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Analysis on Extraction of Potential Radiated Emission Limit line for Data Center Equipment from 10 GHz to 40 GHz

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***Abstract*—The radiated emission (RE) potential limit line for router system is analyzed from 10 GHz to 40 GHz based on CISPR TR 16-4-4 standard. Statistical data is collected for the limit line extraction from measurement, numerical analysis, 3D full-wave simulation and literature studies. All the factors considered in limit line calculation are analyzed for data center equipment operation. The result of extracted potential limit line shows the rising limit line between 10 GHz and 40 GHz frequency band for potential future radiated emission limit line above 40 GHz targeted for high-speed equipment radiated emission. This paper is not a standard document, but provides insight to the trend for future limit lines above 40GHz.**

Keywords—Radiated Emission, Limit line, Standard, Data center equipment, High frequency

I. Introduction

The limit line for Electromagnetic Interference (EMI) standard tests defines the pass and fail criteria for radiated emission tests for general Class A equipment. For example, between 30 MHz ~ 1 GHz frequency band, for radiated emission (RE) test, detailed measurement setup and RE limit line, measurement verifications methods are predefined by different regulatory authorities.

Among many standards, for example IEC standards, basic standards are included in CISPR 16 series and limit lines are defined in CISPR 32 [1] for multimedia product family EMI standard. CISPR 32 references to CISPR 16 and provides exclusions and additional considerations to CISPR 16. CISPR 16 outlines measurement setups, requirements, methods, uncertainty and limit line. Since CISPR 16-1 series only defines the measurement setup up to 18 GHz and the limit line is only specified up to 6 GHz, there are some active interests for CISPR 16 to establish a measurement setup and standards up to 40 GHz.

For the United States, considering FCC and ANSI, the limit lines are defined as FCC CFR Title 47, Part 15 [2]. Intentional and unintentional radio frequency devices are included in CFR Title 47 Part 15. Industrial, scientific, and medical (ISM) equipment are included in CFR Title 47 Part 18 [3] and terminal equipment connected to the telephone network are in CFR Title 47 Part 68 [4]. FCC references ANSI C 63.4 [5] standard and the measurement range is defined as 9 kHz ~ 40 GHz. Since ANSI C 63.4 provides a measurement environment for frequencies up to 40 GHz, it can be effectively concluded that there is potential for future EMI limit above 40 GHz.

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On the other hand, as one of the classic multi-module devices, data center devices play an important role in the data set extracted by RE limit lines. Serializers/Deserializers (SerDes) are commonly used in advanced communication technologies for high-speed communication. The increasing demand for speed is driving higher data throughput, and high frequency radiated emissions follows. As technology improves and the types of operating scenarios increase, so does the complexity and difficulty of compliance testing. However, current requirements for RE limits, such as the FCC RE limits shown in Fig. 1 [2], are based on older generation equipment. Therefore, the impact of RE limit lines from 10 GHz to 40 GHz for data center equipment belonging to Class A was investigated to further investigate the extraction of high frequency RE limit lines.

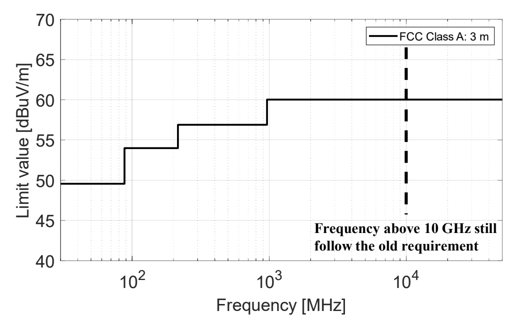

Fig. 1. FCC 47 CFR, Part 15, Subpart B defined Class A digital device radiated emission limits (Converted to 3 m).

