Channel Selection for Spectrum Sharing in Wireless Networks

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In this paper, we study a spectrum sharing network (SSN) where a spectrum sharing device (SSD) coexists with multiple wireless communication systems (WCSs) in the same channel. The SSD can operate with either a duty cycle (DC) channel access mechanism or a listen-before-talk (LBT) channel access mechanism, whereas WCSs operate with an LBT mechanism. An opportunistic channel selection scheme for the SSD in the SSN is first proposed to minimize the outage probability. The optimal data transmission time for the DC-based SSD is derived to further improve the outage probability. We also derive the exact and closed-form outage probability of the proposed channel selection in the SSN by assuming that the number of WCSs operating in each channel is uniformly distributed. The simulation results show that the proposed channel selection scheme outperforms other channel selection schemes. It was also observed that a DC-based SSD with an optimal data transmission time provides a better outage performance than an LBT-based SSD. As the number of available channels increases, the channel selection scheme plays an important role in minimizing the outage probability of the SSNs.

Keywords: Channel selection, Duty cycle, Listen-before-talk, Outage probability, Spectrum sharing.

I. Introduction

Spectrum sharing has received significant attention in effectively utilizing limited spectrum resources [1]–[9]. Because not all similar and dissimilar wireless communication systems (WCSs) in a spectrum sharing network (SSN) can be coordinated with each other, a suitable coexistence mechanism is required for successful spectrum sharing among the WCSs [1], [2]. When a spectrum sharing device (SSD) coexists with a licensed WCS such as a licensed shared access system, the coexistence mechanism should be designed to protect the licensed WCS [3]–[7]. On the other hand, when the SSD shares a channel with an unlicensed WCS such as a Wi-Fi system, an LTE-unlicensed system, or an LTE licensed-assisted access system, the coexistence mechanism should be designed to support fair spectrum sharing of the unlicensed WCSs and enhance the overall achievable data rate over the SSN [1], [2], [8], [9].

In general, to transmit data efficiently, an SSD selects one or more operating channels among the multiple available channels. For example, there are about 20 available channels with a 20 MHz channel spacing each within the unlicensed 5-GHz band [10]. Because each channel has different channel characteristics according to the number of operating WCSs, channel qualities, and other factors, the performance of the SSD depends on the selected channel(s). Accordingly, many previous works have considered channel selection techniques to enhance the network performance [11]–[16]. Dynamic channel selection has been considered to maximize the throughput for dense-urban wireless networks where low-cost residential access points (APs) coexist with actively managed service provider APs [11]. For multi-channel WLAN systems, a channel switching scheme was investigated to optimize the

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throughput of the systems [12]. The dynamic rate and channel selection were studied to maximize the number of packets successfully transmitted over a finite duration of time [13]. Contention-aware channel selection was also proposed to protect primary users as well as minimize the collision probability among users for the throughput optimization [14]. Based on the game theory approach, an optimal channel selection was designed to minimize the weighted aggregate interference when the active users and channel environment vary dynamically [15]. In addition, channel selection and power allocation were proposed to minimize the total transmit power under the rate constraints [16]. However, there is no opportunistic channel selection for a duty cycle (DC) based SSD with multiple available channels in the presence of dissimilar listen-before-talk (LBT) based unlicensed WCSs, which has motivated the consideration of a new channel selection scheme for an SSN.

This paper aims to provide an opportunistic channel selection scheme for DC- and LBT-based SSDs to minimize the outage probability of an SSN with multiple available channels. We derived the exact and closed-form expression of the outage probability for the proposed channel selection in the SSN using order statistics. The optimal data transmission time was also derived to further improve the outage probability.

The rest of this paper is organized as follows. Section II describes the system model considered herein. Section III proposes a channel selection scheme. The exact and closed-form outage probability is derived in Section IV. Section V derives the optimal data transmission time and proposes a channel selection algorithm. Simulation results are given in Section VI. Finally, some concluding remarks are provided in Section VII.

II. System Model

1. Channel Access Model

Figure 1 compares the DC and LBT mechanisms. As shown in Fig. 1(a), a DC-based SSD utilizes an available channel during T_{ON} every T_{S} without a carrier sensing (CS) [1], [2], [17]. The non-data transmission time of the SSD, T_{OFF}, is reserved for WCSs. The normalized data transmission time for a DC-based SSD is defined as

$$\tau = \frac{T_{\mathrm{ON}}}{T_{\mathrm{S}}}. \qquad (1)$$

Hence, the data rates of the DC-based SSD and WCSs are linearly proportional to τ and $(1 - \tau)$, respectively. As shown in Fig. 1(b), if the channel is idle during a distributed interframe space (DIFS) period, the WCS (or LBT-based SSD) can transmit a packet. Otherwise, if the channel is sensed to be busy during one DIFS period, the WCS (or LBT-based SSD) should continuously monitor the channel until it is measured to be idle during another DIFS period. After finishing the data transmission of the WCS, the LBT-based SSD still waits for a random backoff period to avoid a collision between the WCSs and SSD. The acknowledgement (ACK) is immediately transmitted at the end of the packet after a period of time called a short interframe space (SIFS). Because the SIFS is shorter than a DIFS, no other station is able to detect an idle channel for a DIFS until the end of the ACK [17]–[19].

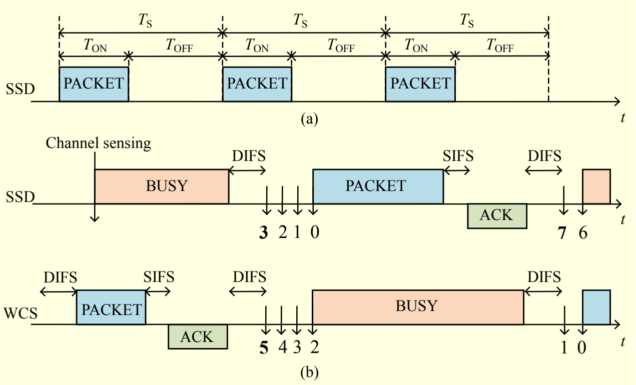

Fig. 1. (a) DC channel access mechanism and (b) LBT channel access mechanism.

