Cognitive Heterogeneous Networks with Multiple Primary Users and Unreliable Backhaul Connections

Received November 21, 2018, accepted December 13, 2018, date of publication December 18, 2018, date of current version January 11, 2019.

Digital Object Identifier 10.1109/ACCESS.2018.2887344

Cognitive Heterogeneous Networks With Multiple Primary Users and Unreliable Backhaul Connections

CHENG YIN[1], EMILIANO GARCIA-PALACIOS[1], NGUYEN-SON VO[2], AND TRUNG Q. DUONG[1], (Senior Member, IEEE)

[1]School of Electronics, Electrical Engineering and Computer Science, Queen's University Belfast, Northern Ireland, U.K.
[2]Duy Tan University, Da Nang, Vietnam

Corresponding author: Trung Q. Duong (trung.q.duong@qub.ac.uk)
This work was supported in part by the U.K. Engineering and Physical Sciences Research Council (EPSRC) under Grant EP/P019374/1 and by the Newton Fund Institutional Link through the Fly-by Flood Monitoring Project under Grant ID 428328486, which is delivered by the British Council.

ABSTRACT Wireless backhaul has emerged as a suitable and flexible alternative to wired backhaul; however, it is not as reliable as its wired counterpart. This paper presents, for the first time, a comprehensive model including a heterogeneous underlay cognitive network with small cells also acting as multiple secondary users, multiple primary users, and unreliable wireless backhaul. In this system, a macro-base station connects to multiple secondary transmitters via wireless backhaul links. In addition, multiple secondary transmitters send information to a secondary receiver by sharing the same spectrum with multiple primary users. A Bernoulli process is adopted to model the backhaul reliability. A selection combining protocol is used at the secondary receiver side to maximize the received signal-to-noise ratio. We investigate the impact of the number of secondary transmitters, the number of primary users, as well as the backhaul reliability on the system performance in Rayleigh fading channels. Two key constraints are considered on the system performance: 1) maximum transmit power at the secondary transmitters and 2) peak interference power at the primary users caused by secondary transmitters. Closed-form expressions for outage probability, ergodic capacity, and symbol error rate and the asymptotic expressions for outage probability and symbol error rate are derived. Moreover, closed-form expressions are also applicable to non-cooperative scenarios.

INDEX TERMS Cognitive radio network, wireless unreliable backhaul, heterogeneous network, multiple primary users.

I. INTRODUCTION

In order to satisfy the increasing data traffic demand, future networks are expected to be more dense and heterogeneous [1]. The increasing demand for wireless frequencies has caused the spectrum to be exhausted. In heterogeneous networks (HetNets), frequency sharing is essential to increase the spectral efficiency and system capacity, thus achieving better system performance. The cognitive radio network (CRN) concept was firstly proposed by Mitola and Maguire in 1999 [2] to increase the frequency utilization, and it is considered to be a promising solution to solve the spectrum scarcity. To cope with increasingly demand at the access, the millimeter wave band can be exploited [3]. Another approach to cope with traffic demand is exploiting HetNets, where low power small cells (i.e., microcells, picocells and femtocells) are deployed within the high power macrocell coverage area to achieve substantial gain in coverage and capacity [4], [5]. A two-tier cognitive network with macrocells and small cells was investigated in [4] and [6] which proves that the HetNet cognitive network concept can be deployed.

The conventional wired backhaul provides solid connections between macrocells and small cells, but the cost for the deployment and maintenance is high, especially when a large number of small cells is needed to cover dense scenarios. Wireless backhaul has emerged as a suitable and flexible solution to overcome cost. However, a wireless backhaul is not as reliable as wired backhaul because of non-line of sight (nLOS) and channel fading [7]. So, the impact of wireless backhaul on system performance is a concern.

Previous research has been carried out to model the nLOS wireless backhaul propagation channel, but only simulation was provided [8]. Coldrey *et al.* [8] consider point to point microwave links as backhaul. The channel model considers the effects of rain, oxygen absorption, antenna misalignment, noise, etc. on the system performance for a range of frequencies from 2.3 GHz to 73 GHz. The performance is determined by the operating frequency and the scenario. As frequencies increase there is a significant difference between ideal scenarios (no rain and no antenna alignment errors) and non-ideal scenarios (rain and antenna alignment errors). We assume one shot cooperative communication as in [1] meaning that if the message does not arrive through the dedicated backhaul, the transmitter (macro BS) refrains from re-transmission. In this way the backhaul reliability can be modeled as a Bernoulli process as in [1].

In recent years, some research has studied the impact of unreliable backhaul on system performance using Bernoulli process to model the backhaul link success or failure in order to propose an analytical framework to study the insight of the system model [1], [7], [9]–[18]. In [7], [11], and [14]–[17], the impact of unreliable backhaul on cooperative relay systems was investigated. In [17], 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. Previous research in [7], [11], [14], and [15] has taken into account physical layer security in relay systems with unreliable backhaul. In [14], the secrecy performance of finite-sized cooperative systems with unreliable backhaul was studied. A relay was considered in this system to extend the communication coverage and multiple eavesdroppers that could wiretap information from the relay and transmitters were also considered. In related research in [7] and [11], the authors also studied the secrecy performance in a cooperative relay system with unreliable backhaul. Liu *et al.* [11] examined full-duplex relay systems. Energy harvesting was taken into consideration in [7] and [18] to achieve green communications. In related research in [15], a friendly jammer was used to generate interference signals to eavesdroppers. On all the previously mentioned research, the backhaul reliability is a key factor for the system performance.

In underlay CRNs, 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, hence in this way overall capacity can be increased. In [19], the outage probability of a cognitive radio network was evaluated, and the impact of a single PU on the SUs was studied. In [20], other aspects such as the impact of the PU on an energy harvesting CRN was also studied. However, in CRNs models, SUs cooperating with just a single PU has some drawbacks i) it is not realistic and ii) it is not sufficient to exploit the cooperation benefits. Recently, some cooperation schemes have been extended to more complicated scenarios with multiple PUs, which is more practical and realistic [21], [22]. In [21], the outage probability of a multi-source multi-relay CRN with multiple primary transmitters and multiple primary receivers was investigated. In [22], the cooperative jamming between multiple PUs and a single SU in CRN was studied. In our research, a more complete system with multiple PUs is considered. It is worth pointing out that all of the above mentioned research related to CRN [19], [21]–[23] ignored the impact of unreliable backhaul.

Only recent research in [9], [10], and [12] examined the impact of backhaul reliability on CRNs. In [9], a single transmitter acting as a small cell was considered in the system, however, a single small cell is insufficient to exploit the cooperation benefits in real scenarios. It will be more practical to deploy several small cells connected to a macrocell to cooperate and achieve better system performance. In [10], a macrocell was transmitting to a secondary user via multiple secondary transmitters (small cells). The transmit power of secondary transmitters was limited by a single PU. As an extension to research in [10], a relay was considered to extend the coverage from transmitters to destination in [12]. However, both [10] and [12] considered a simplified scenario where there was only one PU in the system. As discussed before, a single PU is neither realistic nor sufficient in real scenarios. Moreover, we show that considering multiple PUs has important implications in performance. Therefore, in our research, we extend the single small cell model in [9] to multiple small cells and also extend the single PU in [10] and [12] to multiple PUs. This setting can account for more realistic scenarios and system performance has the potential to be improved. Until now the influence of multiple PUs and small cells on the secondary system performance with unreliable backhaul in such a cognitive HetNet context remained unknown. In addition, to the best of our knowledge, there is no previous research that study backhaul reliability in a CRN with multiple PUs. In our research, we show important consequences as multiple PUs decrease the performance of the secondary network.

Motivated by this, we propose an underlay cognitive heterogeneous network with multiple small cells acting as secondary transmitters and multiple PUs in the system that limit the transmit power of secondary transmitters. Our main contributions are summarized as follows:

- For the first time we propose an underlay cognitive heterogeneous network with multiple secondary transmitters and multiple PUs to investigate the impact of backhaul reliability, the number of secondary transmitters and the number of PUs on the system performance.
- 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 $P(\mathbb{I}_{k^*} = 0) = 1 - s_k$.
- Selection combining (SC) is used to choose the best secondary transmitter that has the maximum SNR at the secondary receiver. SC [24] is a switch technique that allows the receiver to only pick up the best signal and

use this one only as the other signals do not contribute to the system.

- A new closed-form expression for the CDF of the end-to-end SNR is derived. Compared with previous work [9], [10], [12], we consider a more practical and realistic scenario with multiple PUs and multiple secondary transmitters, and the system has the potential to be improved.
- The closed-form expressions for outage probability, ergodic capacity and symbol error rate of the are derived. The impacts of backhaul reliability, the number of secondary transmitters and the number of PUs on the system performance are investigated.
- In order to provide a complete study and explore the benefits of secondary transmitters' cooperation, we also derive closed-forms for special non-cooperative scenarios. The results show that the system performance with multiple cooperative secondary transmitters is improved compared with non-cooperative transmitter network as studied in [9].
- Asymptotic analysis for outage probability and symbol error rate is also studied to gain insight into the system. Moreover, numerical results are validated using Monte Carlo simulation. We can observe from the figures that both the simulation curves and analytical curves match very well.

