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Comparison of two methodologies on spectrum sharing information for unlicensed use in the 6-GHz band

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Abstract

With the increasing demand for unlicensed spectrum, several regulators have been opening up the 6-GHz band for unlicensed use while ensuring compliance with the technical requirement to avoid harmful interference in the existing primary services (PSs). In this paper, we present two methodologies, a channel-based method and a frequency-based method, which are applicable to a frequency coordination system that calculates the permissible transmit power in the channels or frequencies available to a secondary service (SS). In addition, we have demonstrated that the available transmit power of an SS can be maximized by adjusting the power allocation of the assigned resource units under the condition that the channel of the SS is partially overlapped with that of the PS. Based on the analysis results, it is suggested that it would be better to utilize the two methods selectively according to the operating channel conditions of the PS and the SS.

KEYWORDS

automated frequency coordination, spectrum sharing, unlicensed use, 6-GHz band

1 | INTRODUCTION

With the expansion of various high-definition video streaming services and the advent of the fourth industrial revolution, the demand for radio spectrum is expected to increase gradually [1,2]. Because it is hard to accommodate this demand with a licensed spectrum alone, it is important to supply an unlicensed spectrum so that the traffic burden can be distributed through data offloading [3]. In addition, it is envisioned that the data traffic volume on the unlicensed band will expand due to work-from-home operations, video conferences, online classes, and so forth, which have become part of many people's daily lives following the outbreak of the COVID-19 pandemic [4]. Thus, the need for the unlicensed spectrum that are free to access for all users will undoubtedly further increase. To date, unlicensed wideband access, as represented by radio local area networks (RLANs), has been only available in the 2.4- or 5-GHz bands [5]. However, the 2.4-GHz band involues issues related to poor user experience in terms of quality of service due to the high congestion from the overlapped channelization. Thus, several trials and studies have been conducted to expand the spectrum for unlicensed use with a focus on 5-GHz band, whereas this has not been realized due to the issue of coexistence with the existing services [6]. Within this context, the regulators of many countries have been opening up the 6-GHz band for the unlicensed use based on the spectrum sharing [7,8]. As the primary services (PSs) that must be protected, these include various operations, such as fixed services, fixed satellite services and broadcast auxiliary services (BASs). To prevent unlicensed use from making a harmful interference into the existing services, specific technical requirements, such as the transmit power levels falling in line with the operating conditions of RLAN devices, have been specified. The Federal Communications Commission (FCC) in the United States also introduced the automated frequency coordination system (AFCS), which provides spectrum sharing information (SSI) on available frequencies with a permissible transmit power, depending on the location of the RLAN device [8]. In this paper, we propose two methodologies for the calculation of SSI with a focus on protecting the fixed wireless system (FWS) for fixed services. These can be classified according to whether or not the AFCS utilizes the predefined channelization of the RLAN specification. Accordingly, the SSI can be provided for each RLAN channel or for each unit bandwidth over the 6-GHz band. Meanwhile, we also discuss on adapting the power in the assigned resources such that the RLAN device using the SSI of the unit bandwidth, can maximize the available effective isotropically radiated power (EIRP). Finally, we analyze and compare the maximum available EIRP derived using the SSIs of the two methodologies under the condition that the channel of the RLAN is partially overlapped with that of the FWS. Based on the analysis results, it is suggested that it is necessary for RLANs to utilize both SSI sets selectively according to the operating channel conditions. The remainder of the paper is organized as follows. Section 2 reviews the trends in the activities of the regulatory and standard domains related to the 6-GHz band. Section 3 outlines the procedures for calculating the SSI of the two methodologies with some consideration of the spectrum masks of the RLAN and the FWS and discuss how the available EIRP can be maximized while complying with the regulatory requirements. Section 4 provides the analysis results related to various channel bandwidths of the RLAN under the scenario where the FWS channel is overlapped. Finally, the conclusions are provided in Section 5.

2 | RELATED WORKS

2.1 | Regulatory domains

With the increasing demand for a spectrum for unlicensed devices or networks such as Wi-Fi, LTE-unlicensed, and 5G NR-unlicensed, the regulatory domains in Europe and the United States have been working to allocate an additional band for unlicensed services or to alleviate the attendant technical requirements in the 5-GHz band [9,11]. Specifically, various studies have been conducted in relation to compatibility and spectrum sharing with the existing wireless stations over the 5350 MHz to 5470 MHz and 5725 MHz to 5925 MHz bands. The evaluation of the European Conference of Postal and Telecommunications Administrations (CEPT) determined that the mitigation techniques and operating conditions cannot be specified for sharing those bands [6]. The FCC has also decided not to allow unlicensed use on the 5350 MHz to 5470 MHz band, choosing instead to permit an increase in transmit power while enabling outdoor operation in the 5150 MHz to 5250 MHz band [12]. Thus, the need to discover a new unlicensed spectrum has been raised, and as a result, the 6-GHz band has received a great deal of attention.

Moreover, the related industry has conducted various studies on the possibility of unlicensed use in the 6-GHz band, and submitted opinions and analysis results to the regulatory filings system [13]. In 2020, both the FCC and the Ministry of Science and ICT (MIST) of Korea have released the technical standards for different categories of RLAN devices, enabling operations on the 1.2-GHz bandwidth of 5925 MHz to 7125 MHz band [8]. Meanwhile, in the same year, the CEPT/ECC and Ofcom in the United Kingdom also decided to open the lower 500 MHz (5925 MHz to 6425 MHz) in the 6-GHz band to RLANs, while the national rules still have to be established following the final decision of the European Commission (EC) in 2021. In addition, several countries in South America, including Brazil, have entered the final stage for releasing technical standards or are in the process of attendant consultations. Japan and Taiwan are also planning to begin preparations for the introduction of the unlicensed use in the 6-GHz band in the near future. Figure 1 shows the timeline and the countries pertaining to the released rules and the attendant preparation. The existing PSs in the 6-GHz band, varied fixed services, fixed satellite services, or mobile services have been provided in each country in accordance with ITU-R radio regulations [14]. Therefore, it is essential to ensure that RLANs should share the spectrum without harmfully interfering with the existing PSs. To this end, the three types of RLAN device have been classified into AFC based standard power (AFCSP), low power indoor-only (LPI) and very low power (VLP), with the emission power and operating conditions limited for each type. Table 1 presents the technical standards for three RLAN types adopted in the US, Korea, Europe, UK, and Brazil. The AFCSP defined by only the FCC's rule and order (R&O) can transmit a signal with up to 36 dBm in EIRP, while they must first access to the AFCS in order to obtain information on the available operating frequencies and the attendant permissible transmit power [8]. A standard power access point (SPAP), fixed client, or a proxy serving on the behalf of the non-standalone SPAPs are eligible for inclusion in the AFCSP category. The FCC has prescribed that the AFCS must ascertain the exclusion zone of the AFCSP by utilizing the license information that is registered by the FWS. The main condition for determining the exclusion zone is that the interference to noise ratio (INR) pertaining to a single interference is −6 dB or more. Based on this criterion, the AFCS calculates the frequency and transmit power level available at the location provided by the AFCSP and delivers the result of the SSI back to it as the response. It has been announced that Korea is also planning on introducing a system that is similar to both AFCS and the AFCSP-type RLAN. In the case of LPI type, the operating environment is limited to indoor environments such that any potential interference affecting the existing services is mitigated through building entry loss (BEL). Meanwhile, a VLP is a type of RLAN device that can be used both outdoors and indoors under the condition that very low transmit power is used for the purpose of direct communication between devices