The performance of the LBT mechanism depends highly on the total number of WCSs operating in the same channel, whereas the data rate of the WCSs is inversely proportional to the number of WCSs operating in the same channel.

2. System Description

In this paper, a channel selection scheme for an SSD is designed to minimize the outage probability of an SSN with multiple available channels ($b = 1, 2, \ldots, B$). The number of WCSs operating in channel b is represented as N_b. Here, N_b is assumed to be a uniformly distributed random variable that takes a value of 1 to N. The SSD selects one operating channel among B available channels to transmit the data efficiently. The numbers of available channels and devices in the SSN are summarized as follows:

1) Number of available channels: B
2) Number of SSDs: 1
3) Number of WCSs: $\sum_{b=1}^{B} N_b$

We consider an SSN that consists of one SSD and multiple unlicensed WCSs. The SSD can opportunistically access an available channel based on either a DC channel access mechanism or an LBT channel access mechanism, and it is assumed that unlicensed WCSs only access channels through the LBT mechanism. In the SSN, the SSD consists of one SSD

Table 1. Table of common notations and acronyms.

Notation/Acronym	Description
B	Number of available channels
N_b	Number of WCSs in channel b
$\alpha^a_{N_b}$	Coefficient for the WCS in channel b
$\beta^a_{N_b}$	Coefficient for the SSD in channel b
$\hat{R}^a_b$	Achievable rate of the SSN in channel b
P^a_b	Outage probability of the SSN in channel b
$\hat{R}^a_{b^*}$	Maximum achievable rate of the SSN among B available channels
$P^a_{b^*}$	Outage probability of the SSN with a channel selection
$F_{\hat{R}^a_{b^*}}(R)$	CDF of the maximum achievable rate of the SSN
τ^*_b	Optimal data transmission time for DC-based SSD in channel b
$\hat{R}^{\mathrm{DC}^*}_{b^*}$	Maximum achievable rate of the SSN with the optimal data transmission time
$P^{\mathrm{DC}^*}_{b^*}$	Optimal outage probability of the SSN
AP	Access Point
DC	Duty Cycle
LBT	Listen-Before-Talk
SSD	Spectrum Sharing Device
SSN	Spectrum Sharing Network
WCS	Wireless Communication System

station-user pair, and each WCS consists of one WCS station-user pair. It is assumed that each terminal has a single antenna, the SSD station intends to transmit data to the SSD user, and each WCS station intends to transmit data only to its WCS user. The complex channel coefficient from the SSD station to the SSD user operating in channel b is denoted as $H_{\mathrm{s},b}$, and the complex channel coefficient from the n-th WCS station to the n-th WCS user operating in channel b is denoted as $H_{n,b}$. We assume that all of the channel coefficients are fixed over the channel coherence time with $H_{\mathrm{s},b} \sim CN(0,\ \Omega_{\mathrm{s},b})$, and $H_{n,b} \sim CN(0,\ \Omega_{n,b})$. Here, $H \sim CN(0,\ \Omega)$ indicates a circularly symmetric complex-valued Gaussian random variable with a mean of zero and a variance of Ω.

We let $X_{\mathrm{s},b}$ and $X_{n,b}$ denote the instantaneous signal-to-noise ratios (SNRs) of the link from the SSD station to the SSD user, and the link from the n-th WCS station to the n-th WCS user, both of which are operating in channel b, respectively. The instantaneous SNRs of the SSD link and the n-th WCS link in channel b are given by

$$X_{\mathrm{s},b} = \gamma_{\mathrm{s},b} \left| H_{\mathrm{s},b} \right|^2 \tag{2}$$

and

$$X_{n,b} = \gamma_{n,b} \left| H_{n,b} \right|^2 , \tag{3}$$

where $\gamma_{\mathrm{s},b}$ is the transmission power at the SSD station, and $\gamma_{n,b}$ is the transmission power at the n-th WCS station. The power of the additive white Gaussian noise at each link is assumes to be 1 with $n_{\mathrm{AWGN}} \sim CN(0,\ 1)$. A set of commonly used notations as well as acronyms are summarized in Table 1.

3. Achievable Rates of Spectrum Sharing Device and Wireless Communication Device

In the SSN, the achievable rate of the n-th WCS operating in channel b is given by

$$R^a_{n,b} = \alpha^a_{N_b} \log_2(1 + X_{n,b}) , \tag{4}$$

where

$$\alpha^a_{N_b} = \begin{cases} \dfrac{C^a_{N_b}}{N_b + 1}, & a = \mathrm{LBT}, \\ \dfrac{(1-\tau)C^a_{N_b}}{N_b}, & a = \mathrm{DC}, \end{cases} \tag{5}$$

for $n = 1, 2, \ldots, N_b$ and $b = 1, 2, \ldots, B$. Here, $C^a_{N_b}$ denotes a correction factor for the achievable rate of the WCS when one LBT-based SSD (or DC-based SSD) and N_b WCSs share channel b [17], [18]. The correction factor reflects the overhead for the channel access mechanism and collision loss among the operating devices. It is known that LBT-based devices share a channel equally. Thus, the achievable data rate of a WCS in an SSN is inversely proportional to the total number of LBT-based devices operating in the same channel. Meanwhile, when the SSD employs the DC channel access mechanism, the achievable data rates of the SSD and WCSs are proportional to τ and $(1 - \tau)$, respectively. In this case, the achievable data rate of the existing WCSs in an SSN is highly influenced by the channel access mechanism of the SSD.

