Spectrum Sensing Scheme Measuring Packet Lengths of Interfering Systems for Dynamic Spectrum Sharing

HIDEYA SO [1,2], **(Member, IEEE), HAYATO SOYA**[3], **AND KAZUHIKO FUKAWA**[1], **(Senior Member, IEEE)**

[1]School of Engineering, Tokyo Institute of Technology, Tokyo 152-8550, Japan
[2]Department of Electrical and Electronic Engineering, Shonan Institute of Technology, Fujisawa, Kanagawa 251-8511, Japan
[3]NPO neko 9 Laboratories, Tokyo 140-0001, Japan

Corresponding author: Hideya So (so.hideya@m.ieice.org)

ABSTRACT For the dynamic spectrum sharing (DSS), this paper proposes a spectrum sensing scheme that measures packet lengths of interfering systems. DSS requires spectrum sensing techniques to measure a length of time for which the interfering systems use a channel during observation time. A ratio of the length of time to the observation time is referred to as the channel occupation ratio (COR). When the observation time is limited, a conventional estimation scheme suffers from large errors of the measured COR. To cope with this problem, another conventional scheme divides the observation time into multiple short slots so as to estimate mean squared estimation errors of COR. However, this conventional scheme cannot accurately estimate errors, because it does not consider the time length of packets. Therefore, this paper proposes a scheme to estimate the variance of measured COR by measuring how long packets from the interfering systems can be observed, which can estimate errors much more accurately than the conventional scheme. Computer simulations evaluate how the observation time affects the standard deviation of the measured COR. It is also demonstrated that the theoretical results of the proposed scheme agree with those of the simulations when the true value of COR is less than 0.4.

INDEX TERMS Dynamic spectrum sharing (DSS), spectrum sensing, channel occupation ratio (COR), observation time, short slot.

I. INTRODUCTION

Since many kinds of wireless communication systems such as wireless LAN (WLAN), worldwide interoperability for microwave access (WiMAX), long-term evolution (LTE) (-Advanced) or the fifth-generation mobile communication system (5G) have emerged, radio resources become insufficient to implement such many systems, especially in the microwave band. The ultra-reliable and low-latency wireless communication (URLLC), which is expected to utilize the microwave band for 5G, should exploit diffraction of the microwave rather than the millimeter wave [1]. When congested radio resources are used, required transmission performance can hardly be achieved. In addition, since more wireless communication systems will be implemented in the future, it becomes necessary to use the radio resources more efficiently.

To overcome a lack of the radio resources, the dynamic spectrum sharing (DSS) is one of the most promising schemes and is well known as the cognitive radio [2], [3]. Since the primary system does not use all the radio resources such as time, frequency, and space, some radio resources are not used during a short period. These vacant radio resources can impair frequency efficiency. DSS, which shares the radio resources with multiple systems, can improve the system throughput and frequency efficiency by exploiting the vacant radio resources. DSS in 5G, which aims to share the channel with the existing system such as LTE, has also been investigated [4]–[6].

Sharing the radio resources should prevent other systems from interfering with the target system. When each system exchanges control signals including information on the radio resource usage, a new-coming system can easily use vacant radio resources. On the other hand, when each system cannot recognize the control signals in the unlicensed band, each system needs to detect the radio resource usage by itself. For such detection without control signals, the spectrum sensing

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technique such as the listen before talk (LBT) [7] is required. LBT usually checks the radio condition before transmission. However, it is more effective to observe the radio resource usage of the other systems during a certain period and to select channels with lower usage [8], [9].

The radio resource usage changes according to the time of day/week and the environment [10], [11]. Since the usage of radio resources depends on the users' behavior [12], it is possible to adequately predict the usage amount on a daily or weekly basis. However, the variations during a short period become large in towns and stations where many users frequently move. To observe the usage of radio resources during a short period, sensing techniques in the physical and MAC layers have been studied. In the physical layer, the energy detection can observe signals over channels [13], [14]. In the MAC layer, the usage period and kind of systems can be inferred from the MAC headers of observed packets [15]. A combination of techniques in the physical and MAC layers has also been investigated [16]. However, the detection technique in the MAC layer requires the MAC header to be correctly received. Furthermore, since it is necessary to recognize the MAC header, this approach cannot detect when a new system appears. In order to enable various systems to employ DSS in the unlicensed band, the spectrum sensing in the physical layer is preferable to that in the MAC layer.