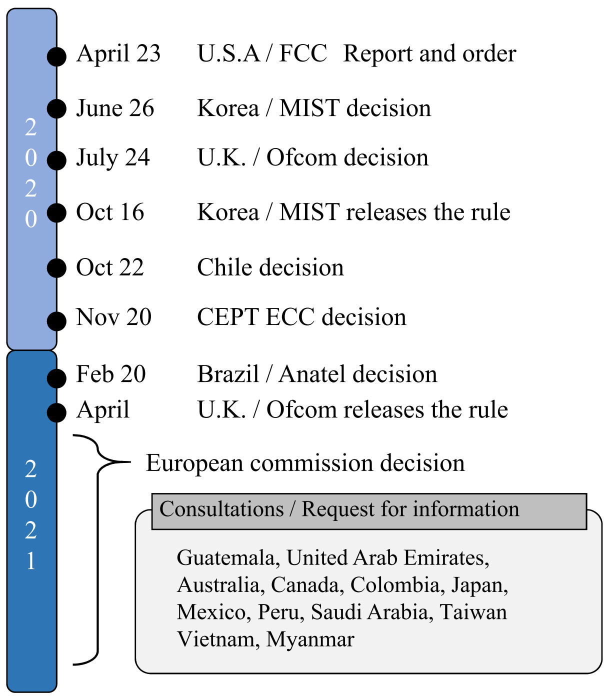

FIGURE 1 Timeline of countries adopting or preparing for unlicensed use in the 6-GHz band

located in close proximity. The FCC is currently reviewing whether or not to introduce VLP-type RLAN through collecting the opinions regarding the announcement of the further notices of proposed rulemaking (FNPRM) [15]. It should be noted that the FCC has divided the 6-GHz band into four sub-bands labeled unlicensed national information infrastructure (U-NII) bands that are considered to be consistent with the 5-GHz band. The numberings and frequency ranges of the U-NII bands are U-NII-5 (5925 MHz to 6425 MHz), U-NII-6 (6425 MHz to 6525 MHz), U-NII-7 (6525 MHz to 6875 MHz), and U-NII-8 (6875 MHz to 7125 MHz). Since mobile applications, such as TV pick-up stations, are allocated in the U-NII-6 and U-NII-8 bands, the operation of an AFCSP is restricted to only the U-NII-5 and U-NII-7 bands, whereas MIST has allowed only the lower 500 MHz of the 6-GHz band to the VLP operations to avoid the band allocated for BASs. Instead, the FCC and MIST have allowed LPI operations in the entire 1.2-GHz bandwidth of the 6-GHz band through stricter restriction of the same power spectrum density (PSD), regardless of the RLAN's channel bandwidth. In Europe, when the EC mandated CEPT/ECC to study the aspect of compatibility and determine the rules for unlicensed use, this was limited to 5925 MHz to 6425 MHz band because concerns were raised by some countries in which there exist relatively many fixed service links in the 6425 MHz to 7125 MHz [16]. The result of the Monte Carlo performance analysis related to both LPI and VLP operations indicated that there was no effect of long-term or short-term interference [17]. The Ofcom and Anatel also established the standards for LPI and VLP types by referring to the FCC's R&O and the CEPT reports [18]. For reference, the FCC and Anatel also stipulate EIRPs and PSDs for clients separately. This is 6 dB lower than the AFCSP or LPI type standard of the AP to which the client is connected.

2.2 | Standard domains

Candidate technologies for unlicensed access in the 6-GHz band include the Wi-Fi of IEEE 802.11 and the 5G New Radio Unlicensed (NR-U) of the 3rd Generation Partnership Project (3GPP) [19]. In terms of the IEEE 802.11ax

TABLE 1 Summary of technical standards established by the FCC, MIST, CEPT/ECC, Ofcom, and Anatel

Types	Features	FCC	MIST	CEPT/ECC	Ofcom	Anatel
AFCSP	Frequency	U-NII-5/7	—	—	—	—
	EIRP	36 dBm				
	PSD	23 dBm/MHz				
LPI	Frequency	5925 MHz to 7125 MHz	5925 MHz to 7125 MHz	5925 MHz to 6425 MHz	5925 MHz to 6425 MHz	5925 MHz to7125 MHz
	EIRP	30 dBm	24 dBm	23 dBm	24 dBm	30 dBm
	PSD	5 dBm/MHz	2 dBm/MHz	10 dBm/MHz	11 dBm/MHz	5 dBm/MHz
VLP	Frequency	—	5925 MHz to 6425 MHz	5925 MHz to 6425 MHz	5925 MHz to 6425 MHz	5925 MHz to 7125 MHz
	EIRP		14 dBm	14 dBm	14 dBm	17 dBm
	PSD		1 dBm/MHz	1 dBm/MHz	11 dBm/MHz	−5 dBm/MHz