The achievable data rate of the LBT (or DC) based SSD in channel b is given by

$$R^a_{\mathrm{s},b} = \beta^a_{N_b} \log_2(1 + X_{\mathrm{s},b}) , \tag{6}$$

where

$$\beta^a_{N_b} = \begin{cases} \dfrac{L^a_{N_b}}{N_b + 1}, & a = \mathrm{LBT}, \\ \tau L^a_{N_b}, & a = \mathrm{DC}, \end{cases} \tag{7}$$

for $b = 1, 2, \ldots, B$. Here, $L^a_{N_b}$ denotes a correction factor for the achievable rate of the SSD when one LBT-based (or DC-based) SSD and N_b WCSs share channel b [17], [18]. The correction factor reflects the overhead for the channel access mechanism, collision loss among the operating devices, and a

Table 2. Coefficients for the achievable rates of an SSD and WCS.

	SSD	WCS
LBT	$\frac{L_{N_b}^{\text{LBT}}}{N_b+1}$	$\frac{C_{N_b}^{\text{LBT}}}{N_b+1}$
DC	$\tau L_{N_b}^{\text{DC}}$	$\frac{(1-\tau)C_{N_b}^{\text{DC}}}{N_b}$

correction for the difference in achievable data rates owing to the dissimilar transmission schemes between the SSD and existing WCSs. Table 2 summarizes the coefficients for the achievable rates of the SSD and WCSs.

III. Proposed Channel Selection

Here, a channel selection scheme for an SSD is proposed to minimize the outage probability of an SSN. When multiple WCSs and one SSD share an available channel for a data transmission, an outage occurs when at least one device provides a lower achievable rate than the target rate *R*. When an SSD coexists with WCSs in channel *b*, the outage probability for the SSN in channel *b* is given by

$$P_b^a(R) = \Pr[\hat{R}_b^a < R], \tag{8}$$

where

$$\hat{R}_b^a = \min\left\{R_{s,b}^a,\ R_{1,b}^a,\ \dots,\ R_{N_b,b}^a\right\}, \tag{9}$$

for $b = 1, 2, \dots, B$. Here, $\hat{R}_b^a$ corresponds to the achievable data rate of the SSN in channel *b*. The outage probability is determined by the minimum data rate among N_b+1 achievable rates. The achievable rate of the WCSs and the achievable rate of the SSD are quite different according to the channel access mechanism of the SSD, as shown in (4) and (6). Therefore, the outage probability is also highly influenced by the channel access mechanism of the SSD. Note that the achievable rate of the SSD, $R_{s,b}^a$, and the achievable rates of the WCSs, $R_{k,b}^a$ $(k=1, 2, \dots, N_b)$, are independent non-identical random variables because the coefficients for the achievable rates of the SSD and the WCSs are different, as shown in Table 2. Therefore, $\hat{R}_b^a$ corresponds to the minimum among N_b+1 independent non-identical random variables.

In the SSN, each channel has different channel characteristics according to the number of operating WCSs, the channel quality, and so on. Herein, we propose a channel selection scheme for the SSD to minimize the outage probability of an SSN. The outage probability with a channel selection that optimizes the outage of an SSN is given by

$$P_{b*}^a(R) = \Pr[\hat{R}_{b*}^a < R], \tag{10}$$

where

$$\hat{R}_{b*}^a = \max\left\{\hat{R}_1^a,\ \hat{R}_2^a,\ \dots,\ \hat{R}_B^a\right\}. \tag{11}$$

The SSD searches a channel that provides the minimum outage probability. The outage optimal channel for the SSD is obtained by solving the following optimization problem:

$$b^* = \arg\max_{b=1,\dots,B}\left\{\hat{R}_b^a\right\}. \tag{12}$$

The outage optimal channel for the SSD in an SSN corresponds to the channel that has the maximum achievable rate of the SSN among *B* available channels.

IV. Exact and Closed-Form Outage Probability

In this section, we derive the exact and closed-form outage probability of the proposed channel selection in an SSN. The SSD operates using either an LBT channel access mechanism or a DC channel access mechanism, whereas the WCSs operate using an LBT channel access mechanism. The outage probability of the proposed channel selection can be rewritten as

$$P_{b*}^a(R) = \Pr\left[\hat{R}_{b*}^a < R\right] = F_{\hat{R}_{b*}^a}(R), \tag{13}$$

for *a* = LBT or *a* = DC. Here, $F_{\hat{R}_{b*}^a}(R)$ denotes the cumulative density function (CDF) of $\hat{R}_{b*}^a$. Note that $\hat{R}_{b*}^a$ corresponds to the maximum among *B* independent non-identical random variables because the average channel powers of each WCS and the SSD are different owing to the different channel conditions. The distribution of $\hat{R}_{b*}^a$ is analyzed using the order statistics [20].

Theorem 1. $X_1, X_2, \dots, X_M$ are independent non-identical random variables. The CDF of $X_{m*} =$ $\max\{X_1, \dots, X_M\}$ is defined as

$$F_{X_{m*}}(x) = \prod_{m=1}^{M} F_{X_m}(x), \tag{14}$$

where $F_{X_m}(x)$ is the CDF of X_m [20], [21].

Based on Theorem 1, the CDF of the maximum achievable rate $\hat{R}_{b*}^a$ of the SSN among *B* available channels is expressed as

$$F_{\hat{R}_{b*}^a}(R) = \prod_{b=1}^{B} F_{\hat{R}_b^a}(R), \tag{15}$$

where $F_{\hat{R}_b^a}^a(R)$ is the CDF of $\hat{R}_b^a$.

To obtain the exact and closed form expression of the outage probability, the CDF of $\hat{R}_b^a$ should first be derived, and is represented as

$$F_{\hat{R}_b^a}(R) = \Pr\Big[\min\Big\{\alpha_{N_b}^a \log_2(1+X_{1,b}),\ \dots,\ \alpha_{N_b}^a \log_2(1+X_{N_b,b}),\ \beta_{N_b}^a \log_2(1+X_{\mathrm{s},b})\Big\} \le R\Big]. \tag{16}$$

From (16), the CDF of $\hat{R}_b^a$ depends on the channel access mechanism of the SSD.