The remainder of the paper is organized as follows. System and channel models are described in Section II. Derivation of the SNR distributions in the proposed system is obtained in Section III. The closed-form expressions for outage probability, ergodic capacity and symbol error rate as well as the asymptotic are carried out in Section IV, while numerical results are presented in Section V. Finally, the paper is concluded in Section VI.

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). max $(\cdot)$ and min $(\cdot)$ denote the maximum and minimum of their arguments, respectively.

II. SYSTEM AND CHANNEL MODELS

We consider an underlay cognitive heterogeneous network consisting of a macro-base station (BS) connected to cloud, K small cells as the secondary transmitters $\{SC_1 \ldots SC_k, \ldots SC_K\}$, a secondary receiver $SU-D$ and N primary users $\{PU_1 \ldots PU_n, \ldots PU_N\}$, as shown in Fig.1. We use the orthogonal frequency division multiple access (OFDMA) as the transmission scheme [13]. The BS is connected to K SCs by unreliable wireless backhaul links. The backhaul reliability for SCs is provided by s_k, and it represents the probability that the SCs can successfully decode the kth SC's signal from BS via unreliable backhaul. The SCs send information to the $SU-D$ while using the same spectrum of PUs. Note that, only the best SC with the highest SNR can be selected at the secondary destination. All nodes are supposed to be equipped with a single antenna. Assuming

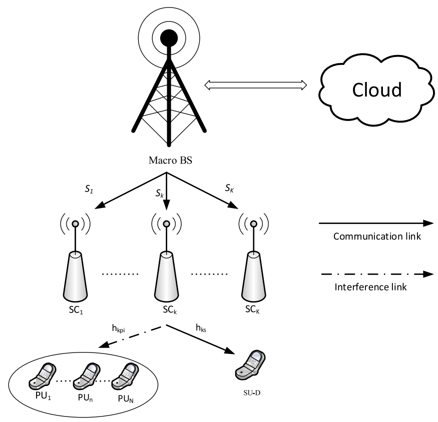

FIGURE 1. A cognitive heterogeneous network with multiple secondary transmitters, a secondary receiver and multiple primary users.

all the channels are Rayleigh fading and are independent and identically distributed (i.i.d), so the channel power gains are exponential distributed [13] with parameter λ_X for $X = \{\lambda_{kp}, \lambda_{ks}\}$. The channel power gain of the link from SCs to PU follows exponential distribution with parameter λ_{kp}, and the channel power gain of the link from SCs to $SU-D$ follows exponential distributed with parameter λ_{ks}. In the system model, the secondary transmitters SCs send the same data to a secondary receiver $SU-D$ using OFDM. We do not assume synchronization among the secondary transmitters SCs [13]. We assume that perfect channel state information (CSI) is available. The secondary receiver $SU-D$ knows perfect CSI of the links from SCs to $SU-D$ and the links from SCs to PU, which is a common assumption in CRNs [19], [23]. The CDF and PDF of the exponential distribution are given as

$$F_X(x) = 1 - \exp(-\lambda x), \tag{1}$$
$$f_X(x) = \lambda \exp(-\lambda x). \tag{2}$$

In underlay CRNs, the secondary network consists K SCs 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 PUs are I_p. Assuming the transmit powers at the SCs are limited to P_T [19]. In this way, the transmit power at the SCs can be written as

$$P_k = \min\left(P_T, \frac{I_p}{\max\limits_{i=1,\ldots,N} |h_{\mathsf{kp}_i}|^2}\right), \tag{3}$$

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

$$\gamma_{\mathsf{ks}} = \min\left(\gamma_{\mathsf{P}}|h_{\mathsf{ks}}|^2, \frac{\gamma_{\mathsf{I}}}{\max\limits_{i=1,\ldots,N} |h_{\mathsf{kp}_i}|^2}|h_{\mathsf{ks}}|^2\right), \tag{4}$$

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 network is given as $\gamma_{\mathsf{P}} = \frac{P_T}{\sigma_n^2}$, where σ_n^2 is the noise variance.

Assuming that x is the desired transmitted signal from BS to $SU-D$. Taken into account the backhaul reliability, the signal received at the destination $SU-D$ is given as

$$y_{ks} = \sqrt{P_k} h_{\mathsf{ks}} \mathbb{I}_k x + n_{ks}, \tag{5}$$

where P_k is given in (3), 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 SCs 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 $P(\mathbb{I}_{k^*}=0)=1-s_k$ [13]. This indicates that the probability of the message successfully delivered over its dedicated backhaul is s_k, however, the failure probability is $1-s_k$.

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

$$k^* = \max_{k=1,\ldots,K} \arg(\gamma_{\mathsf{ks}} \mathbb{I}_k). \tag{6}$$

In this way, considering the backhaul reliability, the end to end SNR at the receiver $SU-D$ (4) can be rewritten as

$$\gamma_{\mathsf{S}} = \min\left(\gamma_{\mathsf{P}}|h_{\mathsf{k^*s}}|^2, \frac{\gamma_{\mathsf{I}}}{\max\limits_{i=1,\ldots,N}|h_{\mathsf{k^*p}_i}|^2}|h_{\mathsf{k^*s}}|^2\right)\mathbb{I}_{k^*} \tag{7}$$

where h_{k^*s} is the channel coefficient from the selected SCs to $SU-D$, and $h_{k^*p_i}$ is the channel coefficient from the selected SCs to PUs.

III. 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 derivation in the next section.

From the end-to-end SNR in (7), assume $Y = \max\limits_{i=1,\ldots,N}|h_{\mathsf{kp}_i}|^2$, the CDF and PDF of Y can be given as

$$F_Y(y) = \left[1-\exp(-\lambda y)\right]^N, \tag{8}$$

$$f_Y(y) = \lambda N \sum_{i=0}^{N-1}(-1)^i \binom{N-1}{i} \exp\left[-\lambda(i+1)y\right]. \tag{9}$$

Without considering the impact of backhaul reliability, the CDF of the end-to-end SNR given in (4) can be written as,

$$\begin{aligned} F_{\gamma_{\mathsf{ks}}}(x) &= 1+\sum_{n=1}^{N}(-1)^n\binom{N}{n}\exp(-\frac{\gamma_{\mathsf{P}}\gamma_{\mathsf{I}}n}{\gamma_{\mathsf{P}}}) - \exp(-\frac{\lambda_{ks}}{\gamma_{\mathsf{P}}}) \\ &- \sum_{n=1}^{N}(-1)^n\binom{N}{n}\exp\left(-\frac{\gamma_{\mathsf{P}}\gamma_{\mathsf{I}}n+\lambda_{ks}x}{\gamma_{\mathsf{P}}}\right) \\ &+ N\sum_{i=0}^{N-1}\frac{(-1)^i}{i+1}\binom{N}{i}\exp\left[-\frac{\gamma_{\mathsf{kp}}\gamma_{\mathsf{I}}(i+1)}{\gamma_{\mathsf{P}}}\right] \\ &- N\sum_{i=0}^{N-1}(-1)^i\binom{N-1}{i}\frac{\lambda_{kp}}{\frac{\lambda_{ks}x}{\gamma_{\mathsf{I}}}+\lambda_{kp}(i+1)} \\ &\times \exp\left[\frac{\gamma_{\mathsf{I}}}{\gamma_{\mathsf{P}}}\left(-\frac{\lambda_{ks}x}{\gamma_{\mathsf{I}}}-\lambda_{kp}(i+1)\right)\right]. \end{aligned} \tag{10}$$

Proof: The proof is given in Appendix A. ■

The above equation 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 (7) as follows.

As individual links are i.i.d Rayleigh distributed, corresponding SNRs are exponentially distributed. Assuming success probability s for each link i.e., $s_k = s, \forall k$. The PDF of $\gamma_{\mathsf{ks}}\mathbb{I}_k$ is modeled by the mixed distribution,

$$f_{\gamma_{\mathsf{ks}}\mathbb{I}_k}(x) = (1-s)\delta(x) + s\frac{\partial F_{\gamma_{\mathsf{ks}}}(x)}{\partial x}, \tag{11}$$

where $\delta(x)$ is the Dirac delta function. According to (11), the CDF of the $\gamma_{\mathsf{ks}}\mathbb{I}_k$ is given as

$$F_{\gamma_{\mathsf{ks}}\mathbb{I}_k}(x) = \int_0^x f_{\gamma_{\mathsf{ks}}\mathbb{I}_k}(t)dt. \tag{12}$$