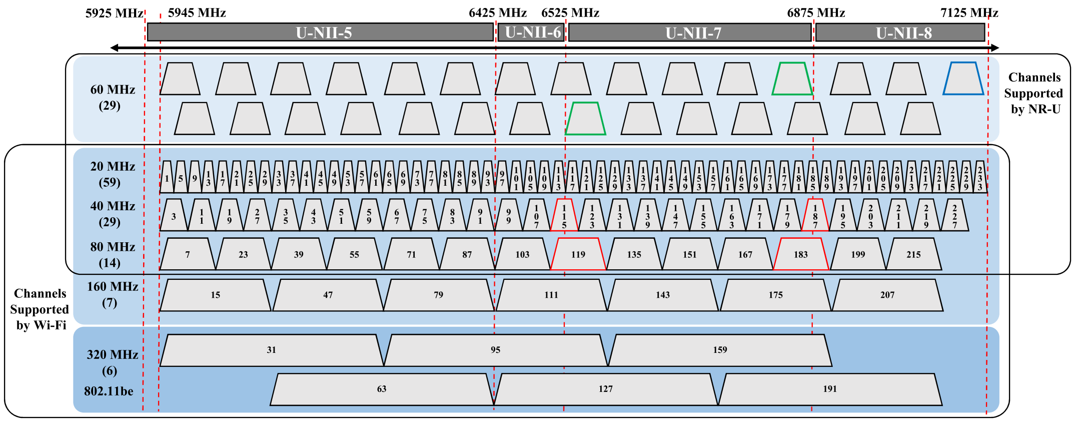

FIGURE 2 Wi-Fi and NR-U channelization, and center frequency index (CFI) values (n_{ch}) for Wi-Fi channels

working group (WG), it is in the stage of finalizing the publication of the specification of the IEEE802.11ax standard (11ax) [20]. In the early stages of the 11ax standard work, the target operating bands were 2.4 GHz and 5 GHz, but the addition of the 6-GHz band was approved in accordance with that the FCC begin considering to open up for unlicensed use in this band. In addition, IEE802.11be (11be) WG is promoting a new standardization for improving Wi-Fi performance and effectively utilizing the 6-GHz band. The center frequency (CF) of the Wi-Fi channels over the 6-GHz band specified in 11ax is defined as one of the integer multiples of 5-MHz resolution as follows [20]:

$$\mathrm{CF}(n_{ch}) = 5940 + 5 \times n_{ch} \ \ [\mathrm{MHz}], \tag{1}$$

where n_{ch} denotes the center frequency index (CFI) and its value can be one among 1, … , 233. The Wi-Fi channelization and CFI values for all channels of the 20-, 40-, 80-, 160-, and 320-MHz bandwidth are shown in Figure 2 [21]. The 320-MHz bandwidth will be included for the first time in the 11be standard, with the number of configurable channels becoming six, including three channels with an 80-MHz offset from 5945 MHz. Meanwhile, NR-U is a version of 5G NR with the inclusion of the additional feature of opportunistic channel access for the use of an unlicensed band [22]. As a successor of long-term evolution License Assisted Access (LTE LAA), NR-U applies the same channel access mechanism of the LAA which is performed with the unit of the 20-MHz resolution [23]. The LAA is restricted to accessing an unlicensed band together with the licensed carrier through the carrier aggregation functionality; however, the NR-U supports the standalone mode, meaning it is possible to construct networks independently. Because its physical layer is derived from the 5G NR that supports the maximum single bandwidth of 10 MHz, the operating bandwidths of the NR-U can be configured with 20 MHz, 40 MHz, 60 MHz, and 80 MHz as depicted in Figure 2. The CF of 20-, 40-, and 80-MHz channels for NR-U is aligned with that of the Wi-Fi. In the case of the 60-MHz channel, it can be configured up to with two within 80-MHz channel [24]. It would appear that an attempt has been made to align it with the channelization of Wi-Fi as far as possible. It is expected that the most anticipated effect of introducing a 60-MHz channel will be the usage of the channels (two green channels) of both the boundary of the U-NII-7 as well as a wider channel (blue channel) within the vicinity of 7125-MHz as shown in Figure 2. Because an AFCSP type is limited to use only U-NII-5 and U-NII-7, the Wi-Fi will not have the chance to use a wider bandwidth of more than 20 MHz at the both edges of U-NII-7 (red channels), while NR-U enables operation through using 60-MHz channel.

3 | SPECTRUM SHARING INFORMATION

In this section, we address two methodologies through which AFCS can calculate the SSI to be utilized by any AFCSPs willing to share a spectrum with the FWS in the 6-GHz band. In addition, we discuss how AFCSP using the SSI based on the unit bandwidth could maximize the available EIRP.

3.1 | Calculation methodologies for spectrum sharing information

The RLANs in the unlicensed band operate by opportunistically selecting a channel without any coordinator depending on the assessment of the frequency utilization situation. In such a case, it would be desirable that the RLAN retains the SSI sets of the candidate operating channels in order to swiftly move to another channel once there is little opportunity for transmission or there is a higher collision rate. Therefore, in this paper, it is assumed that AFCSP will request the SSI for the entire

6-GHz band regardless of FCC rule. From the perspective of AFCS, the criterion or definition related to the frequency range is required to calculate the SSI. This could be each RLAN channel defined in the standard, or the frequency bins with a certain unit bandwidth across a range of the 6-GHz band. Thus, the first methodology is SIM_1 which obtains the SSI based on the per-channel information of the Wi-Fi or NR-U, while the second methodology, SIM_2, revolves around calculating the SSI based on the per-unit-bandwidth (BW_U). The procedures for the two methodologies are represented by the respective algorithms 1 and 2. In both methodologies, the initial conditions are first defined to ensure that the technical rules are complied with. The conditions for initially setting up become maximum transmit powers and the reference Interference to noise ratio ($\mathrm{INR}_{\mathrm{ref}}$). As the power specified by the regulations, $\mathrm{EIRP}_{\max}$ and$\mathrm{EPU}_{\max}$ respectively represent the maximum EIRP from the AFCSP and the maximum EIRP per a unit bandwidth (EPU) of BW_U. $\mathrm{INR}_{\mathrm{ref}}$ is the criterion used to determine whether the signal transmitted by the AFCSP interferes with the FWS. The ITU-R F. 758 recommends using the INR for the study of the compatibility and the sharing between a digital FWS and other systems [25]. In the FCC case, $\mathrm{INR}_{\mathrm{ref}}$ has been designated as −6 dB, while $\mathrm{EIRP}_{\max}$ and $\mathrm{EPU}_{\max}$ are restricted to up to 36 dBm and 23 dBm/MHz, respectively, as shown in Table 1. The position of the AFCSP can be represented in a certain area by considering the location uncertainty that is required with the confidence level of 95% in FCC [8]. Then, this area can be divided into multiple pixels using the resolution of terrain information. The FCC has recommended to use an 1-arc second (around 30 m) resolution as the digital elevation terrain data [8]. We assume that the number of pixels in the area location of the AFCSP is L. After assigning the location of the AFCSP as an interference source, the FWSs located within the target area, or at a specified distance from it, were selected for the interference analysis. The received interference signal strength at the kth FWS from lth pixel of AFCSP was calculated as follows [26]:

$$\mathrm{RISS}_{k,l} = \mathrm{EP} + G_k - L_b - L_a \text{ [dBm]} \tag{2}$$

where EP can be either $\mathrm{EIRP}_{\max}$ or $\mathrm{EPU}_{\max}$, and G_k is the receive antenna gain of the kth FWS. L_b and L_a are the basic transmission loss and the additional loss, respectively. The effects of reflection, scattering, and diffraction are considered in the basic transmission loss, including clutter loss [27,28]. The additional loss comprises the feeder loss, the polarization loss, and BEL [29]. RISS_k is selected by confirming the maximum value among all pixels' $\mathrm{RISS}_{k,l}$ Here, the RISS_k is a value obtained with the assumption that the whole interference signal is fully

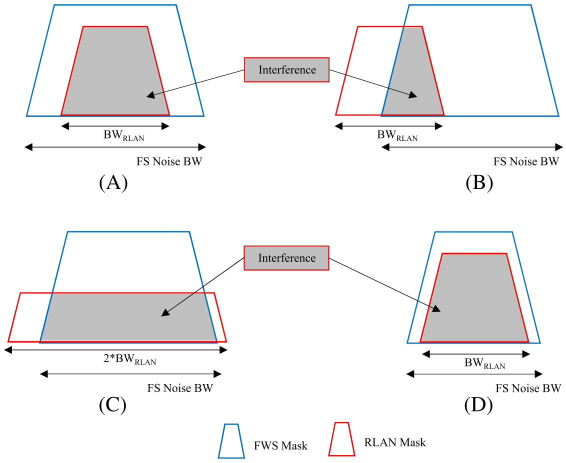

FIGURE 3 (A–D) Coexistence scenarios examples

injected into the FWS receiver. When the spectrum mask and CF are considered, this would be reduced to the actual interference level. Both methods are similar in terms of overall procedure, which involves determining the maximum INR and comparing it with the reference INR. However, the two methodologies differ in terms of calculating the amount of reducible interference and obtaining the SSI results.

The SIM_1 relates to considering the factors by integrating the transmit spectrum mask of the RLAN and the receive spectrum mask of the FWS. Figure 3 shows the examples of four conditions depending on both the CF and the bandwidth of the RLAN and the FWS. Each trapezoid represents a signal considering a spectrum mask from the perspective of bandwidth and signal strength, with blue and red representing the desired signal and the interference signal received at the FWS, respectively. Under all conditions, the RISS is the same, but the interference effects, which are represented by the gray colored areas, are different in (A), (B), and (C). In the case of (D), this becomes the same interference as (A) with the identical bandwidth of the RLAN fully included within the FWS, whereas the INR will be not the same. The bandwidth of the FWS is typically defined as 1.75 MHz, 3.5 MHz, 7 MHz, 14 MHz, 28 MHz, 40 MHz, or 56 MHz, and its channel arrangement is not consistent with that of Wi-Fi or NR-U [30]. As shown in Figure 2, it is expected that the cases of (B) or (C) will occur more frequently in the scenario where the RLAN and the FWS coexist in the 6-GHz band. Then, we adopt the Ffrequency-dependent rejection (FDR) to investigate the interference to be mitigated according to the spectrum masks. This is defined as the summation of the on-tune rejection (OTR) and the off-frequency rejection (OFR) as follows: $\mathrm{FDR}(n_{ch})_k = \mathrm{OTR} + \mathrm{OFR}(\Delta f)$, where Δf is the difference between center frequencies of

CF(n_{ch}) for RLAN and f_k for k-th FWS [31]. Here, the OTR and OFR are defined as follows [32]:

Algorithm 1 SSI Methodology 1 : SIM_1

Set the INR_{ref} and $EIRP_{max}$
Find out $FWS(k)$, $k \in 1, \ldots, K$
For $k = 1, \cdots, K$
  Calculate $RISS_{k,l}$, $l \in 1, \ldots, L$, based on EIRP
  $RISS_k = \max_{l \in L}[RISS_{k,l}]$
  Calcualte $I(n_{ch})_k = RISS_k - FDR(n_{ch})_k$
  Obtain $INR(n_{ch})_k$ from N_k
end
  $INR(n_{ch}) = \max_{k \in K}[INR(n_{ch})_k]$
  Compare $INR(n_{ch})$ with INR_{ref}
  Determine $SIM_1(n_{ch})$

$$\text{OTR} = 10\log_{10}\left[\frac{\int_{f=-\infty}^{f=\infty} m_R(f)df}{\int_{f=-\infty}^{f=\infty} m_R(f)m_F(f)df}\right][\text{dB}], \tag{3}$$

Algorithm 2 SSI Methodology 2 : SIM_2

Set the INR_{ref} and EPU_{max}
Find out $FWS(k)$, $k \in 1, \ldots, K$
For $k = 1, \cdots, K$
  Calculate $RISS_{k,l}$, $l \in 1, \ldots, L$, based on EPU
  $RISS_k = \max_{l \in L}[RISS_{k,l}]$
  Obtain $INR(f)_k$ from $I(f)_k$ and N_{BW_U}
end
  $INR(f) = \max_{k \in K}[INR(f)_k]$
  Compare $INR(f)$ with INR_{ref}
  Determine $SIM_2(f)$

$$\text{OFR}(\Delta f) = 10\log_{10}\left[\frac{\int_{f=-\infty}^{f=\infty} m_R(f)m_F(f)df}{\int_{f=-\infty}^{f=\infty} m_R(f)m_F(f+\Delta f)df}\right][\text{dB}] \tag{4}$$

where m_R and m_F are spectrum masks in absolute of the frequency response on the transmitter of the RLAN and the receiver of the FWS, respectively. Then, $\text{INR}(n_{ch})_k$ is obtained by subtracting the noise floor, N_k, in dB scale upon the system bandwidth of FWS_k. The potential maximum INR on each channel of CFI(n_{ch}) at the location of the AFCSP becomes the following:

$$\text{INR}(n_{ch}) = \max_{k \in K}\left(\text{RISS}_k - \text{FDR}(n_{ch})_k - N_k\right). \tag{5}$$