The former spectrum sensing needs sufficient observation time in order to accurately detect the usage of radio resources. Since 5G is expected to develop the new frequency band [17], the number of channels used for the communication increases. As the number of observed channels increases, the observation time increases sharply and thus the frequency efficiency is degraded [18]. Since the number of RF circuits should be limited, all channels cannot be observed at the same time. As the observation time becomes longer, the usage of previously observed channels may change before selecting one channel. As the observation time becomes short, the channel usage cannot be measured accurately because the channel observer cannot receive a sufficient number of packets. To reduce the observation time, an adaptive spectrum sensing technique that selects the observed channel according to the usage of the interfering system has also been proposed [19]. However, this proposed technique cannot solve the following fundamental problem: When congested channels are selected for communications, the communication quality may deteriorate.

To overcome these problems, the estimation scheme that can evaluate estimation errors of the channel usage is required. A scheme proposed in [20] can theoretically estimate the observation error for the rendezvous schemes. However, the conventional scheme in [20] divides the observation time into multiple short slots and checks whether such slots are used or not, in order to estimate mean squared estimation errors. Such a conventional scheme cannot accurately estimate the mean squared estimation errors, because it does not consider the time length of packets from the interfering systems. Hence, this paper proposes a scheme to estimate
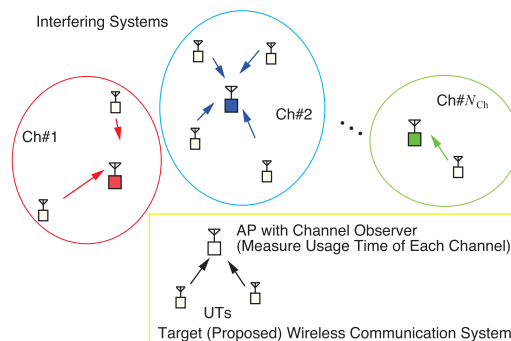

FIGURE 1. System model.

the variance of measured channel usage by measuring how long packets from the interfering systems can be observed during one short slot, which can estimate the mean squared estimation errors much more accurately than the conventional scheme. Since the proposed estimation scheme can measure the channel usage during sufficiently short observation time, DSS can operate well while improving the frequency efficiency. Note that the proposed scheme can be combined with the sensing techniques in [13]–[16], [19], because the proposed scheme aims to accurately estimate the variance of measured COR.

The rest of the paper is organized as follows. Section 2 presents the system model and discusses the problem of the short observation time. Section 3 describes the conventional and proposed estimation schemes for the measured channel usage. In Section 4, computer simulation results are detailed. Finally, Section 5 concludes the paper.

II. SYSTEM MODEL AND PROBLEM FOR SPECTRUM SENSING

A. SYSTEM MODEL

Let us consider a system model shown in Fig. 1, which includes the target (proposed) and other wireless communication systems. These systems are assumed to use N_{Ch} uncorrelated channels with the same bandwidth. It is also assumed that the other systems can randomly assign any user terminals (UTs) into each channel, and that an access point (AP) of the target system selects one channel from the N_{Ch} channels to communicate with its UTs. The AP is equipped with a channel observer that monitors channel usage. The channel observer measures the total length of time, for which received signal strength of each channel exceeds a threshold during observation time T_{OBS}, and the measured length of time is referred to as the channel usage time. As the threshold, the carrier sense level is usually used. Note that the target system can receive control signals from the interfering systems but cannot recognize them. Finally, the AP searches for the channel having the minimum channel usage time and selects such a channel for the communication.

B. PROBLEM OF SHORT OBSERVATION TIME FOR SPECTRUM SENSING

Let us discuss how the short observation time affects the measurement. Fig. 2 shows a time chart of the channel
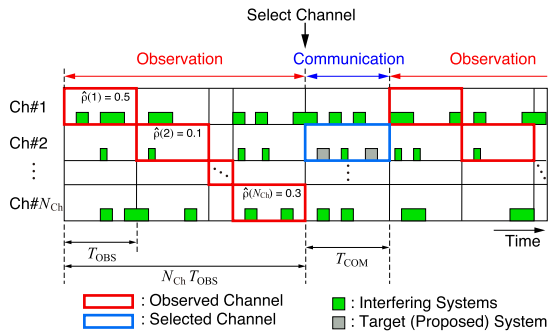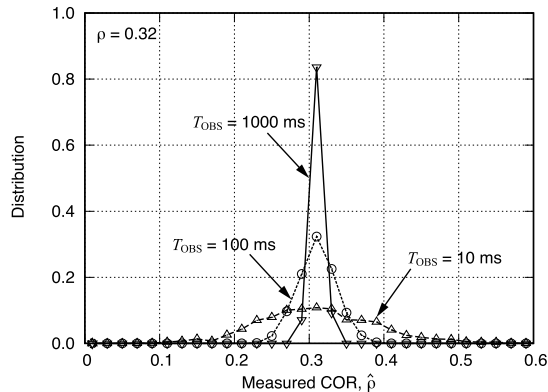
FIGURE 2. **Example of time chart.**