With the help of [25, eq. (3.353.2)], the CDF is expressed as

$$\begin{aligned} F_{\gamma_{\mathsf{ks}}\mathbb{I}_k}(x) &= 1 - s\exp\left(-\frac{\lambda_{ks}x}{\gamma_{\mathsf{P}}}\right) \\ &- s\sum_{n=1}^{N}(-1)^n\binom{N}{n}\exp\left(-\frac{\lambda_{kp}\gamma_{\mathsf{I}}n+\lambda_{ks}x}{\gamma_{\mathsf{P}}}\right) \\ &+ s\sum_{n=1}^{N}(-1)^n\binom{N}{n}\exp\left(-\frac{\lambda_{kp}\gamma_{\mathsf{I}}n}{\gamma_{\mathsf{P}}}\right) \\ &+ sN\sum_{i=0}^{N-1}\frac{(-1)^i}{i+1}\binom{N-1}{i}\exp\left[-\frac{\gamma_{\mathsf{I}}\lambda_{kp}(i+1)}{\gamma_{\mathsf{P}}}\right] \\ &- sN\sum_{i=0}^{N-1}(-1)^i\binom{N-1}{i}\frac{\lambda_{kp}}{\frac{x\lambda_{ks}}{\gamma_{\mathsf{I}}}+\lambda_{kp}(i+1)} \\ &\times \exp\left[-\frac{\gamma_{\mathsf{I}}\lambda_{kp}(i+1)+\lambda_{ks}x}{\gamma_{\mathsf{P}}}\right]. \end{aligned} \tag{13}$$

According to (6), 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

$$\begin{aligned} &F_{\gamma_{\mathsf{S}}}(x) \\ &= F^K_{\gamma_{\mathsf{ks}}\mathbb{I}_k}(x) \\ &= 1-\sum_{k=1}^{K}(-1)^k\binom{K}{k}s^k\sum_{j=0}^{k}\binom{k}{j}\sum_{m=0}^{k-j}\binom{k-j}{m} \end{aligned}$$

$$\times \exp\left[-\frac{\lambda_{ks}x(k-j-m)}{\gamma_{\mathrm{P}}}\right]\sum_{p=0}^{m}(-1)^{p}\binom{m}{p}$$
$$\times \exp\left(-\frac{\lambda_{ks}xp}{\gamma_{\mathrm{P}}}\right)\sum_{a_1,\ldots a_N}\binom{m}{a_1\ldots a_N}\prod_{t=1}^{N}\left[\binom{N}{t}\right]^{a_t}(-1)^{ta_t}$$
$$\times \exp\left(-\frac{\lambda_{kp}\gamma_{\mathrm{I}}ta_t}{\gamma_{\mathrm{P}}}\right)\sum_{q=0}^{k}(N)^{q}\binom{k}{q}$$
$$\times \exp\left(-\frac{\lambda_{ks}xq}{\gamma_{\mathrm{P}}}\right)\sum_{b_0,\ldots b_{N-1}}\binom{q}{b_0\ldots b_{N-1}}$$
$$\times \prod_{r=0}^{N-1}\left[\binom{N-1}{r}\right]^{b_r}(-1)^{rb_r}$$
$$\times \exp\left[-\frac{\lambda_{kp}\gamma_{\mathrm{I}}(r+1)b_r}{\gamma_{\mathrm{P}}}\right]\left[\frac{\lambda_{kp}}{\frac{\lambda_{ks}x}{\gamma_{\mathrm{I}}}+\lambda_{kp}(r+1)}\right]^{b_r}(-N)^{k-q}$$
$$\times \sum_{c_0,\ldots c_{N-1}}^{k-q}\binom{k-q}{c_0\ldots c_{N-1}}\prod_{d=0}^{N-1}\left[\binom{N-1}{d}\right]^{c_d}\frac{(-1)^{c_d d}}{d+1}$$
$$\times \exp\left[-\frac{\lambda_{kp}\gamma_{\mathrm{I}}(d+1)c_d}{\gamma_{\mathrm{P}}}\right]. \quad (14)$$

IV. PERFORMANCE ANALYSIS OF THE PROPOSED SYSTEM

This section studies the performances of outage probability, ergodic capacity and symbol error rate utilizing the SNR distributions obtained in the previous section. Expressions are derived and asymptotic analysis is also provided to evaluate the system performance. In order to investigate a complete study, we extend the equations to special non-cooperative scenarios.

A. OUTAGE PROBABILITY ANALYSIS

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

$$P_{out}(\gamma_{\mathrm{th}}) = P(\gamma_{\mathrm{S}} \le \gamma_{\mathrm{th}}) = F_{\gamma_{\mathrm{S}}}(\gamma_{\mathrm{th}}). \quad (15)$$

The outage probability closed-form expressions of the proposed system (B.1) as shown in the Appendix B.

1) NON-COOPERATIVE SCENARIO

When the number of SC $K = 1$, the outage probability of the proposed system is given as (B.2) in Appendix B.

2) ASYMPTOTIC ANALYSIS

In the high SNR regime, when $\gamma_{\mathrm{P}} \to \infty$ in the proposed cognitive heterogeneous network, the asymptotic is given by

$$P_{out}^{Asy}(\gamma_{\mathrm{th}}) = (1-s)^{K}. \quad (16)$$

Proof: The proof is given in Appendix B. ■

B. ERGODIC CAPACITY ANALYSIS

The ergodic capacity is defined as the average rate averaged over all the SNR distributions. Ergodic secrecy rate (bits/s/Hz) is expressed as

$$\mathcal{C}_{erg} = E_{\gamma_{\mathrm{S}}}[log_2(1+x)] = \int_0^{\infty}\log_2(1+x)f_{\gamma_{\mathrm{S}}}(x)dx. \quad (17)$$

The ergodic capacity of the proposed system is given by (C.1) as shown in the Appendix C where $a_0 = \frac{\gamma_{\mathrm{I}}\lambda_{kp}(r+1)}{\lambda_{ks}}$, $b_0 = \frac{\lambda_{ks}(k-j-m+p+q)}{\gamma_{\mathrm{P}}}$ and $H_{m,n}^{p,q}\left[x \,\middle|\, \begin{smallmatrix}(-,-)\\(-,-)\end{smallmatrix}\right]$ is Fox H-function [26, eq. (1.1.1)].

Proof: The proof is given in Appendix C. ■

1) NON-COOPERATIVE SCENARIO

when the number of SC $K = 1$, the ergodic capacity is given by (C.8) as shown in the Appendix C where $a_1 = \frac{\lambda_{ks}}{\gamma_{\mathrm{P}}}$, $b_1 = \frac{\lambda_{kp}\gamma_{\mathrm{I}}(i+1)}{\lambda_{ks}}$ and $Ei(.)$ is the exponential integral function [25, eq. (8.211.1)].

Proof: The proof is given in Appendix C. ■

C. SYMBOL ERROR RATE ANALYSIS

The symbol error rate (SER) is derived in this subsection. The symbol error rate is given as [10]

$$\mathcal{S} = \frac{A\sqrt{B}}{2\sqrt{\pi}}\int_0^{\infty}x^{-\frac{1}{2}}\exp(-Bx)F_{\gamma_{\mathrm{S}}}(x)dx, \quad (18)$$

where (A,B) is determined by the modulation scheme. In this paper, Binary Phase-shift Keying (BPSK) modulation scheme will be discussed later in the next simulation section, and the parameters (A,B) = (2,1). Applying (14) into (18) and with the help of [27, eq. (2.3.6.9)], symbol error rate can be derived as (D.1) where $e_0 = \frac{\gamma_{\mathrm{I}}\lambda_{kp}(r+1)}{\lambda_{ks}}$, $f_0 = \frac{\lambda_{ks}(k-j-m+p+q)}{\gamma_{\mathrm{P}}} + B$.

1) NON-COOPEARTIVE SCENARIO

In non-cooperative case, the number of SC $K = 1$, the symbol error rate is given by (D.2) with the help of [27, eq. (2.3.6.9)] where $c_0 = \frac{\lambda_{ks}}{\lambda_{kp}\gamma_{\mathrm{I}}(i+1)}$, $d_0 = B + \frac{\lambda_{ks}}{\gamma_{\mathrm{P}}}$.

2) ASYMPTOTIC ANALYSIS

In the high SNR regime, when $\gamma_{\mathrm{P}} \to \infty$ in the proposed cognitive heterogeneous network, the asymptotic analysis of symbol error rate is given by

$$P_{SER}^{Asy}(\gamma_{\mathrm{th}}) = (1-s)^{K}. \quad (19)$$

The proof is similar to (16).

V. NUMERICAL RESULTS AND DISCUSSIONS

In this section, numerical results of the outage probability, ergodic capacity and symbol error rate are studied to evaluate the impact of backhaul reliability, the number of PUs and the number of SCs on the system performance. The 'Sim' curves are the simulation results, 'Ana' curves are analytical results and 'Asy' curves are 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 $\gamma_{\mathrm{th}} = 3$ dB. It is assumed that the location of the nodes in Cartesian coordinate system respectively are $SC = (0.5, 0)$, $SU - D =(0, 0)$, $PU =(0.5, 0.5)$. Hence, the normalized 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. We also assume that the average SNR $\gamma_P = \gamma_I$.