Finally, the $SIM_1(n_{ch})$ is determined as (6) by comparing with INR_{ref}. If the EIRP to be used is denoted by P_1, the AFCSP just needs to follow the SSI calculated as SSM_1 with P_1 for each CFI.

$$SIM_1(n_{ch}) = \begin{cases} \text{EIRP}_{\max} & , \text{if } \text{INR}_{\text{ref}} \geq \text{INR}(n_{ch}) \\ \text{EIRP}_{\max} + \left(\text{INR}_{\text{ref}} - \text{INR}(n_{ch})\right) & , \text{if } \text{INR}_{\text{ref}} < \text{INR}(n_{ch}) \end{cases} \tag{6}$$

On the SIM_2, the transmit mask of the interferer is assumed to be the ideal rectangular mask with the BW_U, and then the rejection factor of mitigating interference is relevant to only receive spectrum mask of the FWS. When the CF of each unit bandwidth of BW_U is f, the $\text{INR}(f)_k$ for the k-th FWS becomes the following:

$$\text{INR}(f)_k = \text{RISS}_k - \text{RF}(f)_k - N_U \tag{7}$$

where N_U is the noise floor in dB scale for the bandwidth of BW_U and $\text{RF}(f)_k$ is the rejection factor by the spectrum mask as defined by

$$\text{RF}(f)_k = 10\log_{10}\left[\frac{\int_{y=-\text{BW}_u/2}^{y=\text{BW}_u/2} m_F(y)\,dy}{\int_{y=-\text{BW}_u/2}^{y=\text{BW}_u/2} m_F(f - f_k + y)\,dy}\right]. \tag{8}$$

Then, after seeking INR(f) for the maximum value among the $\text{INR}(f)_k$, the $SIM_2(f)$ as the permissible maximum EPU at the frequency f is determined as below

$$SIM_2(f) = \begin{cases} \text{EPU}_{\max} & , \text{if } \text{INR}_{\text{ref}} \geq \text{INR}(f) \\ \text{EPU}_{\max} + (\text{INR}_{\text{ref}} - \text{INR}(f)) & , \text{if } \text{INR}_{\text{ref}} < \text{INR}(f). \end{cases} \tag{9}$$

The AFCSP with SSI obtained through SIM_2 can initially consider the EIRP for a channel of CFI(n_{ch}) as the P_2 defined by

$$P_2 = 10\log_{10}\left[\sum_{i=0}^{i=L(n_{ch})-1} \text{epu}(i)\right], \tag{10}$$

where epu(i) is a linear value of EPU on the i-th BW_U and $L(n_{ch})$ is the number of BW_U within an operating bandwidth for the CFI(n_{ch}) channel. Figure 4 shows examples of the SSI results determined using both methodologies in the case where the AFCSP bandwidths were either larger or smaller than those of the FWS. The red and green colors represent on the SIM_1 and SIM_2, respectively, while the dotted lines are $\text{EIRP}_{\max}$ or $\text{EPU}_{\max}$ for the AFCSPs to be specified as rules, and the solid lines of squares are the obtained SSI results. It should be noted that the noise bandwidths considered in SIM_1 and SIM_2 were different. Therefore, when the operating channel of the AFCSP is fully included in the FWS channel, the SSI result of

SIM_2 becomes relatively conservative. If the AFCSP channel bandwidth is larger than that of the FWS, the SSI of SIM_2 can be relatively higher in terms of the EPU in the out-of-band region of the FWS channel. In contrast, in SIM_1 of applying the FDR, the PSD maintains the same level within the overall AFCSP channel bandwidth as shown in Figure 4A.

3.2 | Power allocation based on the SSI of SSM_2

In this subsection, we discuss how the AFCSP using the SIM_2-based SSI allocates the power to each resource assignment bandwidth (BW_{RA}) to maximize its performance while complying with the relevant regulations. Here, it was assumed that the data transmission scheme of the AFCSP is based on the orthogonal frequency division multiple access (OFDMA) scheme and that BW_{RA} is larger than BW_U. The channel estimation in the OFDMA scheme would be performed with reference signals included within at least a unit of resource assignment (RAU). In the case of Wi-Fi, the OFDMA scheme has begun to be applied in IEEE802.11ax to improve the quality of user experience. In the 5G NR or NR-U, a different precoding matrix may be applied to each of the demodulation reference signals included in the resources allocated to a user equipment (UE). Therefore, it can be assumed that the AFCSP allocates the appropriate power level for different RAUs while it maintains an EPU with the same value in there. When the AFCSP adjusts the EPUs to the minimum value in a RAU, the EIRP becomes the following

$$\begin{aligned} \tilde{P}_2 &= 10\log_{10}\left[\sum_{i=0}^{i=N_{RA}-1} N_U^{\mathrm{RAU}}(i)\cdot \mathrm{epu}_m(i)\right], \\ \mathrm{epu}_m(i) &= \min\left[\mathrm{epu}(j),\ \dots\ ,\mathrm{epu}(j+N_{RA}-1)\right], \\ & \qquad j\in\left(0,\ \dots\ ,N_U^{\mathrm{RAU}}\times N_{RA}-1\right), \end{aligned} \tag{11}$$

where j and N_{RA} are the starting index of the i-th RAU and the number of BW_U in a BW_{RA}, respectively. Following this, the AFCSP must ensure that the $\tilde{P}_2$ is lower than the $EIRP_{max}$. Because the EPU_{max} generally tends to be defined based on the minimum bandwidth of the RLAN channel, $\tilde{P}_2$ can exceed $EIRP_{max}$ if the AFCSP operates with a larger bandwidth. In the FCC rule, the linear summation of the EPU_{max} becomes the same as $EIRP_{max}$ under the condition of the 20-MHz bandwidth, which is the minimum value for Wi-Fi. Therefore, it is crucial to adjust the EPU to be applied per each BW_U to ensure compliance with $EIRP_{max}$. In this process, the AFCSP may include specific procedures to maximize the service quality of the RLAN. There may be diverse approaches that can be adopted by the AFCSP to optimize the RLAN performance while complying with $EIRP_{max}$ [33, 34]. One of these approaches

