_r}(-N)^{k-q}\sum_{c_0,\dots c_{N-1}}^{k-q}\binom{k-q}{c_0\dots c_{N-1}} \\
&\prod_{d=0}^{N-1}\left[\binom{N-1}{d}\right]^{c_d}\frac{(-1)^{c_d d}}{d+1}\exp\left[-\frac{\lambda_{kp}\gamma_{\mathsf{I}}(d+1)c_d}{\gamma_{\mathsf{P}}}\right].
\end{aligned}
\tag{17}
$$

Asymptotic Analysis. In the high SNR regime, when $\gamma_{\mathsf{P}} \rightarrow \infty$ in the proposed cognitive heterogeneous network, the asymptotic is given by

$$P_{out}^{Asy}(\gamma_{\mathsf{th}}) = (1 - s)^{K}. \tag{18}$$

5 Numerical Results and Discussions

In this section, numerical results of the outage probability are studied to evaluate the impacts of backhaul reliability, the number of primary transmitters and secondary transmitters on the system performance. The 'Sim' curves are the simulation results, 'Ana' curves indicate analytical results and 'Asy' curves donate the asymptotic results. In the figures, we can observe that both the simulation curves and analytical curves match very well. In this section, the threshold of outage probability is fixed at $\gamma_{\mathsf{th}} = 3$ dB and the location of the nodes are $SC = (0.5, 0)$, $SU - D =(0, 0)$, $PU =(0.5, 0.5)$ in Cartesian coordinate system respectively. Hence, the distance between two nodes can be found as $d_{AB}{=}\sqrt{(x_A - x_B)^2 + (y_A - y_B)^2}$, where A and B have the co-ordinates (x_A, y_A) and (x_B, y_B) and $A, B = \{SC, PU, SU - D\}$. It is assumed that average SNR of each link is dependent on the path loss as $1/\lambda_X = 1/d_X^{pl}$, where pl is the path loss exponent and $pl = 4$ is assumed. Moreover, we also assume that the average SNR $\gamma_{\mathsf{P}}{=}\gamma_{\mathsf{I}}$.

5.1 Outage Probability Analysis

The figures in this section show the impacts of backhaul reliability s, the number of primary users PUs and secondary transmitters SCs on the system performance. In Fig. 2, s is fixed at 0.99 and the number of PUs is 3. Assuming the number of SCs is $K = 1$, $K = 2$, $K = 3$ to evaluate the impact of the number of SCs on system performance. In the figures, when the number of SCs increase, the outage probability decreases and the system can achieve a better performance due to the correlation of multiple signals at the receiver. Also, all the curves converage to the asymptotic limitation.

In Fig. 3, the outage probability behaviour at different backhaul reliability is investigated. $N = 3$ and $K = 3$ is assumed in this scenario. We assume that $s = 0.99$, $s = 0.90$ and $s = 0.80$ to evaluate the impact of backhaul reliability on the system performance. In Fig. 3, when s increases, the system performs better as the outage probability decreases. This is because when the probability of the information successfully delivered over the backhaul links gets higher, the system can achieve a better performance.

In Fig. 4, the outage probability with different number of PUs is investigated. we asume that $s = 0.99$ and $K = 3$. We can observe that in low-SNR regime, when N increases, the system performance gets worse. This is because when the number of PUs increases, SCs must satisfy the power constraints of all the PUs. The power constraints would get tighter when the number of PUs increases. The transmit power of SCs would reduce due to the increasing power constraints.

However, in high SNR regime, increasing the number of PUs does not have any effect on the system performance, as is shown in (18). According to Figs. 2, 3 and 4, in high SNR regime, only the backhaul reliability and the number of SCs can affect the system performance.

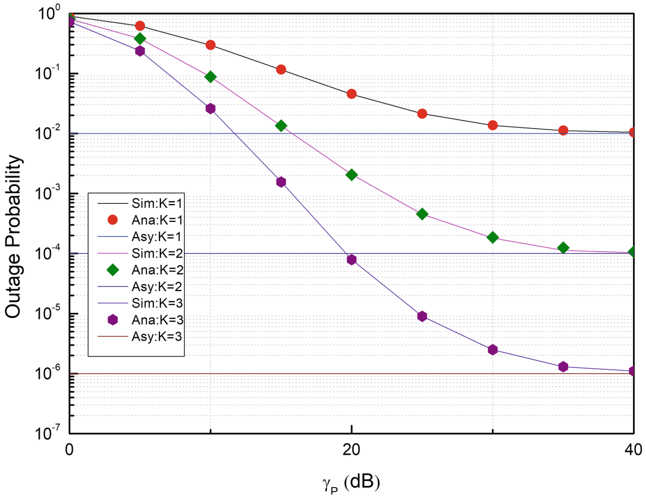

Fig. 2. Outage probability with different number of secondary transmitters at a fixed backhaul reliability ($s = 0.99$) and a fixed number of primary users ($N = 3$)