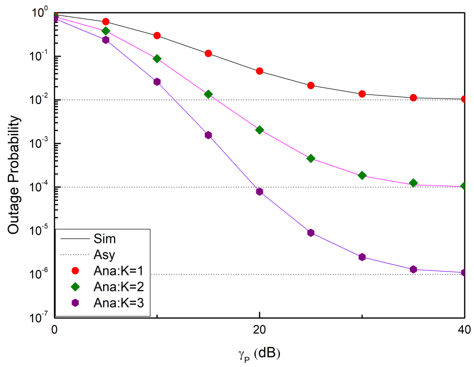

FIGURE 2. Outage probability with different number of secondary transmitters at a fixed backhaul reliability ($s = 0.99$) and a fixed number of primary users ($N = 3$).

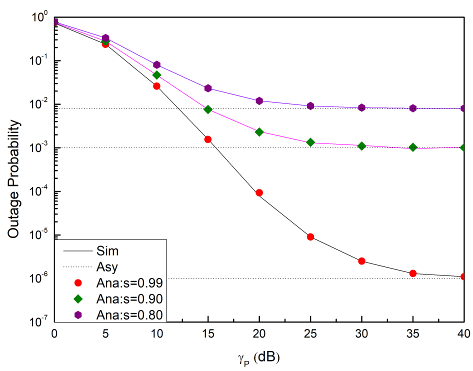

FIGURE 3. Outage probability with different backhaul reliability at a fixed number of secondary transmitters ($K = 3$) and a fixed number of primary users ($N = 3$).

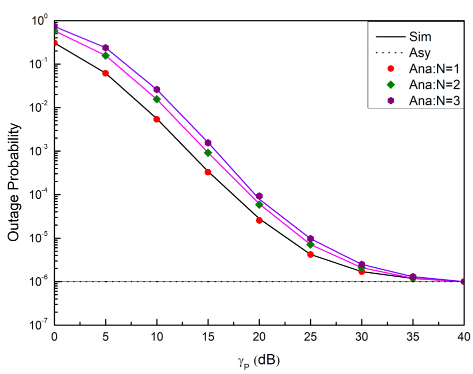

FIGURE 4. Outage probability with different number of *PUs* at a fixed number of *SCs* ($K = 3$) and a fixed backhaul reliability ($s = 0.99$).

A. OUTAGE PROBABILITY ANALYSIS

Fig. 2, 3, 4 and 5 show the impact of backhaul reliability, the number of *PUs* and *SCs* on the system performance.

In Fig. 2, s is fixed at 0.99 and the number of *PUs* N 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 converge to the asymptotic limitation.

In Fig. 3, the outage probability behavior 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. 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. 5, the outage probability with different backhaul reliability has been plotted. We assume that $N = 2$ and $K = 3$. It is obvious that the backhaul reliability has a significant impact on the outage probability. More specifically, when $\gamma_P = 35dB$, the outage probability drops from approximate 0.72 ($s = 0.1$) to 10^{-3} ($s = 0.9$). The system performance improves nearly 10^3 times when backhaul reliability increases from 0.1 to 0.9. Moreover, the system has a better performance when γ_P increases due to the high transmit power.

In Fig. 4, the outage probability with different number of *PUs* N is investigated. we assume 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, the *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 (16).

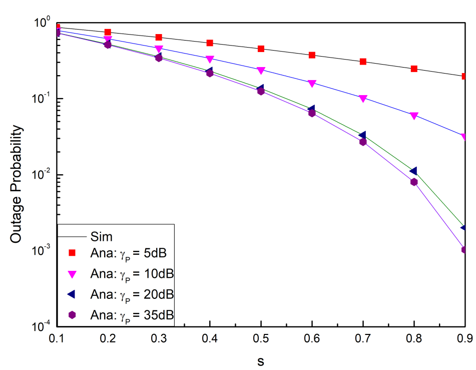

FIGURE 5. Outage probability with different backhaul probability with a fixed number of *PUs* ($N = 2$) and a fixed number of *SCs* ($K = 3$).

According to Fig. 2, Fig. 3, Fig. 4, Fig. 5 and also asymptotic analysis, in low SNR regime, the number of *SCs*, *PUs* and backhaul reliability can affect system performance in terms of outage probability. However, in high SNR regime, only the backhaul reliability and the number of *SCs* can affect the outage probability.

B. ERGODIC CAPACITY ANALYSIS

Fig. 6, 7, 8 and 9 show the impact of backhaul reliability, the number of *PUs* and *SCs* on the system performance in terms of ergodic capacity.

In Fig. 6, s is fixed at 0.99 and N is 3. Assuming the number of *SCs* is $K = 1$, $K = 2$, $K = 3$ to study the effect of the number of *SCs* on system performance. In Fig. 6, when the number of *SCs* increase, the ergodic capacity increases and the system can achieve a better performance.

In Fig. 7, the impact of the backhaul reliability on the ergodic capacity is investigated. In this scenario $N = 3$ and $K = 3$ is assumed. We suppose that $s = 0.99$, $s = 0.90$ and $s = 0.80$. In Fig. 9, when s increases, the system performs better as the ergodic capacity increases. In Fig. 9, the ergodic capacity with different backhaul reliability is shown. We assume that $N = 2$ and $K = 3$. We can observe that the backhaul reliability can affect the ergodic capacity significantly.

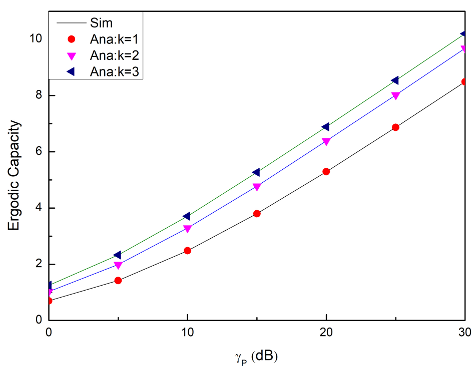

FIGURE 6. **Ergodic capacity with different number of *SCs* at a fixed backhaul reliability ($s = 0.99$) and a fixed number of *PUs* ($N = 3$).**

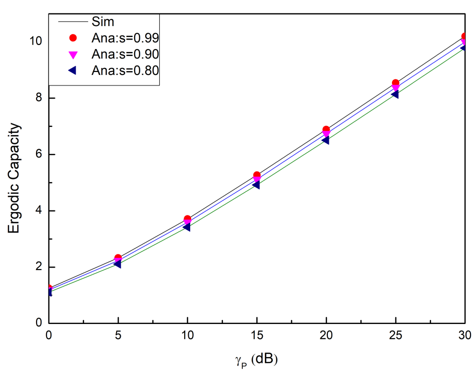

FIGURE 7. **Ergodic capacity with different backhaul reliability at a fixed number of *SCs* ($K = 3$) and a fixed number of *PUs* ($N = 3$).**

In Fig. 8, the ergodic capacity with different number of *PUs* N is investigated. We fix the backhaul reliability at $s = 0.99$ and $K = 3$. Assume $N = 1$, $N = 2$ and $K = 2$. When N decreases, the ergodic capacity increases to achieve a better system performance.

From the figures, we can observe that the number of *PUs*, *SCs* and backhaul reliability can affect the system ergodic capacity.

C. SYMBOL ERROR RATE

Fig. 10, 11, 12 and 13 show the impact of backhaul reliability, the number of *PUs* and *SCs* on the symbol error rate. BPSK is used at the signal constellation.

In Fig. 10, s is fixed at 0.99 and the number of *PUs* N 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* increases, the symbol error rate decreases and the system can achieve a better performance. Moreover, all the curves converge to the asymptotic limitation in the figure.

In Fig. 11, the impact of backhaul reliability on the system performance is evaluated. $N = 3$ and $K = 2$ is assumed in this scenario. We suppose that $s = 0.99$, $s = 0.90$ and $s = 0.80$ to evaluate the impact of backhaul reliability on the system performance. From the figure, when s increases, the system performance improves as the symbol error rate decreases. Fig. 13 also investigate the impact of backhaul reliability on symbol error rate. $N = 2$ and $K = 3$ is assumed. From the figures, backhaul reliability has a huge impact on the system performance.

In Fig. 12, the symbol error rate with different number of *PUs* N is investigated. We assume that $s = 0.99$ and $K = 2$. From the figure, we can observe that in low-SNR regime, when N increases, the symbol error rate increases and the system performs worse. However, in high SNR regime, increasing the number of *PUs* has no impact on the symbol error rate.

From Fig. 10, Fig. 11, Fig. 12, Fig. 13 and also asymptotic analysis, in low SNR regime, the number of *SCs*, *PUs* and backhaul reliability have an impact on symbol error rate.