In addition, wireless services operating at frequencies above 10 GHz are more widely used [6]. These services include satellite-related services, amateur radio services at high frequencies, and 5G new radio (NR) technologies covering the FR2 range. The increased demand for high frequency services has raised concerns about radiated emission limit lines to meet the requirements of the latest technologies. In this paper, a new radiated emission limit line is proposed to evaluate how new technologies could have potentially affected the limit line above 10 GHz. Proposal of a new limit line requires sufficient data and must be in accordance with existing calculation method to be credible. The method of limit line extraction is clearly shown in CISPR TR 16-4-4 [6]. For selected frequency and data center equipment limit line extraction requirements, the limit line extraction method needs to be more specific based on aggressor and victim characteristics.

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The goal of this paper is to provide details to obtain statistics based on [6] for the extraction of radiated emission limit lines from data center equipment. Several models with different factors were utilized in papers from previous publications. Data were obtained from measurements, numerical analysis, 3D full-wave simulations, and other literature studies. Improvements are proposed for trend analysis purpose for future limit line requirements for EMI analysis of data center equipment.

II. Limit Line Extraction Method in CISPRTR 16-4-4 Standard

As CISPR TR 16-4-4 [6] proposed in subclause 5.7, for the frequency above range 1 GHz, the limit line determination formula is shown in (1). Each factor is described as TABLE I according to the standard.

$$E_{Limit} = \mu_W - R_P + \mu_{P1} + \mu_{P2} + \mu_{P3} + \mu_{P4} + \mu_{P5} + \mu_{P6} + \mu_{P7}$$
$$+t_\beta \sigma_i - t_\alpha ({\sigma_{P1}}^2 + {\sigma_{P2}}^2 + {\sigma_{P3}}^2 + {\sigma_{P4}}^2 + {\sigma_{P5}}^2 + {\sigma_{P6}}^2 + {\sigma_{P7}}^2)^{\frac{1}{2}} \quad (1)$$

TABLE I. Description of Each Factor

Var	Description
E_{Limit}	Calculated limit line.
μ_W	Minimum value of the wanted field strength at the edge of the service area of the radio service concerned.
R_P	Minimum acceptable value of the signal-to-disturbance ratio (i.e. the protection ratio) at the receiver's antenna port or feeding point.
μ_{P1}	The expected mean value that the major lobe of the disturbance field strength is not in the direction of the victim receiver.
μ_{P2}	The expected mean value that the directional receiving antenna does not have its maximum pick-up in direction of the disturbance source.
μ_{P3}	The expected mean value that for a mobile receiver the signal to noise ratio can be improved by keeping a certain distance to the disturbance source and that the mobile receiver is used well inside the respective radio service area.
μ_{P4}	The expected mean margin that the disturbance signal is below the limit.
μ_{P5}	The expected mean value that the type of disturbance signal generated will produce a significant effect in the receiving system.
μ_{P6}	The expected mean value that the disturbance source is located in a distance to the receiving system within which interference is likely to occur.
μ_{P7}	The expected mean value that buildings provide a certain degree of additional attenuation.
σ	The standard deviation of the corresponding factor
t_β	β-quantile of the centralized normal distribution
t_α	α-quantile of the centralized normal distribution, suggested to be 0.84

The factors can be divided into three categories: aggressor, victim and loss. Aggressor, which is the disturbance source, is taken into account in μ_{P1}, μ_{P2}, μ_{P3} and μ_{P4}; victim, also considered as the receiver side, is taken into account in μ_W, R_P, μ_{P1}, μ_{P2}, μ_{P3} and μ_{P5}; loss, including the free space path loss and the environmental loss, is considered in μ_{P6} and μ_{P7}.

Due to the lack of sufficient statistics, the paper analyzes all the mean values but assumes the standard deviations to be negligible except for σ_{P4}. In addition, the frequency points are selected based on the emission frequencies measured from the aggressor (i.e., the data center equipment). Other factors will be selected according to the frequency of the aggressor data, following the proximity principle.

III. Data for Each Factor

In CISPR TR 16-4-4 and working documents in IEC, recommendations are made for values in general applications. However, for data center equipment, some factors are inadvertently weighted significantly, resulting in unwanted large margins in the final extracted limit lines. Therefore, all factors are analyzed based on the specifications of the data center equipment.