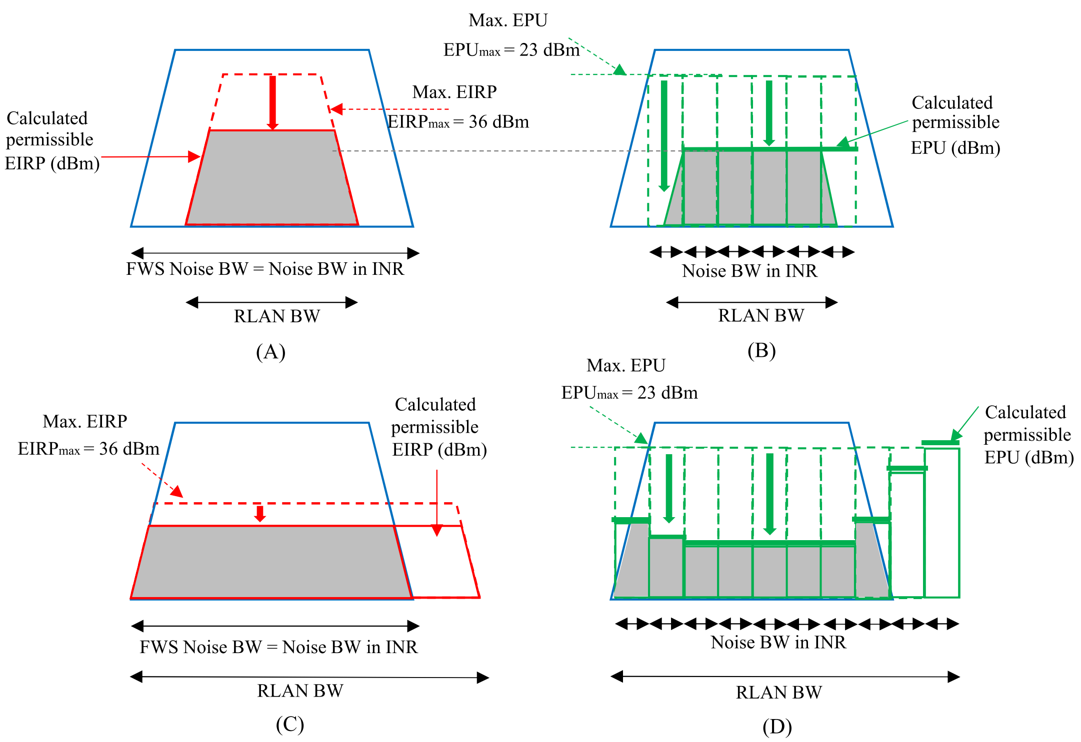

FIGURE 4 The spectrum sharing information (SSI) results obtained via two methodologies (A) and (C) for SIM_1 and (B) and (D) for SIM_2. The red and the green dotted lines represent $EIRP_{max}$ andEPU_{max}, respectively, while the red and green solid lines are the permissible EIRP or EPU. The gray region is the portion of radio local area network (RLAN) signal with the potential of presenting interference at the FWS(Blue)

involves optimally scheduling the resources to the stations and allocating the power while considering with the channel quality in order to maximize the network capacity. However, these aspects will be left for future work, and we will continue to focus on complying with the $EIRP_{max}$ while maximizing the transmit power level on each BW_{RA} as follows:

$$\hat{P}_2 = 10 \cdot \log_{10}\left[\sum_{i=0}^{i=N_{RA}-1}\left(\mathrm{epu}_m(i) - \Delta p(i)\right)\right], \quad (12)$$

where $\Delta p(i)$ denotes the factor for reducing $\mathrm{epu}_m(i)$ at the ith RAU.

4 | SIMULATION ANALYSIS

In this section, we will compare the EIRPs of P_1 and $\hat{P}_2$ for the same CFI depending on the SIM type. The CF and channel bandwidth follow the 6-GHz band CFI of the 11ax. In terms of the $EIRP_{P2}$, BW_U is set at 1 MHz according to the FCC requirements. Further, the 2- and 20-MHz bandwidths are applied as the BW_{RA} with considering the minimum resource unit and preambles of the Wi-Fi, respectively. The transmit spectrum masks of the AFCSP adopt the specification of the 11ax. It is assumed that the receive spectrum masks of the FWS are the same as the transmit spectrum masks that are defined in the European Norm (EN) 302 217-2 [30]. Table 2 presents the values of the parameters for the simulation analysis. Figure 5 shows the P_1 for both the CFI index and the RNR when the bandwidth of the FWS is 40 MHz. $IdxCFI_{20}$ represents the CFI index for the 20-MHz Wi-Fi bandwidth, with its total number = 59, as shown in Figure 2. When considering only the nominal channel bandwidth while excluding spectral masks, the $IdxCFI_{20}$ that is fully included in the FWS bandwidth is 31. The n_{ch} value for this $IdxCFI_{20}$ then becomes 121. It was confirmed that the P_1 begins to decrease with an RNR of −10 dB. Given that we extended the value of the spurious region in the spectrum mask to the whole 6-GHz band, it could be confirmed that P_1 decreased even in the $IdxCFI_{20}$ that is far from the CF of the FWS, f_{FWS}, when the RNR becomes larger than around 27 dB. Therefore, it is important to define the range and characteristics of the spectrum mask applied when analyzing the SSI.