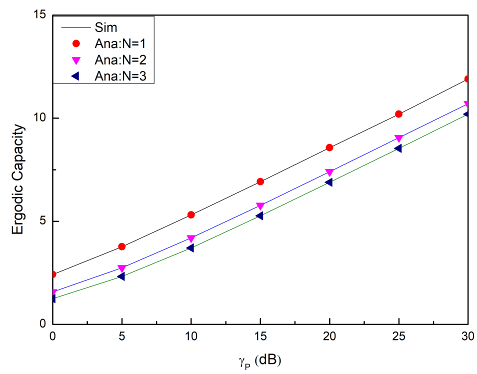

FIGURE 8. **Ergodic capacity with different number of *PUs* at a fixed number of *SCs* ($K = 3$) and a fixed backhaul reliability ($s = 0.99$).**

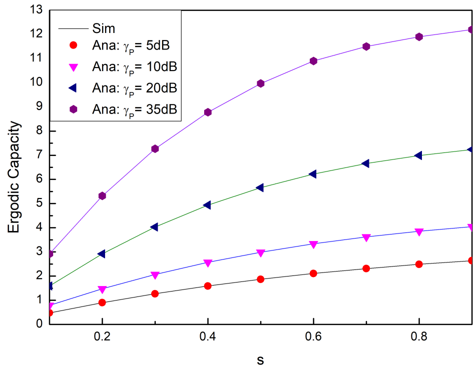

FIGURE 9. Ergodic capacity with different backhaul probability with a fixed number of *PUs* ($N = 2$) and a fixed number of *SCs* ($K = 3$).

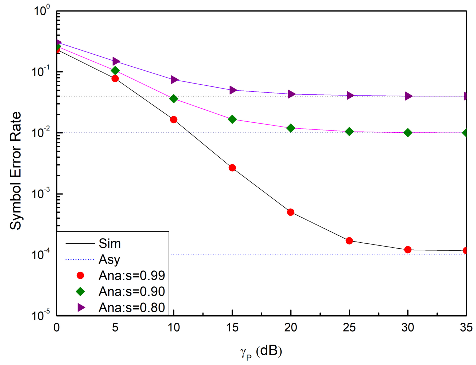

FIGURE 11. Symbol error rate with different backhaul reliability at a fixed number of *SCs* ($K = 2$) and a fixed number of *PUs* ($N = 3$).

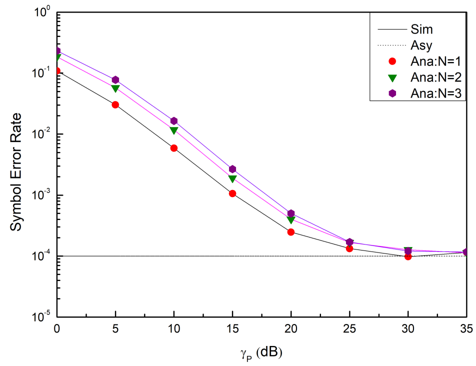

FIGURE 12. Symbol error rate with different number of *PUs* at a fixed number of *SCs* ($K = 2$) and a fixed backhaul reliability ($s = 0.99$).

However, in high SNR regime, only the backhaul reliability and the number of *SCs* can affect the symbol error rate.

VI. CONCLUSIONS

In this paper, we propose a cognitive heterogeneous network with multiple secondary transmitters, multiple primary users and unreliable backhaul. Selection combining is used to choose the best secondary transmitter that having the maximum SNR at the destination. Closed-form expressions for outage probability, ergodic capacity and symbol error rate are derived and asymptotic analysis is provided to gain the insight of the system. The results show that wireless backhaul reliability has a significant impact on system performance and this factor should be considered when designing HetNet systems in the future. This paper also investigates how the number of secondary transmitters and the number of primary users can affect the system performance. Our results show that all of them are important factors in cognitive heterogeneous networks. More specifically, in low SNR regime, both the number of primary users and secondary transmitters can affect the outage probability and symbol error rate. In high SNR regime, only the number of secondary transmitters can affect the outage probability and symbol error rate. Moreover, both the number of secondary transmitters and primary users have a significant impact on ergodic capacity in the entire SNR range.

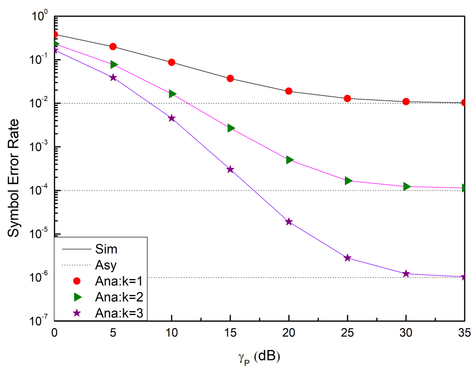

FIGURE 10. Symbol error rate with different number of *SCs* at a fixed backhaul reliability ($s = 0.99$) and a fixed number of *PUs* ($N = 3$).

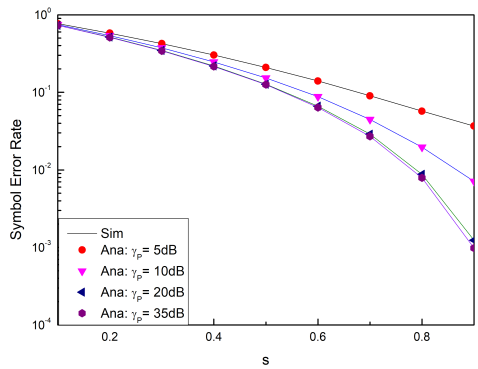

FIGURE 13. Symbol error rate with different backhaul probability with a fixed number of PUs ($N = 2$) and a fixed number of SCs ($K = 3$).

APPENDIX A

The CDF of the end-to-end SNR given in (4) can be written as

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

$$P_{\gamma_s}(\gamma_{th}) = 1 - \sum_{k=1}^{K}(-1)^k\binom{K}{k}s^k\sum_{j=0}^{k}\binom{k}{j}\sum_{m=0}^{k-j}\binom{k-j}{m}\exp\left[-\frac{\lambda_{ks}\gamma_{th}(k-j-m)}{\gamma_P}\right]\sum_{p=0}^{m}(-1)^p\binom{m}{p}$$
$$\times\exp\left(-\frac{\lambda_{ks}\gamma_{th}p}{\gamma_P}\right)\sum_{a_1,\ldots a_N}\binom{m}{a_1\ldots a_N}\prod_{t=1}^{N}\left[\binom{N}{t}\right]^{a_t}(-1)^{ta_t}$$
$$\times\exp\left(-\frac{\lambda_{kp}\gamma_I ta_t}{\gamma_P}\right)\sum_{q=0}^{k}(N)^q\binom{k}{q}\exp\left(-\frac{\lambda_{ks}\gamma_{th}q}{\gamma_P}\right)\sum_{b_0,\ldots b_{N-1}}\binom{q}{b_0\ldots b_{N-1}}\prod_{r=0}^{N-1}\left[\binom{N-1}{r}\right]^{b_r}(-1)^{rb_r}$$
$$\times\exp\left[-\frac{\lambda_{kp}\gamma_I(r+1)b_r}{\gamma_P}\right]\left[\frac{\lambda_{kp}}{\frac{\lambda_{ks}\gamma_{th}}{\gamma_I}+\lambda_{kp}(r+1)}\right]^{b_r}(-N)^{k-q}$$
$$\times\sum_{c_0,\ldots c_{N-1}}^{k-q}\binom{k-q}{c_0\ldots c_{N-1}}\prod_{d=0}^{N-1}\left[\binom{N-1}{d}\right]^{c_d}\frac{(-1)^{c_d d}}{d+1}\exp\left[-\frac{\lambda_{kp}\gamma_I(d+1)c_d}{\gamma_P}\right]. \quad (B.1)$$

$$P_{\gamma_s}^{non}(\gamma_{th}) = 1 - s\exp\left(-\frac{\lambda_{ks}\gamma_{th}}{\gamma_P}\right) - s\sum_{n=1}^{N}(-1)^n\binom{N}{n}\exp\left(-\frac{\lambda_{kp}\gamma_I n+\lambda_{ks}\gamma_{th}}{\gamma_P}\right) + s\sum_{n=1}^{N}(-1)^n\binom{N}{n}\exp\left(-\frac{\lambda_{kp}\gamma_I n}{\gamma_P}\right)$$
$$+sN\sum_{i=0}^{N-1}\frac{(-1)^i}{i+1}\binom{N-1}{i}\exp\left[-\frac{\gamma_I\lambda_{kp}(i+1)}{\gamma_P}\right]$$
$$-sN\sum_{i=0}^{N-1}(-1)^i\binom{N-1}{i}\frac{\lambda_{kp}}{\frac{\gamma_{th}\lambda_{ks}}{\gamma_I}+\lambda_{kp}(i+1)}\exp\left[-\frac{\gamma_I\lambda_{kp}(i+1)+\lambda_{ks}\gamma_{th}}{\gamma_P}\right]. \quad (B.2)$$

$$+\underbrace{P\left[\frac{|h_{ks}|^2}{Y}\le\frac{x}{\gamma_I};\frac{\gamma_I}{Y}\le\gamma_P\right]}_{J_2}. \quad (A.1)$$

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

$$J_1 = P\left[|h_{ks}|^2\le\frac{x}{\gamma_P};Y\le\frac{\gamma_I}{\gamma_P}\right]$$
$$= F_{\gamma_{ks}}(\frac{x}{\gamma_P})\left[F_{\gamma_{kp}}(\frac{\gamma_I}{\gamma_P})\right]^N$$
$$= 1+\sum_{n=1}^{N}(-1)^n\binom{N}{n}\exp(-\frac{\gamma_P\gamma_I n}{\gamma_P})-\exp(-\frac{\lambda_{ks}}{\gamma_P})$$
$$-\sum_{n=1}^{N}(-1)^n\binom{N}{n}\exp\left(-\frac{\gamma_P\gamma_I n+\lambda_{ks}x}{\gamma_P}\right). \quad (A.2)$$