FIGURE 3. **Distributions of the measured COR.**

FIGURE 4. **Time charts of the conventional and proposed schemes.**

observation. The whole time can be divided into two periods; observation and communication periods. During the observation period, the AP measures the channel usage time for each channel during T_{OBS}. The channel occupation ratio (COR) is defined as the ratio of the channel usage time to T_{OBS}. Let $\hat{\rho}(n_{\mathrm{Ch}})$ denote the measured COR at the n_{Ch}-th ($1 \leq n_{\mathrm{Ch}} \leq N_{\mathrm{Ch}}$) channel and $\hat{\rho}(n_{\mathrm{Ch}})$ is given by

$$\hat{\rho}(n_{\mathrm{Ch}}) = \frac{T_{\mathrm{ON}}(n_{\mathrm{Ch}})}{T_{\mathrm{OBS}}}, \qquad (1)$$

where $T_{\mathrm{ON}}(n_{\mathrm{Ch}})$ is the channel usage time at the n_{Ch}-th channel. Here, the COR estimation is assumed to be unbiased, which means that the ensemble average of $\hat{\rho}(n_{\mathrm{Ch}})$ is equal to the true value. After measuring the channel usage of all the channels, the AP selects the channel that corresponds to the minimum COR. In Fig. 2, Ch#2 is selected and used for the communication. During the communication period T_{COM}, the AP continues to communicate with UTs over the selected channel. After T_{COM}, the AP measures the channel usage again and selects one channel corresponding to the minimum COR. Therefore, the period of the channel selection is equal to $N_{\mathrm{Ch}}T_{\mathrm{OBS}} + T_{\mathrm{COM}}$, which increases along with an increase in both the number of observed channels N_{Ch} and the observation time T_{OBS}. Although shorter T_{OBS} is preferable, decreasing T_{OBS} can damage the accuracy of the COR estimation.

From now on, the dependence of $\hat{\rho}(n_{\mathrm{Ch}})$ on n_{Ch} is omitted for simplicity. As an example of the COR measurement, Fig. 3 shows distributions of the measured COR when $T_{\mathrm{OBS}} = 10, 10^2, 10^3$ ms and the true value of COR, ρ, is set to
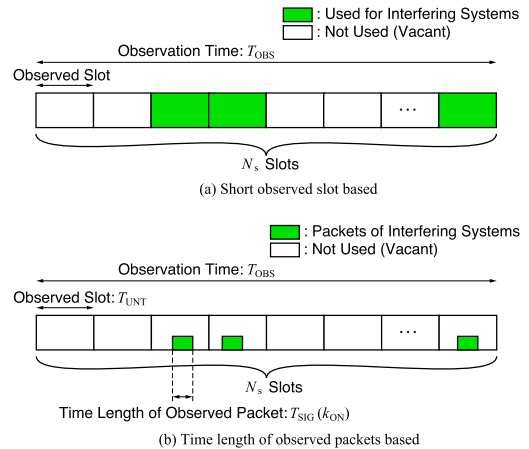
0.32. The computer simulations also assumed that the traffic of the interfering systems follows the Poisson distribution and that the packet length is constant. It can be seen from Fig. 3 that the deviation of the measured COR increases along with a decrease in T_{OBS}, which means that the AP is more likely to select worse channels as T_{OBS} decreases. To overcome such a problem, this paper proposes a measurement scheme that can estimate the deviation of the measured COR.