In the case of SSM_2, the SSI is determined using only the receive spectrum mask of the FWS, regardless of the bandwidth of the AFCSP. As shown in Figure 6, it is confirmed that the EPU is changed according to the bandwidths of the FWS while the EPU_{max} is maintained from the out-of-band region. Given the EPU results, we computed $\hat{P}_2$ for comparison with the P_1 on the same RNR based on the noise power of the FWS channel bandwidth. Figures 7,8, and 9 present the results for the EIRP versus the RNR for 20-, 40-, and 80-MHz AFCSP bandwidths, respectively, when the FWS had a 40-MHz channel bandwidth. The CFs of the AFCSPs are 6555 MHz, 6565 MHz, and 6545 MHz, mean-

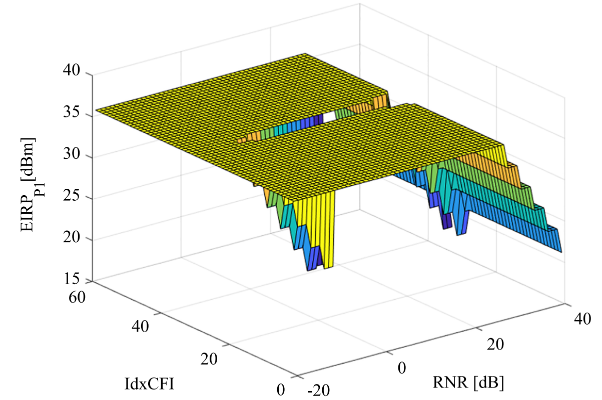

FIGURE 5 P_1 according to both IdxCFI for the automated frequency coordination-based standard power (AFCSP) with a 20-MHz bandwidth and the RISS to noise ratio (RNR) when the bandwidth of the FWS is 40 MHz

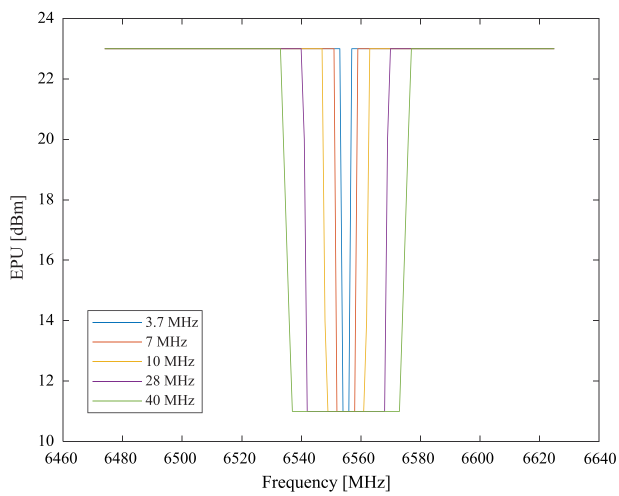

FIGURE 6 Results for $SSM_2(f)$ with the 1-MHz BW_U according to the fixed wireless system (FWS) bandwidth when the RNR = 0 dB and f_{FWS} = 6555 MHz

TABLE 2 Parameters

Parameters	Values
BW_{FWS}	40 MHz
f_{FWS}	6555 MHz
BW_U	1 MHz
BW_{RA}	2 MHz, 20 MHz
$EIRP_{Max}$	36 dBm
EPU_{Max}	23 dBm
INR_{ref}	−10 dB
RNR	−20 dB, …, 40 dB
P_1 : **range / step**	18 dBm to 36 dBm / 3 dB
EPU : **range / step**	5 dBm to 23 dBm / 3 dB

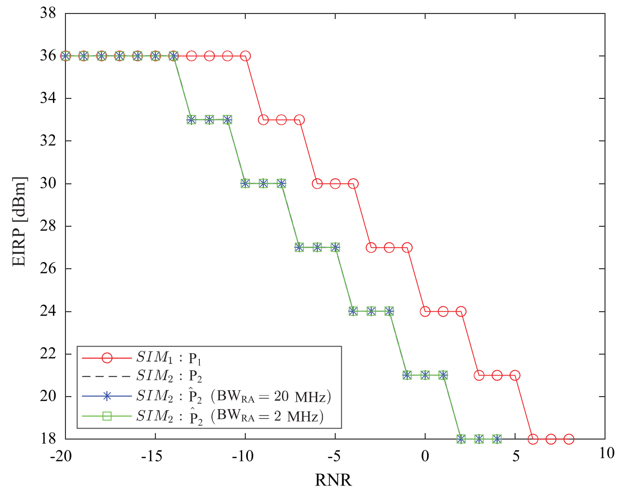

FIGURE 7 P_1, P_2, and $\hat{P}_2$ with the 2- and 20-MHz BW_{RA} in the case of the 20-MHz automated frequency coordination-based standard power (AFCSP) at 6555 MHz

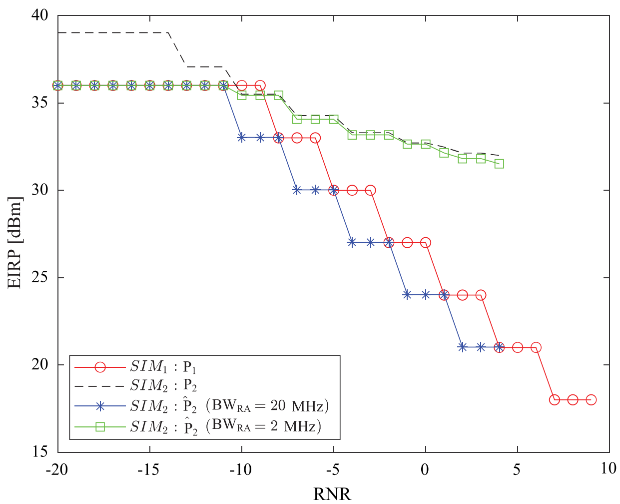

FIGURE 8 P_1, P_2, and $\hat{P}_2$ with the 2- and 20-MHz BW_{RA} in the case of the 40-MHz automated frequency coordination-based standard power (AFCSP) at 6565 MHz

ing the difference in f_{FWS} become 0 MHz, 10 MHz, and −10 MHz, respectively. A number of EIRP results within a certain RNR range are expressed in terms of stairs due to the 3-dB step, as defined in the Table 2 in relation to the FCC rule. The red line represents the P_1 of SIM_1. Because the INR_{ref} is −10 dB, it presents a stepped down from an RNR of greater than -10 dB depending on the FDR factor. The black dash line is the P_1 in a dB scale of 10. As noted in the previous section, the values in Figure 8 and 9 that are larger than the 20-MHz bandwidth can exceed the $EIRP_{max}$. The blue and the green lines for $\hat{P}_2$ relate to the 20 MHz and 2 MHz for BW_{RA}, respectively. In the Figure 7, the bandwidth of the AFCSP is fully included in the FWS as Figure 3A,D. The AFCSP can transmit a signal with a higher EIRP when it uses the SIM_1 results rather than any