For the term J_2, the concept of probability theory is used, and with the help of (2) (9), J_2 is expressed as

$$J_2 = P\left[|h_{ks}|^2\le\frac{xY}{\gamma_I};Y\ge\frac{\gamma_I}{\gamma_P}\right]$$
$$= \int_0^{\frac{xY}{\gamma_I}}f_{|h_{ks}|^2}(y)\int_{\frac{\gamma_I}{\gamma_P}}^{\infty}f_{|h_{kp_i}|^2}(z)dydz$$
$$= N\sum_{i=0}^{N-1}\frac{(-1)^i}{i+1}\binom{N-1}{i}\exp\left[-\frac{\gamma_{kp}\gamma_I(i+1)}{\gamma_P}\right]$$
$$-N\sum_{i=0}^{N-1}(-1)^i\binom{N-1}{i}\frac{\lambda_{kp}}{\frac{\lambda_{ks}x}{\gamma_I}+\lambda_{kp}(i+1)}$$
$$\times\exp\left[\frac{\gamma_I}{\gamma_P}\left(-\frac{\lambda_{ks}x}{\gamma_I}-\lambda_{kp}(i+1)\right)\right]. \quad (A.3)$$

APPENDIX B

The outage probability closed-form expressions of the proposed system (B.1), shown at the top of this page. See (B.2), shown at the top of this page.

The CDF of the outage probability can be expressed as,

$$P_{\gamma_s}(\gamma_{th}) = \left[P_{\gamma_s}^{non}(\gamma_{th})\right]^K. \quad (B.3)$$

In the high SNR regime, when $\gamma_P\to\infty$, $-\frac{1}{\gamma_P}\to 0$, so $\exp(-\frac{1}{\gamma_P})\approx 1$. In non-cooperative scenario,

$$P_{\gamma_s}^{non}(\gamma_{th})\approx 1-s. \quad (B.4)$$

Since (B.3), we obtain the CDF of outage probability,

$$P_{Out}^{Asy}(\gamma_{th}) = (1-s)^K. \quad (B.5)$$

APPENDIX C

See (C.1) and (C.2), shown at the top of the next page. According to (17), the ergodic capacity can be expressed as

$$\mathcal{C} = \frac{1}{\ln(2)}\sum_{k=1}^{K}(-1)^k\binom{K}{k}s^k\sum_{j=0}^{k}\binom{k}{j}\sum_{m=0}^{k-j}\binom{k-j}{m}$$

$$\mathcal{C} = \frac{1}{\ln(2)}\sum_{k=1}^{K}(-1)^k\binom{K}{k}s^k\sum_{j=0}^{k}\binom{k}{j}\sum_{m=0}^{k-j}\binom{k-j}{m}\sum_{p=0}^{m}(-1)^p\binom{m}{p}\sum_{a_1,\ldots a_N}^{m}\binom{m}{a_1\ldots a_N}\prod_{t=1}^{N}\left[\binom{N}{t}\right]^{a_t}(-1)^{ta_t}$$
$$\times\exp\left(-\frac{\lambda_{kp}\gamma_I ta_t}{\gamma_P}\right)\sum_{q=0}^{k}(N)^q\binom{k}{q}\sum_{b_0,\ldots b_{N-1}}^{q}\binom{q}{b_0\ldots b_{N-1}}\prod_{r=0}^{N-1}\left[\binom{N-1}{r}\right]^{b_r}(-1)^{rb_r}$$
$$\times\exp\left[-\frac{\lambda_{kp}\gamma_I(r+1)b_r}{\gamma_P}\right](-N)^{k-q}\sum_{c_0,\ldots c_{N-1}}^{k-q}\binom{k-q}{c_0\ldots c_{N-1}}\prod_{d=0}^{N-1}\left[\binom{N-1}{d}\right]^{c_d}\frac{(-1)^{dc_d}}{d+1}$$
$$\times\exp\left[-\frac{\lambda_{kp}\gamma_I(d+1)c_d}{\gamma_P}\right]\left(\frac{\lambda_{kp}\gamma_I}{\lambda_{ks}a_0}\right)^{b_r}\frac{1}{\Gamma(b_r)b_0}H^{1,1,1,1,1}_{1,[1:1],0,[1:1]}\left[\begin{matrix}\frac{1}{a_0 b_0}\\ \frac{1}{b_0}\end{matrix}\middle|\begin{matrix}(1,1)\\(1-b_r,1):(0,1)\\ \overline{\quad}\\(0,1);(0,1)\end{matrix}\right]. \quad \text{(C.1)}$$

$$\mathcal{C}^{non} = -s\frac{1}{\ln(2)}\exp\left(\frac{\lambda_{ks}}{\gamma_P}\right)\mathrm{Ei}\left(-\frac{\lambda_{ks}}{\gamma_P}\right) - s\frac{1}{\ln(2)}\sum_{n=1}^{N}(-1)^n\binom{N}{n}\exp\left(-\frac{\lambda_{kp}\gamma_I n-\lambda_{ks}}{\gamma_P}\right)\mathrm{Ei}\left(-\frac{\lambda_{ks}}{\gamma_P}\right)$$
$$+sN\frac{1}{\ln(2)}\sum_{i=0}^{N-1}(-1)^i\binom{N-1}{i}\exp\left[-\frac{\lambda_{kp}\gamma_I(i+1)}{\gamma_P}\right]\frac{\lambda_{kp}\gamma_I}{\gamma_P}\frac{a_1}{b_1}H^{1,2,1,1,1}_{1,[2:1],1,[2:1]}\left[\begin{matrix}\frac{1}{a_1}\\ \frac{1}{a_1 b_1}\end{matrix}\middle|\begin{matrix}(1,1)\\(1,1)(1,1):(0,1)\\ \overline{\quad}\\(1,1);(0,1):(0,1)\end{matrix}\right]$$
$$+sN\frac{1}{\ln(2)}\sum_{i=0}^{N-1}(-1)^i\binom{N-1}{i}\exp\left[-\frac{\lambda_{kp}\gamma_I(i+1)}{\gamma_P}\right]\frac{\lambda_{kp}\gamma_I}{\lambda_{ks}}\left(\frac{1}{b_1}\right)^2\frac{1}{a_1}H^{1,2,1,1,1}_{1,[2:1],0,[2:1]}\left[\begin{matrix}\frac{1}{a_1}\\ \frac{1}{a_1 b_1}\end{matrix}\middle|\begin{matrix}(1,1)\\(1,1)(1,1):(-1,1)\\ \overline{\quad}\\(1,1);(0,1):(0,1)\end{matrix}\right]. \quad \text{(C.2)}$$

$$\times\sum_{p=0}^{m}(-1)^p\binom{m}{p}\sum_{a_1,\ldots a_N}^{m}\binom{m}{a_1\ldots a_N}\prod_{t=1}^{N}\left[\binom{N}{t}\right]^{a_t}(-1)^{ta_t}$$
$$\times\exp\left(-\frac{\lambda_{kp}\gamma_I ta_t}{\gamma_P}\right)\sum_{q=0}^{k}(N)^q\binom{k}{q}\sum_{b_0,\ldots b_{N-1}}^{q}\binom{q}{b_0\ldots b_{N-1}}$$
$$\times\prod_{r=0}^{N-1}\left[\binom{N-1}{r}\right]^{b_r}(-1)^{rb_r}\exp\left[-\frac{\lambda_{kp}\gamma_I(r+1)b_r}{\gamma_P}\right]$$
$$\times(-N)^{k-q}\sum_{c_0,\ldots c_{N-1}}^{k-q}\binom{k-q}{c_0\ldots c_{N-1}}$$
$$\times\prod_{d=0}^{N-1}\left[\binom{N-1}{d}\right]^{c_d}\frac{(-1)^{dc_d}}{d+1}$$
$$\times\exp\left[-\frac{\lambda_{kp}\gamma_I(d+1)c_d}{\gamma_P}\right]\left(\frac{\lambda_{kp}\gamma_I}{\lambda_{ks}a_0}\right)^{b_r}$$
$$\times\underbrace{\int_0^\infty\left(\frac{1}{\frac{x}{a_0}+1}\right)^{b_r}\frac{1}{1+x}\exp(-b_0x)\,dx}_{Q_3}. \quad \text{(C.3)}$$

In order to solve Q_3, we first transform $\left(\frac{1}{\frac{x}{a_0}+1}\right)^{b_r}$, $\frac{1}{x+1}$ and $\exp(-b_0x)$ into Meijer-G function which is defined in [25, eq. (9.301)], and then covert the Meijer-G function into Fox H-function which is defined in [26, eq. (1.1.1)]. According to [26, eq. (1.7.1)], Meijier-G function can transform into Fox H-function easily as follows,

$$G^{p,q}_{m,n}\left[x\middle|\begin{matrix}a_p\\b_p\end{matrix}\right] = H^{p,q}_{m,n}\left[x\middle|\begin{matrix}(a_p,1)\\(b_p,1)\end{matrix}\right]. \quad \text{(C.4)}$$