Theorem 2. $X_1, X_2, \dots, X_M$ are independent non-identical random variables. The CDF of $\hat{X} = \min\{X_1, \dots, X_M\}$ is defined as

$$F_{\hat{X}}(x) = \sum_{i=1}^{M}\sum_{S_i}\left[\prod_{l=1}^{i} F_{X_{j_l}}(x)\right]\left[\prod_{l=i+1}^{M}\left\{1-F_{X_{j_l}}(x)\right\}\right], \tag{17}$$

where $F_{X_m}(x)$ is the CDF of X_m, and $\sum_{S_i}$ denotes the sum over all permutations $(j_1, j_2, \dots, j_M)$ of $(1, 2, \dots, M)$ for $j_1 < j_2 \cdots < j_i$ and $j_{i+1} < j_{i+2} \cdots < j_M$ [20], [21].

1. Listen-Before-Talk Based SSD

When an LBT-based SSD selects one operating channel using the proposed channel selection, the outage probability of the SSN is given by

$$P_{b^*}^{\mathrm{LBT}}(R) = F_{\hat{R}_{b^*}^{\mathrm{LBT}}}(R) = \prod_{b=1}^{B} F_{\hat{R}_b^{\mathrm{LBT}}}(R), \tag{18}$$

where

$$F_{\hat{R}_b^{\mathrm{LBT}}}(R) = \Pr\Big[\min\Big\{\alpha_{N_b}^{\mathrm{LBT}} \log_2(1+X_{1,b}),\ \dots,\ \alpha_{N_b}^{\mathrm{LBT}} \log_2(1+X_{N_b,b}),\ \beta_{N_b}^{\mathrm{LBT}} \log_2(1+X_{\mathrm{s},b})\Big\} \le R\Big]. \tag{19}$$

The number (N_b) of WCSs in channel b is assumed to be a uniformly distributed random variable taking a value of 1 to N. Therefore, the CDF of $\hat{R}_b^{\mathrm{LBT}}$ is reformulated as

$$F_{\hat{R}_b^{\mathrm{LBT}}}(R) = \frac{1}{N}\sum_{k=1}^{N} \Pr\Big[\min\Big\{\hat{R}_{k,b}^{\mathrm{LBT}},\ R_{\mathrm{s}(k),b}^{\mathrm{LBT}}\Big\} \le R\Big], \tag{20}$$

where

$$\hat{R}_{k,b}^{\mathrm{LBT}} = \alpha_k^{\mathrm{LBT}} \times \min\left\{\log_2(1+X_{1,b}), \dots, \log_2(1+X_{k,b})\right\} \tag{21}$$

and

$$R_{\mathrm{s}(k),b}^{\mathrm{LBT}} = \beta_k^{\mathrm{LBT}} \log_2(1+X_{\mathrm{s},b}). \tag{22}$$

This corresponds to the minimum of two independent non-identical random variables. From Theorem 2, the CDF of $\hat{R}_b^{\mathrm{LBT}}$ is given by

$$F_{\hat{R}_b^{\mathrm{LBT}}}(R) = \frac{1}{N}\sum_{k=1}^{N}\left\{F_{\hat{R}_{k,b}^{\mathrm{LBT}}}(R) + F_{R_{\mathrm{s}(k),b}^{\mathrm{LBT}}}(R) - F_{\hat{R}_{k,b}^{\mathrm{LBT}}}(R)F_{R_{\mathrm{s}(k),b}^{\mathrm{LBT}}}(R)\right\}, \tag{23}$$

where $F_{\hat{R}_{k,b}^{\mathrm{LBT}}}(R)$ denotes the CDF of the minimum data rate among the achievable data rates for the k WCSs in channel b. Using Theorem 2, $F_{\hat{R}_{k,b}^{\mathrm{LBT}}}(R)$ can be rewritten as

$$F_{\hat{R}_{k,b}^{\mathrm{LBT}}}(R) = \sum_{i=1}^{k}\sum_{S_i}\left[\prod_{l=1}^{i}\left\{1-\exp\left(-\lambda_{j_l,b}\left(2^{\frac{R}{\alpha_k^{\mathrm{LBT}}}}-1\right)\right)\right\}\right] \times\left[\prod_{l=i+1}^{k}\exp\left(-\lambda_{j_l,b}\left(2^{\frac{R}{\alpha_k^{\mathrm{LBT}}}}-1\right)\right)\right], \tag{24}$$

where $\lambda_{n,b} = (\gamma_n \Omega_{n,b})^{-1}$. In addition, $F_{R_{\mathrm{s}(k),b}^{\mathrm{LBT}}}(R)$ denotes the CDF of the achievable data rate for the LBT-based SSD, and is represented as

$$F_{R_{\mathrm{s}(k),b}^{\mathrm{LBT}}}(R) = 1-\exp\left(-\lambda_{\mathrm{s},b}\left(2^{\frac{R}{\beta_k^{\mathrm{LBT}}}}-1\right)\right), \tag{25}$$

with $\lambda_{\mathrm{s},b} = (\gamma_{\mathrm{s}}\Omega_{\mathrm{s},b})^{-1}$. The exact and closed-form outage probability of the SSN with the proposed channel selection is finally obtained by inserting (23), (24), and (25) into (18) when the LBT-based SSD and the unlicensed LBT-based WCSs share *B* available channels.