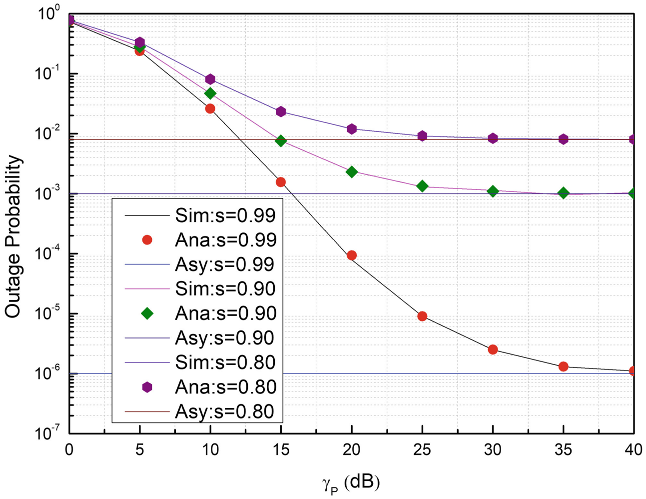

Fig. 3. Outage probability with different backhaul reliability at a fixed number of secondary transmitters ($K = 3$) and a fixed number of primary users ($N = 3$)

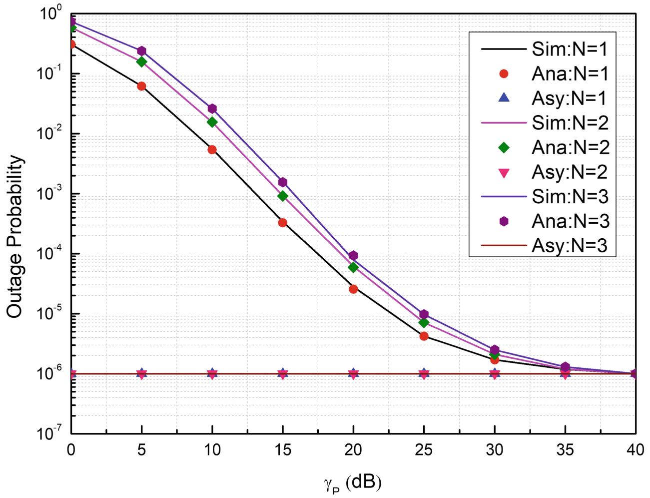

Fig. 4. Outage probability with different number of primary users at a fixed number of secondary transmitters ($K = 3$) and a fixed backhaul reliability ($s = 0.99$)

6 Conclusions

In this paper, we propose a cognitive heterogeneous network with multiple small cell transmitters and primary users to investigate the impacts of backhaul reliability, the number of small cells and primary users on the system performance. The backhaul reliability is modeled as Bernoulli process. Selection combining is used to choose the best small cell, having the maximum SNR at the destination. Closed-form expressions for outage probability are derived and asymptotic analysis is provided. It has been shown that, when the number of cooperative nodes and backhaul reliability increase, the system performs better. Moreover, the increase of the primary users' number can decrease the system performance within low-SNR regime.

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References

1. Kim, K.J., Khan, T.A., Orlik, P.V.: Performance analysis of cooperative systems with unreliable backhauls and selection combining. IEEE Trans. Veh. Technol. **66**(3), 2448–2461 (2017)
2. Scott-Hayward, S., Garcia-Palacios, E.: Channel time allocation PSO for gigabit multimedia wireless networks. IEEE Trans. Multimed. **16**(3), 828–836 (2014)