Another problem is that the channel observer of the AP cannot receive signals from hidden terminals. To solve this problem, UTs perform distributed sensing and send sensing results to AP, which has been proposed in [21], [22]. The amount of feedback information on the sensing results is considerable. To overcome this issue, Ref. [23] has proposed cluster of the channel observers and aggregation of the sensing results. However, the distributed sensing requires high cost when every UT is equipped with the channel observer. Considering the serious drawback, this paper does not consider the distributed sensing by UTs and installs the channel observer into only AP, which can hardly solve the above-mentioned problem. Note that the proposed scheme focuses on estimating the variance of the observed COR for the single channel observer, and can be combined with the above distributed sensing techniques.

III. ESTIMATION OF COR DEVIATION

This section discusses how to estimate the deviation of the measured COR. For comparison, the conventional scheme to divide the observation time into multiple short slots is explained at first. Next, the proposed estimation scheme is detailed under reasonable conditions with short T_{OBS}.

A. CONVENTIONAL ESTIMATION SCHEME BASED ON OBSERVED SHORT SLOTS

The estimation scheme proposed in [20] divides the observation time into N_{s} observed short slots as shown in Fig. 4 (a). The interfering systems are assumed to randomly use the observed short slots. The channel observer monitors whether each observed short slot includes any signals. When the channel observer detects any signals (indicated by green blocks

in Fig. 4 (a)), the corresponding observed short slots are classified into "ON". Otherwise (indicated by white blocks in Fig. 4 (a)), the corresponding observed short slots are classified into "OFF". On the assumption that the sensing results are statistically independent of each other, the probability that $\hat{\rho} = K_{\text{ON}}/N_{\text{s}}$ is given by

$$P(K_{\text{ON}}|\rho, N_{\text{s}}) = \binom{N_{\text{s}}}{K_{\text{ON}}} \rho^{K_{\text{ON}}}(1 - \rho)^{N_{\text{s}}-K_{\text{ON}}}, \quad (2)$$

where K_{ON} (≥ 0) is the number of "ON" observed short slots. When $N_{\text{s}}\rho(1 - \rho) \gg 1$ holds, the binomial distribution can be approximated as the following Gaussian distribution according to the De Moivre-Laplace theorem [24]:

$$P(K_{\text{ON}}|\rho, N_{\text{s}}) \simeq \frac{1}{\sqrt{2\pi N_{\text{s}}\rho(1 - \rho)}} \exp\left[-\frac{(K_{\text{ON}} - N_{\text{s}}\rho)^2}{2 N_{\text{s}}\rho(1 - \rho)}\right]. \quad (3)$$

When K_{ON} is transformed into $\hat{\rho} = K_{\text{ON}}/N_{\text{s}}$, (3) is rewritten as

$$P(\hat{\rho}|\rho, N_{\text{s}}) = \frac{1}{\sqrt{2\pi\rho(1 - \rho)/N_{\text{s}}}} \exp\left[-\frac{(\hat{\rho} - \rho)^2}{2\dfrac{\rho(1 - \rho)}{N_{\text{s}}}}\right]. \quad (4)$$

Let σ^2 denote the variance of the above Gaussian distribution and σ^2 is given by

$$\sigma^2 = \frac{\rho(1 - \rho)}{N_{\text{s}}}. \quad (5)$$

The variance is inversely proportional to N_{s}. Therefore, when the length of the observed short slot is kept constant, longer observation time T_{OBS} is required to reduce the variance of the measured COR.

B. PROPOSED ESTIMATION SCHEME MEASURING PACKET LENGTHS

In real packet transmission systems, the length of each packet is not the same but different. The conventional scheme proposed in [20] does not consider this situation because the length of the observed short slots is not determined. Conversely, the proposed estimation scheme considers the time lengths of the observed short slots and observed packets in order to estimate the variance of the measured COR. Therefore, the proposed scheme is expected to estimate the variance of the measured COR more accurately than the conventional one, and thus to avoid selecting worse channels. Fig. 4 (b) shows a time chart of the proposed scheme. Considering it, $\hat{\rho}$ of (1) can be rewritten as

$$\hat{\rho} = \frac{\sum_{k_{\text{ON}}=1}^{K_{\text{ON}}} T_{\text{SIG}}(k_{\text{ON}})}{T_{\text{OBS}}}, \quad (6)$$

where $T_{\text{SIG}}(k_{\text{ON}})$ denotes the time length of the k_{ON}-th ($1 \leq k_{\text{ON}} \leq K_{\text{ON}}$) packet. For simplicity, the time lengths of the observed packets are assumed to be constant during T_{OBS}. Since T_{EXP} denotes an expectation of the constant time length, the following equation holds:

$$T_{\text{SIG}}(1) = T_{\text{SIG}}(2) = \cdots = T_{\text{SIG}}(K_{\text{ON}}) = T_{\text{EXP}}. \quad (7)$$

TABLE 1. Simulation conditions.