2. Duty-Cycle Based SSD

When a DC-based SSD selects one operating channel with the proposed channel selection, the outage probability of the SSN is given by

$$P_{b^*}^{\mathrm{DC}}(R) = F_{\hat{R}_{b^*}^{\mathrm{DC}}}(R) = \prod_{b=1}^{B} F_{\hat{R}_b^{\mathrm{DC}}}(R), \tag{26}$$

where

$$F_{\hat{R}_b^{\mathrm{DC}}}(R) = \Pr\Big[\min\Big\{\alpha_{N_b}^{\mathrm{DC}} \log_2(1+X_{1,b}),\ \dots,\ \alpha_{N_b}^{\mathrm{DC}} \log_2(1+X_{N_b,b}),\ \beta_{N_b}^{\mathrm{DC}} \log_2(1+X_{\mathrm{s},b})\Big\} \le R\Big]. \tag{27}$$

To obtain the closed form expression of the outage probability, the CDF of $\hat{R}_b^{\mathrm{DC}}$ is reformulated as

$$F_{\hat{R}_b^{\mathrm{DC}}}(R) = \Pr\Big[\min\Big\{\hat{R}_{N_b,b}^{\mathrm{DC}}, R_{\mathrm{s},b}^{\mathrm{DC}}\Big\} \le R\Big], \tag{28}$$

where

$$\hat{R}_{N_b,b}^{\mathrm{DC}} = \alpha_{N_b}^{\mathrm{DC}} \times \min\left\{\log_2(1+X_{1,b}), \dots, \log_2(1+X_{N_b,b})\right\} \tag{29}$$

and

$$R_{\mathrm{s},b}^{\mathrm{DC}} = \beta_{N_b}^{\mathrm{DC}} \log_2(1+X_{\mathrm{s},b}). \tag{30}$$

This corresponds to the minimum of two independent non-identical random variables. From Theorem 2, the CDF of $\hat{R}_b^{\mathrm{DC}}$ is given by

$$F_{\hat{R}_b^{\mathrm{DC}}}(R) = F_{\hat{R}_{N_b,b}^{\mathrm{DC}}}(R) + F_{R_{\mathrm{s},b}^{\mathrm{DC}}}(R) - F_{\hat{R}_{N_b,b}^{\mathrm{DC}}}(R)F_{R_{\mathrm{s},b}^{\mathrm{DC}}}(R), \tag{31}$$

where $F_{\hat{R}_{N_b,b}^{\mathrm{DC}}}(R)$ denotes the CDF of the minimum data rate among the achievable data rates for the N_b WCSs in channel b.

Using Theorem 2, it can be rewritten as

$$F_{\hat{R}_{N_b,b}^{\mathrm{DC}}} = \frac{1}{N}\sum_{k=1}^{N}\sum_{i=1}^{k}\sum_{S_i}\left[\prod_{l=1}^{i}\left\{1-\exp\left(-\lambda_{j_l,b}\left(2^{\frac{R}{\alpha_k^{\mathrm{DC}}}}-1\right)\right)\right\}\right]$$
$$\times\left[\prod_{l=i+1}^{k}\exp\left(-\lambda_{j_l,b}\left(2^{\frac{R}{\alpha_k^{\mathrm{DC}}}}-1\right)\right)\right], \qquad (32)$$

where $\lambda_{n,b}=(\gamma_n\Omega_{n,b})^{-1}$. In addition, $F_{R_{\mathrm{s},b}^{\mathrm{DC}}}(R)$ denotes the CDF of the achievable data rate for the DC-based SSD, and is represented as

$$F_{R_{\mathrm{s},b}^{\mathrm{DC}}}(R)=1-\exp\left(-\lambda_{\mathrm{s},b}\left(2^{\frac{R}{\beta_{N_b}^{\mathrm{DC}}}}-1\right)\right), \qquad (33)$$

with $\lambda_{\mathrm{s},b}=(\gamma_{\mathrm{s}}\Omega_{\mathrm{s},b})^{-1}$. The exact and closed-form outage probability of the SSN with the proposed channel selection is finally obtained by inserting (31) through (33) into (26) when the DC-based SSD and the unlicensed LBT-based WCSs share B available channels.

V. Optimal Data Transmission Time for DC-based SSD

In the previous section, we derived an exact and closed- form outage probability $P_{b^*}^{\mathrm{DC}}(R)$ of an SSN in terms of the channel selection with a given data transmission time, τ, when a DC-based SSD coexists with multiple LBT-based WCSs. However, the outage probability of an SSN with a DC-based SSD depends highly on the data transmission time. In this section, we derive an optimal data transmission time for a DC-based SSD to further improve the outage probability. The optimal outage probability of the SSN can be accordingly achieved by employing the optimal data transmission time as well as the proposed channel selection scheme. The optimal outage probability of the SSN is represented as

$$P_{b^*}^{\mathrm{DC}^*}(R)=\min_{b=1,\,\dots\,,\,B}\left\{P_b^{\mathrm{DC}^*}(R)\right\}, \qquad (34)$$

where

$$P_b^{\mathrm{DC}^*}(R)=\min_{0\le\tau\le1}\left\{P_b^{\mathrm{DC}}(R)\right\}=\Pr\left[\hat{R}_b^{\mathrm{DC}*}<R\right]. \qquad (35)$$

Here, $P_b^{\mathrm{DC}^*}(R)$ denotes the outage probability of an SSN in channel b with the optimal data transmission time τ_b^*, and $\hat{R}_b^{\mathrm{DC}*}$ is the corresponding maximum achievable rate of the SSN in channel b. The optimal data transmission time that minimizes the outage probability maximizes the achievable data rate of the SSN. Therefore, the optimal data transmission time in channel b is obtained by solving the following optimization problem:

$$\tau_b^*=\arg\min_{0\le\tau\le1}\left\{P_b^{\mathrm{DC}}(R)\right\}=\arg\max_{0\le\tau\le1}\left\{\breve{R}_b^{\mathrm{DC}}\right\}, \qquad (36)$$

where

$$\hat{R}_b^{\mathrm{DC}}=\min\left\{\alpha_{N_b}^{\mathrm{DC}}\log_2(1+\hat{X}_{n,b}),\ \beta_{N_b}^{\mathrm{DC}}\log_2(1+X_{\mathrm{s},b})\right\} \qquad (37)$$