A. μ_W, R_P

1) Wireless services

The two factors represent the minimum wanted field strength from the victim's side and the protection ratio that the field strength requires to receive the signal before it enters the receiver antenna. This value requires a large data set from all different receivers and corresponding test environments. For data center equipment test analysis, the specifications are mostly band-based rather than application-based, so the data collected in other references listed in [7, 8, 9, 10, 11, 12, 13, 14, 15, 16] and [17, 18] can be applied to the specified data center equipment test. The data collected are all for the wireless services working at 28GHz. The distributions of the sensitivity data and the protection ratio are shown in Fig. 2 and Fig. 3.

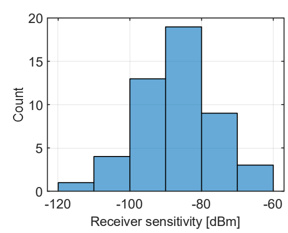

Fig. 2. Receiver sensitivity distribution from collected data. All working at 5G NR FR2 range.

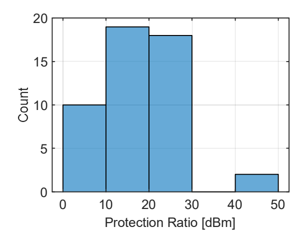

Fig. 3. Protection Ratio distribution from collected data. All working at 5G NR FR2 range.

Apart from the collected data, 3GPP TS 38.817-02 10.3 [19] provides the characterization method of Over-The-Air (OTA) Reference sensitivity level, which is the only sensitivity requirement used for base stations working at FR2 range. The reference sensitivity calculation for effective isotropic sensitivity (EIS) is calculated in (2).

$$EIS_{REFSENS} = -174dBm + 10log_{10}(BW)$$
$$+NF + IM + SNR - G \quad (2)$$

where BW is the noise bandwidth of fixed reference channel, NF is the noise figure, IM is the 2 dB implementation margin not related to antenna array, SNR is the required SNR for demodulation, G is the antenna gain.

As required in 3GPP TS 38.104 [20], three categories of base stations are defined according to the cell type. The minimum distance between the user equipment and the base station for all categories is 2 m, 5 m and 35 m, corresponding to Local Area (LA), Medium Range (MR) and Wide Area (WA), respectively. The characteristics of the data center apply to the wide area, considering that the wireless service is at least 35 meters away from the equipment.

In [19], the assumptions of each parameter for different frequency bands are provided as reference. Choose NF = 10 dB, IM = 2 dB, SNR = -1.1 dB, BW is 1 MHz, which is the measurement bandwidth. G is 10 dBi as the worst case for 24.25 – 29.5 GHz band and 12 dBi as the worst case for 37 – 40 GHz band. Use the worst SNR = 16 dB in [19] regarding the radiated performance requirement for PUSCH as the protection ratio.

The sensitivity requirement used for user equipment working at FR2 range is provided in 3GPP TS 38.101-2 7.3 [21]. Choose power class 1 and use 1 MHz as the measurement bandwidth. Use the worst SNR = 19 dB in 3GPP TS 38.101-4 [22] regarding the demodulation radiated performance requirement for PDSCH as the protection ratio.

The conversion between dBm and dBμV/m is the transformation from the received power to the E field strength measured at the receiver antenna. Referring to [23], conversion between dBm and dBμV/m can be done by:

$$E = \sqrt{\frac{4\pi\eta_0 P_r}{\lambda^2 G}} \tag{3}$$

The average of the collected data and the formula-derived points for the base station and user devices are the three equally weighted points used in the FR2 range. For the formula calculation range, intermediate frequencies are used for each band to obtain a ready-made desired field strength. Including the data collected from CISPR TR 16-4-4 [6], all data for μ_W and R_P for different frequency bands are shown in Table II.