Payload length	512 Bytes
Preamble length	24 μsec
L-SIG length	4 μsec
Header length of MAC layer	30 Bytes
ACK length	14 bytes
DIFS length, T_{DIFS}	34 μsec
SIFS length, T_{SIFS}	16 μsec
Slot length, T_{ST}	9 μsec
Packet length, T_{SIG}	0.11–0.68 ms

Substituting (7) into (6) yields

$$\hat{\rho} = \frac{K_{\text{ON}}T_{\text{EXP}}}{T_{\text{OBS}}}. \quad (8)$$

On the other hand, let T_{UNT} be the time length of the observed short slot, and the observation time can be expressed as

$$T_{\text{OBS}} = N_{\text{s}}T_{\text{UNT}}. \quad (9)$$

Substituting (9) into (8) results in

$$\hat{\rho} = \frac{K_{\text{ON}}T_{\text{EXP}}}{N_{\text{s}}T_{\text{UNT}}}. \quad (10)$$

Considering $\hat{\rho} = K_{\text{ON}}/N_{\text{s}}$ in the conventional scheme, the factor of $T_{\text{EXP}}/T_{\text{UNT}}$ is also needed for ρ in the proposed scheme. Thus, σ^2 of (5) is modified into

$$\sigma^2 = \frac{\rho\dfrac{T_{\text{EXP}}}{T_{\text{UNT}}}\left(1 - \rho\dfrac{T_{\text{EXP}}}{T_{\text{UNT}}}\right)}{N_{\text{s}}}$$
$$= \frac{\rho\dfrac{T_{\text{EXP}}}{T_{\text{UNT}}}\left(1 - \rho\dfrac{T_{\text{EXP}}}{T_{\text{UNT}}}\right)}{T_{\text{OBS}}/T_{\text{UNT}}}$$
$$= \frac{\rho T_{\text{EXP}}}{T_{\text{OBS}}}\left(1 - \rho\dfrac{T_{\text{EXP}}}{T_{\text{UNT}}}\right). \quad (11)$$

Let T_{NUL} denote the time length for which the channel observer cannot detect any signals during T_{UNT}, and T_{UNT} is expressed as

$$T_{\text{UNT}} = T_{\text{NUL}} + T_{\text{EXP}}. \quad (12)$$

When $T_{\text{NUL}} \gg T_{\text{EXP}}$ holds, (11) can be approximated as

$$\sigma^2 \simeq \frac{\rho T_{\text{EXP}}}{T_{\text{OBS}}}, \quad (13)$$

where $T_{\text{EXP}}/T_{\text{UNT}} \simeq 0$ was used for the derivation.

Note that the value of T_{OBS} can be obtained from (13) using target values of σ^2, ρ, and T_{EXP}.

IV. COMPUTER SIMULATION
A. SIMULATION CONDITIONS
Computer simulations were conducted to verify the effectiveness of the proposed estimation scheme. Since the finite buffer model was employed, the packet generation of the interfering systems was assumed to follow the Poisson distribution. As the payload length of the observed packets was set to 512 bytes, the packet length varied according to the selected modulation and coding scheme (MCS) index.
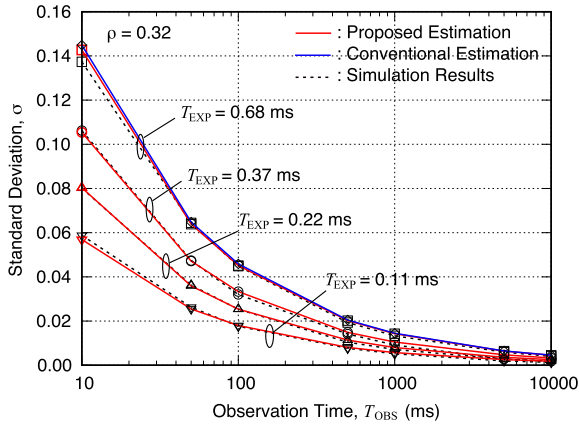
FIGURE 5. Standard deviation of the proposed estimation scheme versus the observation time.

The control overhead was set in the same manner as [25] and each parameter was listed in Table 1. It was assumed that the channel observer can receive all packets from the interfering systems.