with

$$\hat{X}_{n,b}=\min\left\{X_{1,b},\,\dots\,,\,X_{N_b,b}\right\}. \qquad (38)$$

Because $\hat{R}_b^{\mathrm{DC}}$ is a concave function, a unique optimal data transmission time exists [22]. Here, $\alpha_{N_b}^{\mathrm{DC}}\log_2(1+\hat{X}_{n,b})$ is a decreasing function of τ and becomes zero when τ is 1. On the other hand, $\beta_{N_b}^{\mathrm{DC}}\log_2(1+X_{\mathrm{s},b})$ is an increasing function of τ and becomes zero when τ is zero. Therefore, the intersection between $\alpha_{N_b}^{\mathrm{DC}}\log_2(1+\hat{X}_{n,b})$ and $\beta_{N_b}^{\mathrm{DC}}\log_2(1+X_{\mathrm{s},b})$ always exists between zero and 1. The achievable data rate becomes the maximum value at the intersection. The optimal data transmission time satisfies the following equation:

$$\frac{(1-\tau_b^*)C_{N_b}^{\mathrm{DC}}}{N_b}\log_2\left(1+\hat{X}_{n,b}\right)=\tau_b^*L_{N_b}^{\mathrm{DC}}\log_2(1+X_{\mathrm{s},b}). \qquad (39)$$

The optimal data transmission time is given by

$$\tau_b^*=\frac{C_{N_b}^{\mathrm{DC}}\log_2(1+\hat{X}_{n,b})}{N_bL_{N_b}^{\mathrm{DC}}\log_2(1+X_{\mathrm{s},b})+C_{N_b}^{\mathrm{DC}}\log_2(1+\hat{X}_{n,b})}. \qquad (40)$$

Figure 2 depicts the outage optimal channel selection algorithm for a DC-based SSD in an SSN. The optimal channel selection algorithm is composed of two steps. In the first step, the DC-based SSD computes the optimal data transmission time τ_b^*, and then computes the maximum achievable rate $\hat{R}_b^{\mathrm{DC}*}$ of the SSN with the optimal data transmission time in channel b. In the second step, the maximum achievable rate obtained in the first step is compared with the maximum temporal value. When the maximum achievable rate is larger than the maximum temporal value, the optimal channel index is updated with the current channel index b, and the maximum temporal value is updated with the current maximum achievable rate. The channel selection algorithm starts with $b=1$ and repeats until b becomes larger than B. The last updated channel index is selected for the operating channel for the DC-based SSD.

VI. Simulation Results

Here, three channel selection schemes are employed to evaluate the outage performance: *conventional*, *random*, and the *proposed* schemes. The conventional method selects an operating channel where the minimum number of WCSs exists

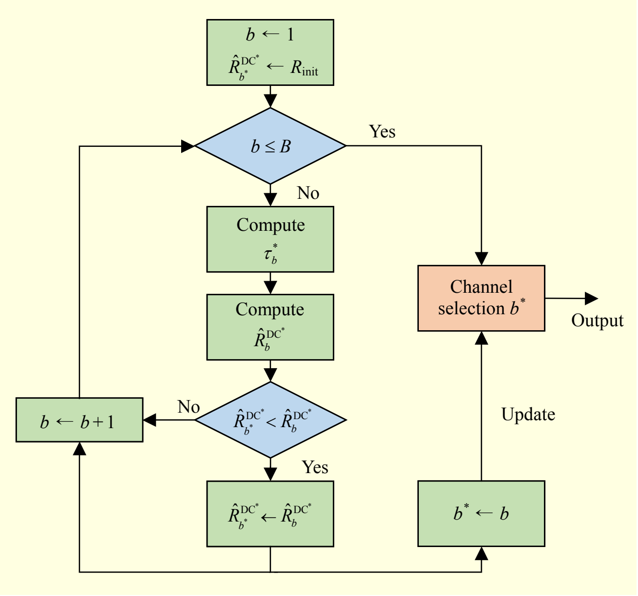

Fig. 2. Outage optimal channel selection algorithm for a DC-based SSD.

among the available channels, the random method selects an operating channel randomly, and the proposed method selects an operating channel using the outage metric of (11). We double checked the accuracy of the obtained outage probability result by comparing our analytical results with the computer-based Monte Carlo simulations. The simulation parameters are given in Table 3.

We first investigated the maximum achievable rate of an SSN by employing the proposed channel selection. Figure 3 shows the CDF of the maximum achievable rate of an SSN at an average SNR of 20 dB. From Fig. 3, one can see that the analytical results exactly match the simulation results. Figure 3 shows the probability that the maximum achievable rate of the SSN is less than *R*. Therefore, the curves on the right-hand side of Fig. 3 provide a higher achievable rate of an SSN than the left-hand side. The achievable rate performance of an SSN with a DC-based SSD is not better than that with an LBT-based SSD when the data transmission time τ is not optimized. In addition, the achievable rate of an SSN with a DC-based SSD is seriously affected by the data transmission time. This means that the outage probability of an SSN with a DC-based SSD is highly influenced by the data transmission time. Thus, the data transmission time should be suitably determined according to the SSN conditions. Figure 4 compares the maximum achievable rate of an SSN with an LBT-based SSD, and the maximum achievable rate of an SSN with a DC-based SSD employing the optimal data transmission time τ_b according to the three channel selection schemes at an average SNR of 20 dB. The proposed channel selection scheme clearly outperforms the other two channel selection schemes. The

Table 3. Simulation parameters.