With the help of [28, eq. (8.4.2.5)],

$$\frac{1}{x+1} = G^{1,1}_{1,1}\left[x\middle|\begin{matrix}0\\0\end{matrix}\right] = H^{1,1}_{1,1}\left[x\middle|\begin{matrix}(0,1)\\(0,1)\end{matrix}\right], \quad \text{(C.5)}$$
$$\left(\frac{1}{\frac{x}{a_0}+1}\right)^{b_r} = \frac{1}{\Gamma(b_r)}G^{1,1}_{1,1}\left[\frac{x}{a_0}\middle|\begin{matrix}1-b_r\\0\end{matrix}\right]$$
$$= \frac{1}{\Gamma(b_r)}H^{1,1}_{1,1}\left[\frac{x}{a_0}\middle|\begin{matrix}(1-b_r,1)\\(0,1)\end{matrix}\right]. \quad \text{(C.6)}$$

Applying [26, eq. (2.6.2)], the integral Q_3 can be solved as

$$Q_3 = \frac{1}{\Gamma(b_r)b_0}H^{1,1,1,1,1}_{1,[1:1],0,[1:1]}\left[\begin{matrix}\frac{1}{a_0b_0}\\ \frac{1}{b_0}\end{matrix}\middle|\begin{matrix}(1,1)\\(1-b_r,1):(0,1)\\ \overline{\quad}\\(0,1);(0,1)\end{matrix}\right]. \quad \text{(C.7)}$$

With the help of [25, eq. (4.337.1)], the expression of ergodic capacity of non-cooperative scenario is given by

$$\mathcal{C}^{non}$$
$$= -s\frac{1}{\ln(2)}\exp\left(\frac{\lambda_{ks}}{\gamma_P}\right)\mathrm{Ei}\left(-\frac{\lambda_{ks}}{\gamma_P}\right)$$
$$-s\frac{1}{\ln(2)}\sum_{n=1}^{N}(-1)^n\binom{N}{n}\exp\left(-\frac{\lambda_{kp}\gamma_I n-\lambda_{ks}}{\gamma_P}\right)\mathrm{Ei}\left(-\frac{\lambda_{ks}}{\gamma_P}\right)$$
$$+sN\frac{1}{\ln(2)}\sum_{i=0}^{N-1}(-1)^i\binom{N-1}{i}\exp\left[-\frac{\lambda_{kp}\gamma_I(i+1)}{\gamma_P}\right]\frac{\lambda_{kp}\gamma_I}{\gamma_P}$$
$$\times\underbrace{\int_0^\infty\ln(1+x)\exp(-a_1x)\frac{1}{x+b_1}dx}_{Q_1}$$

$$\begin{aligned}\mathcal{S} &= \frac{A}{2} + \frac{A\sqrt{B}}{2\sqrt{\pi}} \sum_{k=1}^{K} (-1)^k \binom{K}{k} s^k \sum_{j=0}^{k} \binom{k}{j} \sum_{m=0}^{k-j} \binom{k-j}{m} (-1) \sum_{p=0}^{m} (-1)^p \binom{m}{p} \sum_{a_1,\ldots a_N} \binom{m}{a_1 \ldots a_N} \prod_{t=1}^{N} \left[\binom{N}{t} (-1)^t \right. \\ &\quad \times \left. \exp\left(-\frac{\lambda_{kp}\gamma_I t}{\gamma_P}\right)\right]^{a_t} \sum_{q=0}^{k} (N)^q \binom{k}{q} \sum_{b_0,\ldots b_{N-1}}^{q} \binom{q}{b_0 \ldots b_{N-1}} \prod_{r=0}^{N-1} \left[\binom{N-1}{r} (-1)^r \right. \\ &\quad \times \left. \exp\left[-\frac{\lambda_{kp}\gamma_I (r+1)}{\gamma_P}\right]\right]^{b_r} (-N)^{k-q} \sum_{c_0,\ldots c_{N-1}}^{k-q} \binom{k-q}{c_0 \ldots c_{N-1}} \prod_{d=0}^{N-1} \left[\binom{N-1}{d} \frac{(-1)^d}{d+1} \right. \\ &\quad \times \left. \exp\left[-\frac{\lambda_{kp}\gamma_I (d+1)}{\gamma_P}\right]\right]^{c_d} \sqrt{\pi} e_0^{\frac{1}{2}-b_r} \Psi\left(\frac{1}{2}, \frac{3}{2} - b_r; f_0\, e_0\right). \end{aligned} \tag{D.1}$$

$$\begin{aligned}\mathcal{S}^{non} &= \frac{A}{2} - \frac{sA\sqrt{B}}{2\left(B + \frac{\lambda_{ks}}{\frac{1}{2}}\right)^{\frac{1}{2}}} - \frac{sA\sqrt{B}}{2} \sum_{n=1}^{N} \binom{N}{n} (-1)^n \times \exp\left(\frac{-\lambda_{kp}\gamma_I n}{\gamma_P}\right) \frac{1}{\left(B + \frac{\lambda_{ks}}{\frac{1}{2}}\right)^{\frac{1}{2}}} + \frac{sA}{2} \sum_{n=1}^{N} \binom{N}{n} (-1)^n \\ &\quad \times \exp\left(\frac{-\lambda_{kp}\gamma_I n}{\gamma_P}\right) + \frac{sNA}{2} \sum_{i=0}^{N-1} \binom{N-1}{i} \frac{(-1)^i}{i+1} \exp\left[\frac{-\lambda_{kp}\gamma_I (i+1)}{\gamma_P}\right] \\ &\quad - \frac{A\sqrt{B}}{2\sqrt{\pi}} sN \sum_{i=0}^{N-1} \binom{N-1}{i} \frac{(-1)^i}{i+1} \exp\left[\frac{-\lambda_{kp}\gamma_I (i+1)}{\gamma_P}\right] \frac{1}{c_0} \sqrt{c_0 \pi}\, \Psi\left(\frac{1}{2}, \frac{1}{2}; \frac{d_0}{c_0}\right). \end{aligned} \tag{D.2}$$

$$\begin{aligned} &- sN \frac{1}{\ln(2)} \sum_{i=0}^{N-1} (-1)^i \binom{N-1}{i} \exp\left[-\frac{\lambda_{kp}\gamma_I (i+1)}{\gamma_P}\right] \frac{\lambda_{kp}\gamma_I}{\lambda_{ks}} \\ &\times \underbrace{\int_0^\infty \ln(1+x) \exp(-a_1 x) \left(\frac{1}{x+b_1}\right)^2 dx}_{Q_2}. \end{aligned} \tag{C.8}$$

With the help of [28, eq. (8.4.6.5)], [26, eq. (2.6.2)], (C.6), Q_1 and Q_2 can be solved as

$$Q_1 = \frac{a_1}{b_1} H^{1,2,1,1,1}_{1,[2:1],1,[2:1]} \left[\begin{array}{c|c} \frac{1}{a_1} & (1,1) \\ \frac{1}{a_1 b_1} & (1,1)(1,1):(0,1) \\ & \underline{(1,1);(0,1):(0,1)} \end{array} \right], \tag{C.9}$$

$$Q_2 = \left(\frac{1}{b_1}\right)^2 \frac{1}{a_1} H^{1,2,1,1,1}_{1,[2:1],0,[2:1]} \left[\begin{array}{c|c} \frac{1}{a_1} & (1,1) \\ \frac{1}{a_1 b_1} & (1,1)(1,1):(-1,1) \\ & \underline{(1,1);(0,1):(0,1)} \end{array} \right]. \tag{C.10}$$

APPENDIX D

See (D.1) and (D.2), shown at the top of this page.

REFERENCES

[1] K. J. Kim, T. Khan, and P. Orlik, "Performance analysis of cooperative systems with unreliable backhauls and selection combining," *IEEE Trans. Veh. Technol.*, vol. 66, no. 3, pp. 2448–2461, Mar. 2017.

[2] J. Mitola and G. Q. Maguire, Jr., "Cognitive radio: Making software radios more personal," *IEEE Pers. Commun.*, vol. 6, no. 4, pp. 13–18, Apr. 1999.

[3] S. Scott-Hayward and E. Garcia-Palacios, "Channel time allocation PSO for gigabit multimedia wireless networks," *IEEE Trans. Multimedia*, vol. 16, no. 3, pp. 828–836, Apr. 2014.

[4] H. ElSawy, E. Hossain, and D. I. Kim, "Hetnets with cognitive small cells: User offloading and distributed channel access techniques," *IEEE Commun. Mag.*, vol. 51, no. 6, pp. 28–36, Jun. 2013.

[5] R. Madan, J. Borran, A. Sampath, N. Bhushan, A. Khandekar, and T. Ji, "Cell association and interference coordination in heterogeneous LTE-A cellular networks," *IEEE J. Sel. Areas Commun.*, vol. 28, no. 9, pp. 1479–1489, Dec. 2010.