The following two conditions were considered. One keeps the packet length constant because the MCS index is fixed. The other employs the adaptive modulation and coding (AMC) and changes the packet length according to the selected MCS index. Let T_{DATA} and T_{ACK} denote the time lengths of data and acknowledgement (ACK) packets, respectively. Thus, the time length of the observed packet is denoted by T_{SIG} and obtained as

$$T_{SIG} = T_{DATA} + T_{ACK}. \quad (14)$$

Under the former condition, T_{EXP} is equal to T_{SIG}. Under the latter condition, T_{EXP} is the expectation of T_{SIG}. Note that the packet length and measured COR were assumed to be perfectly estimated, because the purpose of the computer simulations is to clarify the basic performance of the proposed estimation scheme. It is also noteworthy that the above assumption can be considered reasonable. The reason is that the MAC header can be correctly decoded under considerable SNR conditions and that the packet length can be perfectly estimated from the decoded MAC header.

B. CONSTANT PACKET LENGTH CONDITION

On the condition that the packet length is constant during T_{OBS}, Fig. 5 shows how the observation time T_{OBS} affects the standard deviation of the proposed estimation scheme with T_{EXP} being a parameter. The true value of COR, ρ, was set to 0.32. T_{EXP} was fixed at 0.68/0.37/0.22/0.11 ms that corresponds to 512-byte packets using MCS0/1/3/9. It can be seen that the theoretical results of (13) for the proposed estimation scheme agree with those of the computer simulation. The standard deviation, σ, decreases along with an increase in observation duration, T_{OBS}. When $T_{OBS} >$ 5000 ms, σ becomes negligible and $\sigma < 0.01$. On the other hand, σ increases along with an increase in T_{EXP}. This is because the number of packets decreases as T_{EXP} becomes large even if the true value of COR is the same. When the
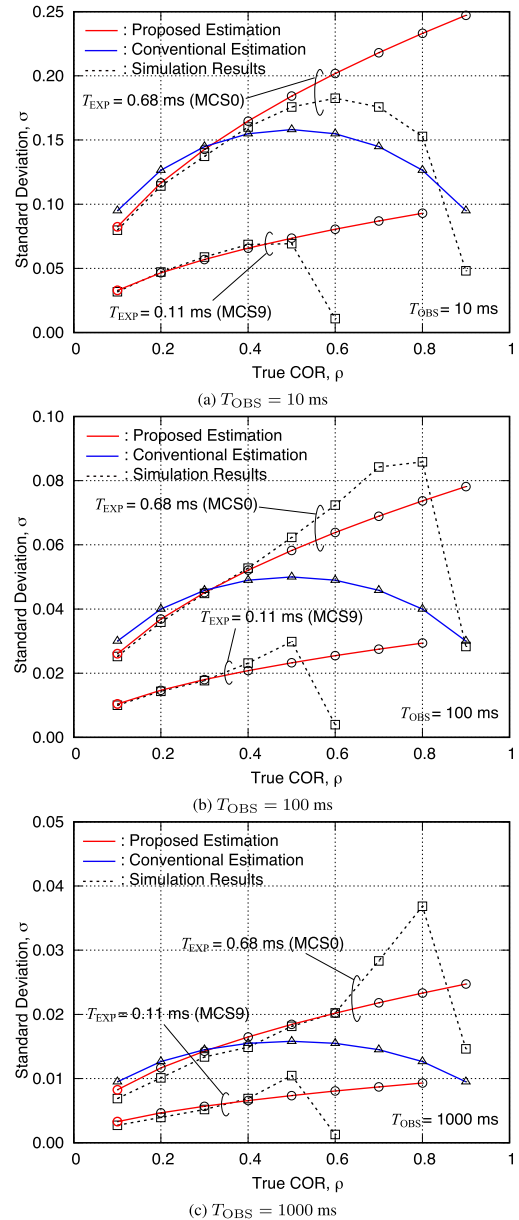

FIGURE 6. Standard deviation of the COR estimation schemes under constant packet length condition.

number of packets is small, a large variation can be seen in the packet generation during the observation time. For comparison, the theoretical results of (5) for the conventional estimation scheme were also plotted in the figure. The results of the conventional estimation scheme are almost the same as those of the simulation when $T_{EXP} = 0.68$ ms, but does not match the simulation results when $T_{EXP} = 0.37, 0.22, 0.11$ ms. The reason is that as T_{EXP} increases and approaches T_{UNT}, the result of the conventional estimation scheme converges to that of the simulation. Evidently, from the above simulation results, the conventional estimation scheme cannot operate well when T_{EXP} is much shorter than T_{UNT}.