Parameter	Notation	Value
Number of WCSs	N	10
Number of available channels	B	10
Target rate	R	0.5, 1 b/s/Hz
Correction factor for WCS	$C^{\mathrm{LBT}}_{N_b}$	0.82
	$C^{\mathrm{DC}}_{N_b}$	0.78
Correction factor for SSD	$L^{\mathrm{LBT}}_{N_b}$	0.82
	$L^{\mathrm{DC}}_{N_b}$	0.95

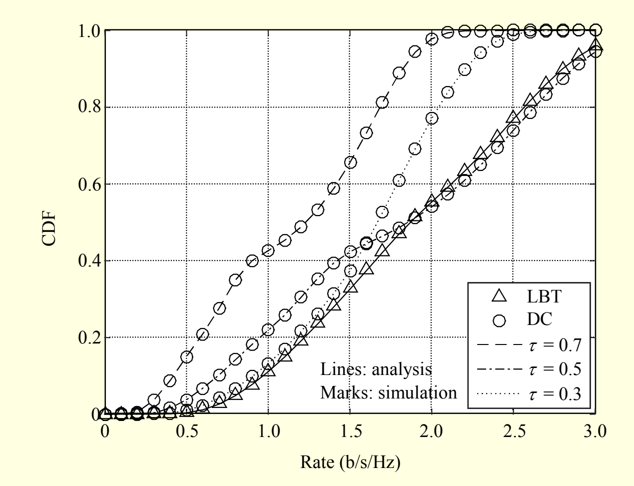

Fig. 3. CDF of the maximum achievable rate of an SSN using the proposed channel selection scheme at an average SNR of 20 dB.

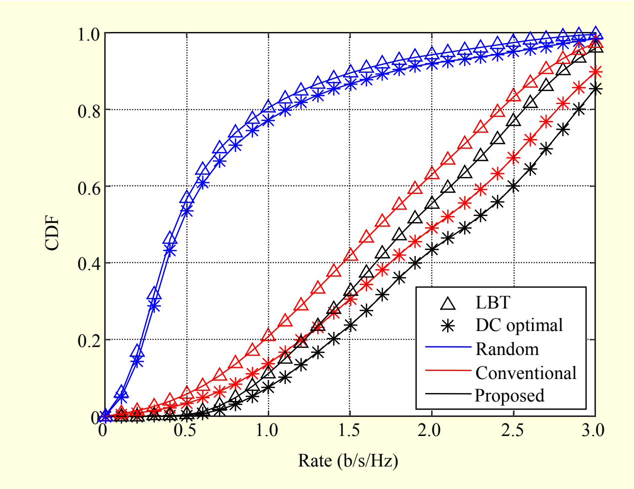

Fig. 4. CDF of the maximum achievable rates of an SSN according to three channel selection schemes at an average SNR of 20 dB.

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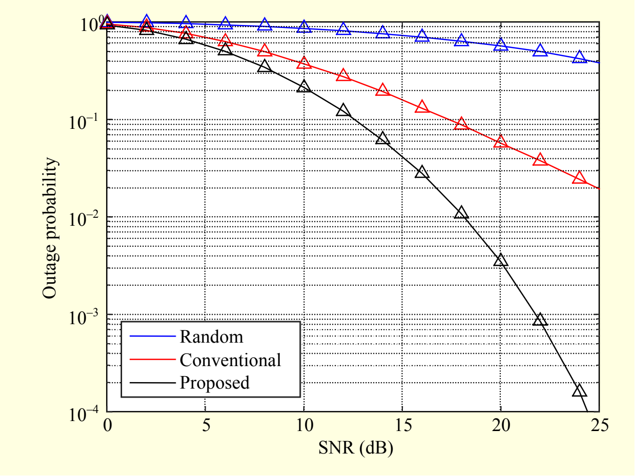

Fig. 5. Outage probability of an SSN with an LBT-based SSD as a function of the average SNR.

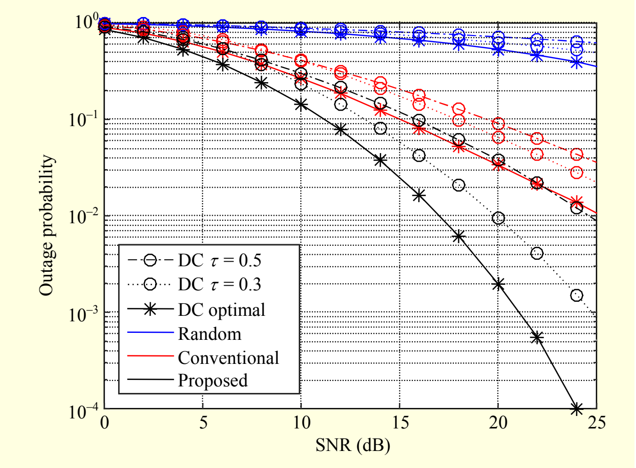

Fig. 6. Outage probability of an SSN with a DC-based SSD as a function of the average SNR.

achievable rate performance of an SSN with a DC-based SSD and the optimal data transmission time is better than that with an LBT-based SSD for all channel selection schemes.

Figure 5 shows the outage probability of an SSN with an LBT-based SSD as a function of the average SNR for the three channel selection schemes. It can be seen that the proposed channel selection scheme outperforms the other channel selection schemes, and the performance gap between the proposed channel selection and the conventional channel selection increases as the average increases in SNR. Figure 6 shows the outage probability of an SSN with a DC-based SSD using three data transmission times, 0.5, 0.3, and τ_b^*, as a function of the average SNR. It is shown that the optimal data transmission time improves the outage probability significantly. The outage probability obtained by a DC-based SSD with the optimal data transmission time is at minimum when applied to