[6] H. ElSawy and E. Hossain, "Two-tier HetNets with cognitive femtocells: Downlink performance modeling and analysis in a multichannel environment," *IEEE Trans. Mobile Comput.*, vol. 13, no. 3, pp. 649–663, Mar. 2014.

[7] C. Yin, H. T. Nguyen, C. Kundu, Z. Kaleem, E. Garcia-Palacios, and T. Q. Duong, "Secure energy harvesting relay networks with unreliable backhaul connections," *IEEE Access*, vol. 6, pp. 12074–12084, Jan. 2018.

[8] M. Coldrey *et al.*, "Small-cell wireless backhauling: A non-line-of-sight approach for point-to-point microwave links," in *Proc. IEEE Veh. Technol. Conf. (VTC Fall)*, Sep. 2012, pp. 1–5.

[9] H. T. Nguyen, T. Q. Duong, O. A. Dobre, and W.-J. Hwang, "Cognitive heterogeneous networks with best relay selection over unreliable backhaul connections," in *Proc. IEEE VTC-Fall*, Toronto, ON, Canada, Sep. 2017, pp. 1–5.

[10] H. T. Nguyen, D.-B. Ha, S. Q. Nguyen, and W.-J. Hwang, "Cognitive heterogeneous networks with unreliable backhaul connections," *Mobile Netw. Appl.*, vol. 23, no. 6, pp. 1525–1538, Dec. 2017.

[11] H. Liu, K. J. Kim, T. A. Tsiftsis, K. S. Kwak, and H. V. Poor, "Secrecy performance of finite-sized cooperative full-duplex relay systems with unreliable backhauls," *IEEE Trans. Signal Process.*, vol. 65, no. 23, pp. 6185–6200, Dec. 2017.

[12] H. T. Nguyen, T. Q. Duong, and W.-J. Hwang, "Multiuser relay networks over unreliable backhaul links under spectrum sharing environment," *IEEE Commun. Lett.*, vol. 21, no. 10, pp. 2314–2317, Oct. 2017.

[13] T. A. Khan, P. Orlik, K. J. Kim, and R. W. Heath, "Performance analysis of cooperative wireless networks with unreliable backhaul links," *IEEE Commun. Lett.*, vol. 19, no. 8, pp. 1386–1389, Aug. 2015.

[14] K. J. Kim, P. L. Yeoh, P. V. Orlik, and H. V. Poor, "Secrecy performance of finite-sized cooperative single carrier systems with unreliable backhaul connections," *IEEE Trans. Signal Process.*, vol. 64, no. 17, pp. 4403–4416, Sep. 2016.

[15] H. T. Nguyen, J. Zhang, N. Yang, T. Q. Duong, and W.-J. Hwang, "Secure cooperative single carrier systems under unreliable backhaul and dense networks impact," *IEEE Access*, vol. 5, pp. 18310–18324, Jul. 2017.

[16] K. J. Kim, P. V. Orlik, and T. A. Khan, "Performance analysis of finite-sized co-operative systems with unreliable backhauls," *IEEE Trans. Wireless Commun.*, vol. 15, no. 7, pp. 5001–5015, Jul. 2016.

[17] H. Liu and K. S. Kwak, "Outage probability of finite-sized selective relaying systems with unreliable backhauls," in *Proc. 8th Int. Conf. Inf. Commun. Technol. Converg. (ICTC)*, Jeju, South Korea, Oct. 2017, pp. 1232–1237.

[18] H. T. Nguyen, S. Q. Nguyen, and W.-J. Hwang, "Performance analysis of energy harvesting relay systems under unreliable backhaul connections," *IET Commun.*, vol. 12, no. 15, pp. 1763–1770, 2018.

[19] T. Q. Duong, V. N. Q. Bao, and H.-J. Zepernick, "Exact outage probability of cognitive AF relaying with underlay spectrum sharing," *Electron. Lett.*, vol. 47, no. 17, pp. 1001–1002, Aug. 2011.

[20] J. Zhang, N.-P. Nguyen, J. Zhang, E. Garcia-Palacios, and N. P. Le, "Impact of primary networks on the performance of energy harvesting cognitive radio networks," *IET Commun.*, vol. 10, no. 18, pp. 2559–2566, Dec. 2016.

[21] H. Huang, Z. Li, and J. Si, "Multi-source multi-relay underlay cognitive radio networks with multiple primary users," in *Proc. IEEE Int. Conf. Commun. (ICC)*, London, U.K., Jun. 2015, pp. 7558–7563.

[22] X. Feng, X. Gao, and R. Zong, "Cooperative jamming for enhancing security of cognitive radio networks with multiple primary users," *China Commun.*, vol. 14, no. 7, pp. 1–15, Jul. 2017.

[23] T. Q. Duong, P. L. Yeoh, V. N. Q. Bao, M. Elkashlan, and N. Yang, "Cognitive relay networks with multiple primary transceivers under spectrum-sharing," *IEEE Signal Process. Lett.*, vol. 19, no. 11, pp. 741–744, Nov. 2012.

[24] D. G. Brennan, "Linear diversity combining techniques," *Proc. IRE*, vol. 47, no. 6, pp. 1075–1102, Jun. 1959.

[25] A. Jeffrey and D. Zwillinger, *Table of Integrals, Series, and Products*. New York, NY, USA: Academic, 2007.

[26] A. M. Mathai and R. K. Saxena, *The H Function With Applications in Statistics and Other Disciplines*. New Delhi, India: Wiley, 1978.

[27] A. Prudnikov, I. Brychkov, and O. Marichev, *Integrals and Series: Elementary Functions*, vol. 1. Gordon and Breach Science, 1998.

[28] A. Prudnikov, I. Brychkov, and O. Marichev, *Integrals and Series: More Special Functions*, vol. 3. Gordon and Breach Science, 1986.

CHENG YIN received the B.Eng. degree in communication engineering from Hangzhou Dianzi University, in 2016. She is currently pursuing the Ph.D. degree with Queen's University Belfast. Her research interests include physical layer security, cognitive radio, relay networks, and energy harvesting communications.

EMILIANO GARCIA-PALACIOS received the Ph.D. degree from Queen's University Belfast, in 2000. Since 2000, he has been leading research in wireless network resource management. He is currently a Lecturer with the Institute of Electronics, Communications and Information Technology, Queen's University Belfast. His research interests include wireless protocols, wireless resource allocation, and optimization and traffic management for next-generation gigabit networks.

NGUYEN-SON VO received the Ph.D. degree in communication and information systems from the Huazhong University of Science and Technology, China, in 2012. Since 2014, he has been a Lecturer with the Faculty of Electrical and Electronics Engineering, Duy Tan University, Vietnam. He is also the Head of a research group at the Research Center of New Technology established in 2014. He is working on self-powered multimedia wireless communications as well as the quality-of-experience provision in wireless networks for smart cities. He has authored one book chapter, 11 journals, 22 conference papers, and nine projects. Many of them were published in highly reputable journals and conferences, such as the IEEE Transactions on Circuits and Systems for Video Technology, the IEEE Systems Journal, the *IET Communications*, *Journal of Communications*, the IEEE Global Communications Conference, and the IEEE International Conference on Communications. He received the Best Paper Award at the IEEE Global Communications Conference 2016. He has been serving as a Guest Editor for *ACM/Springer Mobile Networks & Applications*, Special Issue on Wireless Communications and Networks for Smart Cities, since 2017.

TRUNG Q. DUONG is a Reader (Associate Professor) with Queen's University Belfast, U.K. His current research interests include the IoT (applied to disaster management, agriculture, hydrometeorological hazards, and smart grid), 5G networks (small-cell networks, ultra-dense networks, HetNets, physical layer security, massive MIMO, cell-free massive MIMO, caching, and energy-harvesting), and nanoscale, molecular communications networks. He has authored or co-authored more than 300 papers, including over 180 ISI journal articles with over 6500 citations and an h-index 44 in Google Scholar. He received the Best Paper Award at the IEEE Vehicular Technology Conference (VTC-Spring) 2013, the IEEE International Conference on Communications 2014, the IEEE GLOBECOM 2016, and the IEEE Digital Signal Processing 2017. He was a recipient of the prestigious Royal Academy of Engineering Research Fellowship from 2016 to 2021 and has won the prestigious Newton Prize 2017. He has served as a chair/organizer for more than 20 IEEE conferences/workshops, including the IEEE Global Communications Conference (GLOBECOM) 2016 Symposium Chair. He currently serves as an Editor for the IEEE Transactions on Wireless Communications, the IEEE Transactions on Communications, and the *IET Communications* and as a Lead Senior Editor for the IEEE Communications Letters. He has served as the Guest Editor for more than 22 times on ISI-index journals, including the IEEE Journal on Selected Areas on Communications, in 2015, the *IET Communications* in 2014, 2016, and 2017, the *IEEE Communications Magazine*, in 2014 and 2015, the IEEE Access from 2016 to 2018, the IEEE *Wireless Communications Magazine*, in 2015, EURASIP JWCN, and EURASIP JASP. He was an Editor of *Electronics Letters*, *Emerging Telecommunications Technologies*, and the IEEE Communications Letters.