Fig. 6 shows how the true value of COR, ρ, affects the standard deviation of the measured COR with T_{OBS} being a parameter. T_{EXP} was set to 0.68/0.11 ms. In all the cases,
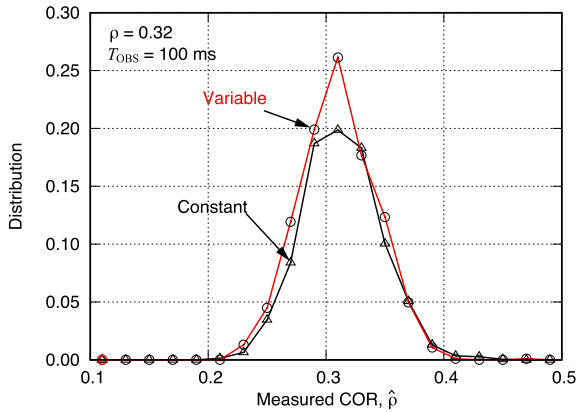
FIGURE 7. Distribution of the measured COR under the variable packet length condition.

it can be seen that σ increases along with an increase in ρ when $\rho < 0.5$. On the other hand, when $\rho > 0.5$, σ decreases along with an increase in ρ. This is because the number of observed packets, which depends on the true value of COR, increases, and the deviation of the measured COR decreases. The theoretical results of the proposed estimation scheme almost agree with the results of the simulation when $\rho \leq 0.4$. However, the former results do not match the latter results when $\rho > 0.4$. For comparison, the results of the conventional estimation scheme were also plotted in the figures and did not depend on T_{EXP}. When $\rho \leq 0.4$, the results of the conventional estimation scheme agree with those of the simulation when $T_{EXP} = 0.68$ ms. However, when $T_{EXP} = 0.11$ ms (the packet length is short), the results of the conventional estimation scheme are completely different from those of the simulation irrespective of ρ.

Since the proposed estimation scheme assumes that one packet falls within one short slot, the results of the proposed estimation scheme deviate from those of the simulation when the number of observed packets increases. Although the proposed estimation scheme is not effective in such a case, the communication quality is degraded even if the channel whose COR is larger than 0.4 is selected. When $\rho > 0.4$, the longer observation time and the shorter communication time are preferable.

C. VARIABLE PACKET LENGTH CONDITION

Next, computer simulations were conducted under the condition that the packet length varies. The packet length, T_{SIG}, ranged from 0.11 ms to 0.68 ms in which the MCS index was randomly selected from MCS0 through MCS9. The true value of COR was kept constant during the observation time. The other parameters were the same as those of the previous simulation.

Fig. 7 shows the distributions of the measured COR under the condition of the variable packet length. The true value of COR was set to 0.32 in the same manner as Fig. 3 while T_{OBS} was set to 100 ms. For comparison, the results with T_{SIG} being constant 0.37 ms were plotted. It can be seen that the observed results with the variable packet length are almost the same as

(a) Standard deviation of the COR estimation schemes.
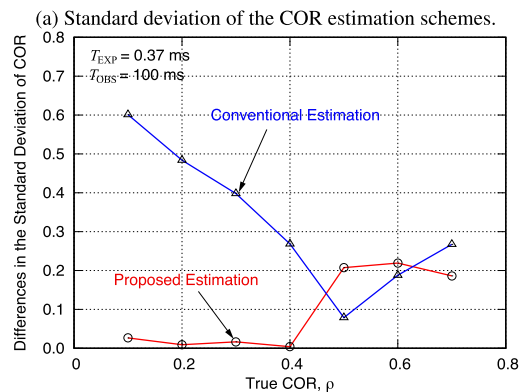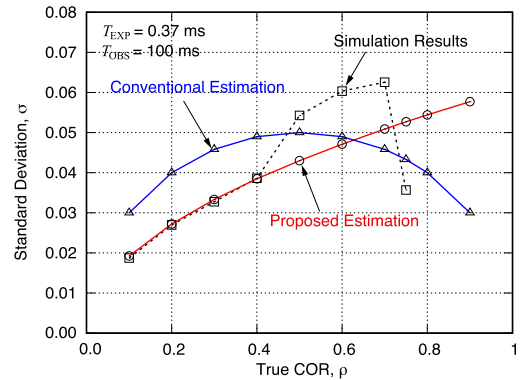
(b) Differences in the standard deviation of COR between

FIGURE 8. Performance under variable packet length condition.

those with constant T_{SIG}. This is because the expected packet length, T_{EXP}, of the variable packet length is the same as that with T_{SIG} of 0.37 ms.