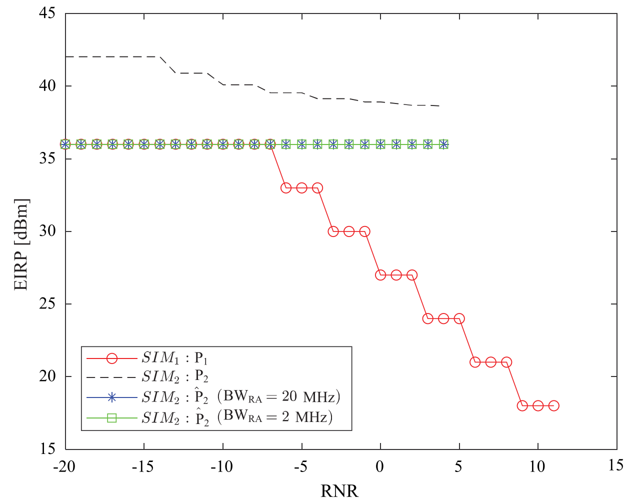

FIGURE 9 P_1, P_2, and $\hat{P}_2$ with the 2- and 20-MHz BW_{RA} in the case of the 80-MHz automated frequency coordination-based standard power (AFCSP) at 6545 MHz

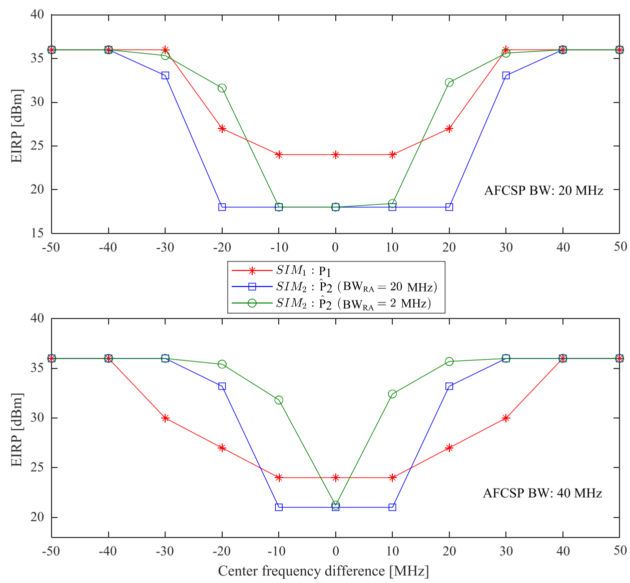

FIGURE 10 P_1 and $\hat{P}_2$ with the 20- and 2-MHz of BW_{RA} versus the difference between center frequency of automated frequency coordination-based standard power (AFCSP) (bandwidth: upper = 20 MHz, lower = 40 MHz) and f_{FWS}

$\hat{P}_2$ of SIM_2. As discussed in Section 3, the SIM_2 does not consider the spectrum mask of the interference source, so it is calculated as if the interference is largely imposed from the perspective of the overall bandwidth of the FWS. On the other hand, the SIM_1 obtains a comparatively lower INR with the interference strength being reduced in the RISS due to the FDR. The Figure 8 shows the case when the CF of the AFCSP is 10 MHz away from the CF of the FWS and the its channel partially overlaps with that of the FWS, as shown in Figure 3B. Because the BW_{RA} of 20 MHz have to use a low EPU with the same level as that shown in Figure 7 for the overlapped region, it is clear that $\hat{P}_2$ becomes lower than P_1 of SIM_1 in the range of −10 dB or with a higher RNR. In the case of 2 MHz with a smaller resource allocation unit, the highest EIRP can be available since the $\text{EPU}_{\max}$ can be applied at the out-of-band region of the FWS. For the same reason, even in the case shown in Figure 9, where the AFCSP is 80 MHz, two BW_{RA} of SIM_2 can achieve the maximum EIRP. However, when the RNR is greater than 5 dB, it would appear that there would be no allowable EIRP of SIM_2 under the conditions of a 40 MHz and 80 MHz of the AFCSP. This is due to the analysis conditions that limited the minimum value of EPU to 5 dBm. If the range of the SSI provided by the AFCS and the AFCSP can use a lower EPU value, allowable EIRP values for all RNRs can be probably defined. Throughout three results, it is found that the selection either SIM_1 and SIM_2 according to the system parameters of AFCSP should be necessary for maximizing the EIRP. The SIM_1 would be more preferred if the AFCSP operating spectrum is fully included within the FWS's channel as shown in Figure 7. On the other hand, even though it might be different depending on the BW_{RA}, there could be the case when SIM_2 is more effective than SIM_1 when the portion of the overlapped spectrum is reduced due to the difference of CF between FWS and AFCSP. Figure 10 shows P_1 and $\hat{P}_2$ for AFCSP with 20- and 40-MHz bandwidth according to the difference in center frequency when RNR is 2 dB. When AFCSP is a 40-MHz channel, SIM_1 is better if FWS and CF are the same, but if there is 20-MHz difference in CF, SIM_2 can make that AFCSP uses with higher EIRP regardless of BW_{RA}. Therefore, it can be identified that the usable EIRP can be maximized by selectively adopting either SSIs according to the its bandwidth, the difference of center frequency from FWS, and BW_{RA}.

5 | CONCLUSIONS

In this paper, we have presented the trends of activities relating to unlicensed use over the 6-GHz band and proposed two methodologies of AFCSP to calculate the operation conditions of AFCSP for sharing the spectrum with FWS. Given the location of AFCSP, AFCS should enable to inform the availability of the frequencies, which are defined as per-channel or per-unit-bandwidth depending on two methods, and the permissible transmission power level on there. Through the analysis results, we found that it was necessary to selectively apply the two methods depending on the AFCSP's system parameters. The use of SSI based on the SIM_1 is recommended when the AFCSP operating bandwidth is completely included on the FWS channel bandwidth. On the other hand, it was shown that the SSI from the SIM_2 can maximize the allowable EIRP in the case of partially overlapping spectrum. From the analysis results, we confirmed that both methods would be necessary to be supported in AFCS so that one of the two methods can be selectively applied according to the operating conditions of AFCSP.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest.

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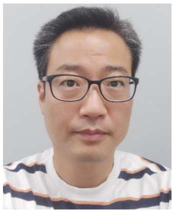

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