3. ElSawy, H., Hossain, E., Kim, D.I.: Hetnets with cognitive small cells: user offloading and distributed channel access techniques. IEEE Commun. Mag. **51**(6), 28–36 (2013)
4. Madan, R., Borran, J., Sampath, A., Bhushan, N., Khandekar, A., Ji, T.: Cell association and interference coordination in heterogeneous LTE-A cellular networks. IEEE J. Sel. Areas Commun. **28**(9), 1479–1489 (2010)
5. Nguyen, L.D., Tuan, H.D., Duong, T.Q.: Energy-efficient signalling in QoS constrained heterogeneous networks. IEEE Access **4**, 7958–7966 (2016)
6. Yin, C., Nguyen, H.T., Kundu, C., Kaleem, Z., Garcia-Palacios, E., Duong, T.Q.: Secure energy harvesting relay networks with unreliable backhaul connections. IEEE Access **6**, 12074–12084 (2018)
7. Ali, M.S., Synthia, M.: Performance analysis of JT-CoMP transmission in heterogeneous network over unreliable backhaul. In: 2015 International Conference on Electrical Engineering and Information Communication Technology (ICEEICT), pp. 1–5. IEEE (2015)
8. Nguyen, H.T., Duong, T.Q., Dobre, O.A., Hwang, W.-J.: Cognitive heterogeneous networks with best relay selection over unreliable backhaul connections. In: 2017 IEEE 86th Vehicular Technology Conference (VTC-Fall), pp. 1–5. IEEE (2017)
9. Nguyen, H.T., Ha, D.-B., Nguyen, S.Q., Hwang, W.-J.: Cognitive heterogeneous networks with unreliable backhaul connections. Mob. Netw. Appl., 1–14 (2017)
10. Liu, H., Kim, K.J., Tsiftsis, T.A., Kwak, K.S., Poor, H.V.: Secrecy performance of finite-sized cooperative full-duplex relay systems with unreliable backhauls. IEEE Trans. Signal Process. **65**(23), 6185–6200 (2017)
11. Liu, H., Kwak, K.S.: Outage probability of finite-sized selective relaying systems with unreliable backhauls. In: 2017 International Conference on Information and Communication Technology Convergence (ICTC), pp. 1232–1237. IEEE (2017)
12. Nguyen, H.T., Duong, T.Q., Hwang, W.-J.: Multiuser relay networks over unreliable backhaul links under spectrum sharing environment. IEEE Commun. Lett. **21**(10), 2314–2317 (2017)
13. Khan, T.A., Orlik, P., Kim, K.J., Heath, R.W.: Performance analysis of cooperative wireless networks with unreliable backhaul links. IEEE Commun. Lett. **19**(8), 1386–1389 (2015)
14. Kim, K.J., Yeoh, P.L., Orlik, P.V., Poor, H.V.: Secrecy performance of finite-sized cooperative single carrier systems with unreliable backhaul connections. IEEE Trans. Signal Process. **64**(17), 4403–4416 (2016)
15. Nguyen, H.T., Zhang, J., Yang, N., Duong, T.Q., Hwang, W.-J.: Secure cooperative single carrier systems under unreliable backhaul and dense networks impact. IEEE Access **5**, 18310–18324 (2017)
16. Kim, K.J., Orlik, P.V., Khan, T.A.: Performance analysis of finite-sized cooperative systems with unreliable backhauls. IEEE Trans. Wirel. Commun. **15**(7), 5001–5015 (2016)
17. Kim, K.J., Wang, L., Duong, T.Q., Elkashlan, M., Poor, H.V.: Cognitive single-carrier systems: joint impact of multiple licensed transceivers. IEEE Trans. Wirel. Commun. **13**(12), 6741–6755 (2014)
18. Deng, Y., Kim, K.J., Duong, T.Q., Elkashlan, M., Karagiannidis, G.K., Nallanathan, A.: Full-duplex spectrum sharing in cooperative single carrier systems. IEEE Trans. Cogn. Commun. Netw. **2**(1), 68–82 (2016)
19. Yin, C., Doan, T.X., Nguyen, N.-P., Mai, T., Nguyen, L.D.: Outage probability of full-duplex cognitive relay networks with partial relay selection. In: International Conference on Recent Advances in Signal Processing, Telecommunications & Computing (SigTelCom), pp. 115–118. IEEE (2017)

20. Duong, T., Bao, V.N.Q., Zepernick, H.-J.: Exact outage probability of cognitive AF relaying with underlay spectrum sharing. Electron. Lett. **47**(17), 1001–1002 (2011)
21. Zhang, J., Nguyen, N.-P., Zhang, J., Garcia-Palacios, E., Le, N.P.: Impact of primary networks on the performance of energy harvesting cognitive radio networks. IET Commun. **10**(18), 2559–2566 (2016)
22. Huang, H., Li, Z., Si, J.: Multi-source multi-relay underlay cognitive radio networks with multiple primary users. In: 2015 IEEE International Conference on Communications (ICC), pp. 7558–7563. IEEE (2015)
23. Feng, X., Gao, X., Zong, R.: Cooperative jamming for enhancing security of cognitive radio networks with multiple primary users. China Commun. **14**(7), 1–15 (2017)
24. Duong, T.Q., Yeoh, P.L., Bao, V.N.Q., Elkashlan, M., Yang, N.: Cognitive relay networks with multiple primary transceivers under spectrum-sharing. IEEE Signal Process. Lett. **19**(11), 741–744 (2012)
25. Tran, H., Duong, T.Q., Zepernick, H.-J.: Performance analysis of cognitive relay networks under power constraint of multiple primary users. In: 2011 IEEE Global Telecommunications Conference (GLOBECOM 2011), pp. 1–6. IEEE (2011)
26. Duong, T., Bao, V.N.Q., Tran, H., Alexandropoulos, G.C., Zepernick, H.-J.: Effect of primary network on performance of spectrum sharing AF relaying. Electron. Lett. **48**(1), 25–27 (2012)
27. Jeffrey, A., Zwillinger, D.: Table of Integrals, Series, and Products. Academic press, Cambridge (2007)