Fig. 8 (a) shows the standard deviation of the COR while Fig. 8 (b) shows differences in the standard deviation of COR between the simulation result and the proposed or conventional estimation schemes, where T_{EXP} of the proposed scheme was set to 0.37 ms. It can be seen from these figures that the conventional estimation scheme suffers from larger errors because the conventional scheme does not consider the variable packet length condition. When $\rho \leq 0.4$, the proposed scheme can reduce the difference or error of the standard deviation below 0.05. On the other hand, when $\rho > 0.4$, the result of the proposed scheme becomes large, which does not cause any problems for the following reasons: When the true value of COR is equal to 0.5, it is evident from Fig. 8 (a) that the standard deviation is near 0.055. In this case, the probability that the measured COR lies within [0.39, 0.61] reaches 95%, which can be inferred from the Gaussian distribution with the standard deviation of 0.055 and the mean of 0.5. Therefore, excluding the channels with the measured COR being greater than $0.4 \simeq 0.39$ can prohibit the channels with larger COR from being selected. When the measured COR is less than 0.4, however, the proposed estimation scheme can select the channels with smaller COR.

V. CONCLUSION

In this paper, the novel spectrum sensing technique that can estimate the standard deviation of the channel usage time

has been proposed for the dynamic spectrum sharing. The proposed scheme divides the observation time into multiple short slots and measures how long packet from the interfering systems can be observed during one short slot, in order to deal with the case of short observation time. Computer simulations have shown that how the observation time affects the standard deviation of the measured COR. It has also been demonstrated that the theoretical results of the proposed estimation scheme agree with those of the simulation when the true value of COR is less than or equal to 0.4. Although the standard deviation increases along with a decrease in the observation time, it has been verified that the proposed estimation scheme can detect the channels with smaller COR even under a short observation time condition.

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HIDEYA SO (Member, IEEE) received the B.E. degree from Tokyo University of Science, Japan, in 2009, and the M.E. and Dr.Eng. degrees from Tokyo Institute of Technology, Japan, in 2011 and 2021, respectively. From 2011 to 2021, he was with the NTT Access Network Service Systems Laboratories, NTT Corporation. He currently works with Shonan Institute of Technology. His research interests include high-reliability radio access, base station antennas, and adaptive arrays for the future wireless access systems. He is a member of IEICE. He received the IEICE Radio Communication Systems (RCS) Active Researcher Award, in 2011; the IEICE Young Researcher's Award, in 2016; and the IEICE Best Paper Award, in 2016.

HAYATO SOYA received the D.E. degree from Shinshu University, Nagano, Japan, in 2018. He was a Lecturer with the Department of Electrical Engineering, Nagano Prefectural Institute of Technology, from 2013 to 2018. He is concurrently an Engineer with the Nagano Prefecture General Industrial Technology Center, Precision, Electronics and Aviation Technology Department, since 2018. He is also the member of the Neko 9 Laboratories, which is a non-profit organization in Tokyo. His current research interest includes cognitive radio technologies.

KAZUHIKO FUKAWA (Senior Member, IEEE) received the B.S. and M.S. degrees in physics and the Dr.Eng. degree in electrical and electronics engineering from Tokyo Institute of Technology, Tokyo, Japan, in 1985, 1987, and 1998, respectively. He joined Nippon Telegraph and Telephone Corporation (NTT), Japan, in 1987. Since then, he has been engaged in research on digital mobile radio communication systems and applications of the adaptive signal processing, including adaptive equalization, interference cancellation, and adaptive arrays. He was a Senior Research Engineer at NTT Mobile Communications Network Inc. (NTT DoCoMo), from 1994 to 2000, and an Associate Professor at Tokyo Institute of Technology, from 2000 to 2014, where he has been a Professor, since March 2014. He received the Best Paper Award from IEICE, in 1995, 2007, 2009, and 2012; the Best Paper Prize from the European Wireless Technology Conference (EuWiT); and the Achievement Award from IEICE, in 2009.

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