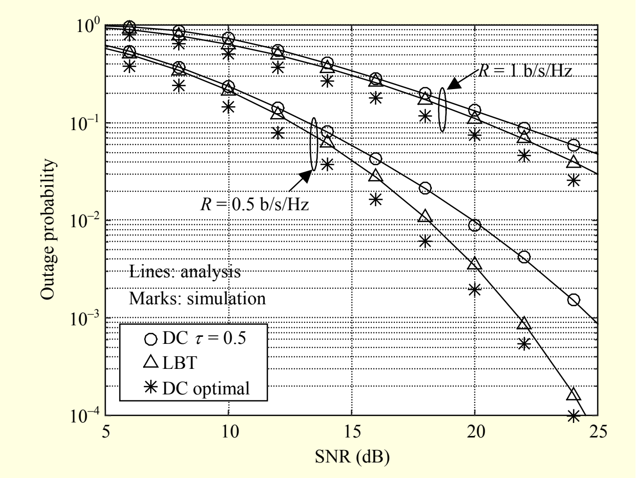

Fig. 7. Comparison of the outage probability of an SSN with a DC-based SSD and that with a LBT-based SSD as a function of the average SNR.

an SSN. The performance gain achieved using the optimal data transmission time is about 3 dB (8 dB) when compared with the performance using $\tau = 0.3$ ($\tau = 0.5$) at a 1% outage probability. To improve the outage probability of an SSN with a DC-based SSD, the data transmission time should be suitably selected. As shown in Figs. 5 and 6, the conventional method, which selects an operating channel where the minimum number of WCSs exists among the available channels, is not optimal from an outage perspective.

Figure 7 compares the outage probabilities of an SSN as a function of the average SNR when an LBT-based SSD and a DC-based SSD are employed. The analytical results match the simulation results exactly. It is shown that a DC-based SSD with the optimal data transmission time provides a better outage probability than an LBT-based SSD regardless of the target rate. However, an LBT-based SSD has a better outage probability than a DC-based SSD with $\tau = 0.3$. Therefore, the data transmission time for a DC-based SSD should be determined suitably to enhance the outage performance of an SSN.

Figures 8(a) and 8(b) compare the outage probabilities of an SSN as a function of the number of WCSs. The outage performance degrades as the number of WCSs increases because the data rate of the WCSs is inversely proportional to the number of WCSs. As shown in Fig. 8, the performance gain obtained by the channel selection is much higher than the performance gain obtained by the channel access mechanism, as the average SNR increases. It can be seen that the performance gap between the proposed channel selection and the conventional channel selection decreases as the number of WCSs increases. Figure 9 compares the outage probabilities of an SSN as a function of the number of available channels. It is

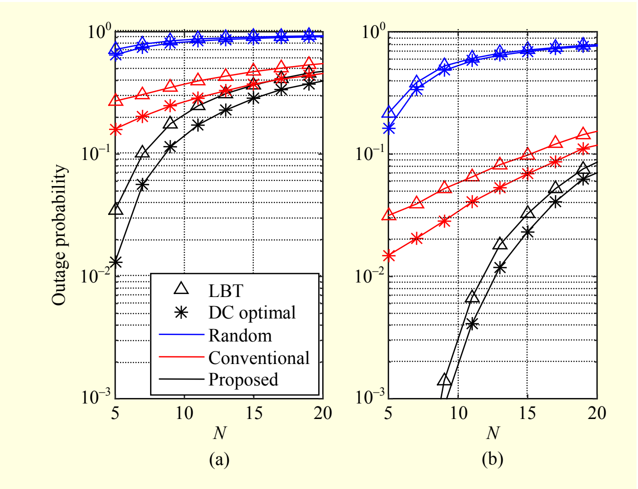

Fig. 8. Comparison of the outage probability of an SSN with a DC-based SSD and that with a LBT-based SSD as a function of the number of WCSs at an average SNR of (a) 10 dB and (b) 20 dB.

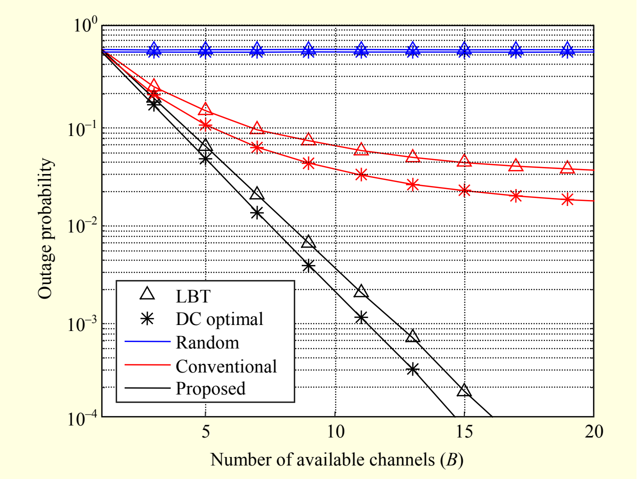

Fig. 9. Comparison of the outage probability of an SSN with a DC-based SSD and that with an LBT-based SSD as a function of the number of available channels at an average SNR of 20 dB.

shown that the outage probability improves as the number of available channels increases. In addition, as the number of available channels increases, the performance gain obtained by the channel selection is much higher than the performance gain obtained by the channel access mechanism. From Figs. 8 and 9, one can see that the channel selection scheme has an important role in enhancing the SSNs.

VII. Conclusion

In this paper, we studied an SSN where an SSD coexists with multiple unlicensed WCSs to efficiently utilize the spectrum resources. We proposed a channel selection scheme for a DC-based SSD as well as for an LBT-based SSD to minimize the outage probability of an SSN with multiple available channels. We first derived an exact and closed-form outage probability of an SSN when the proposed channel selection with a given data transmission time is exploited. An optimal data transmission time for a DC-based SSD was then derived to further improve the outage probability. We confirmed that the analytical results match exactly the simulation results. The results indicate that the DC channel access mechanism with the optimal data transmission time outperforms the LBT channel access mechanism. From our studies, we can conclude that the channel selection issue becomes more important than the channel access mechanism issue in practical network deployment scenarios where the number of opportunistically available channels increases.

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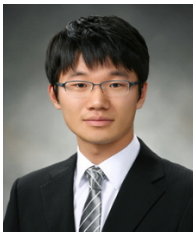

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