2) Considering data center equipment as victim

Generally, the aggressor refers to data center devices, while the victim refers to all wireless services operating between 10 GHz and 40 GHz. However, the router system itself can be one of the victims, but the maximum disturbance strength that a router system can stand should be verified by radiated immunity test. Fig. 4 shows how to set up a router system for radiated immunity testing according to the recommendations of IEC 61000-4-3 [24]. The transmitter antenna and the line card, which transmits and receives network traffic through optical modules, are placed at a certain height. The antenna is oriented towards the center pair of the optical module. Failure or performance degradation can be observed by monitoring the traffic of the optical module. The testing distance is 30 cm. This distance is much shorter than the one suggested in [24], since it was observed that the line card was very robust to the radiated immunity test. Therefore, a more severe case was performed to ensure the measured result.

TABLE II. COLLECTED μ_W AND R_P AT DIFFERENT FREQUENCY BANDS

Radio System Name	**Receiving frequency (GHz)**	**Wanted field strength μ_W (dBμV/m)**	**Protection Ratio R_P (dB)**
Radio amateur	10 – 10.31	17	6
Sat. Broad./1MHz	11.4 – 12.4	60	23
Fixed service	12.75 – 13.25	60	36
Fixed service	15.32 – 15.35	59	36
Base station (from formula)	24.25 – 29.5	42.7	16
User Equipment (from formula)	24.25 – 29.5	41.3	19
Collected wireless services	24.25 – 29.5	61.3	12.4
Base station (from formula)	37 – 40	41.8	16
User Equipment (from formula)	37 – 40	45.4	19

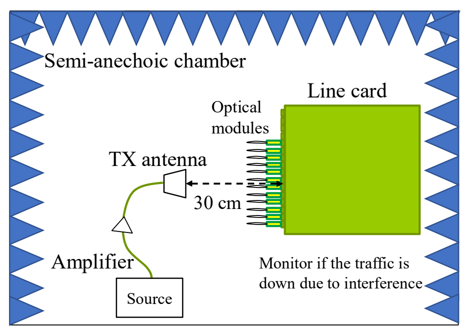

Fig. 4. Radiated immunity test on line card inside the semi-anechoic chamber. 30 cm is short enough so that no need for extra absorbers on

The other setup, shown in Fig. 5, does not comply with the standard tests in [24], but allows for extreme immunity testing. The top metal cover of the line card is completely removed. The TX antenna is placed very close to each part of the motherboard. An acrylic plate was placed in between to prevent accidental electrical short or physical damage.

For both setups, the tested line card was able to withstand up to 26 V/m of interference, which is limited by the maximum output power of the high frequency amplifier, at 12.89 GHz and 25.78 GHz with no throughput degradation or loss of service for more than 6 hours. This means that the line card can withstand almost the fourth level of immunity testing, which is the highest level specified in IEC 61000-4-3 [24]. This result shows that the line card is not a potential victim in extreme line extraction. Based on the immunity test results, the victim's data collection excluded data center equipment.

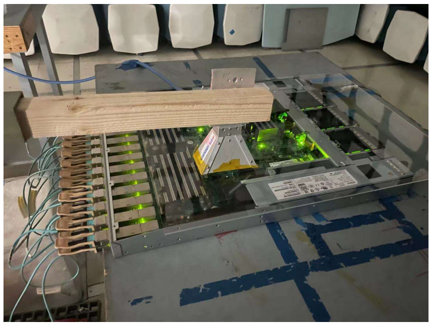

Fig. 5. Extreme radiated immunity test setup.

B. μ_{P1}

It is possible that the measured radiation pattern is not oriented towards the maximum radiation E field. As shown in [25], the possibility of missing E_{max} increases with increasing turntable angle, height and observation distance. The wireless service has the same possibility at any angle of the radiation pattern, so it is expected that there is difference between the average of the E field at different angles and the E_{max}. the variation of the difference between the average E field and the peak E field ranges from 7 dB ~ 10 dB. therefore, 8.5 dB is used as the average of μ_{P1}.

C. μ_{P2}

The factor μ_{P2} describes the probability that the receiver antenna is not in the maximum pickup direction of the interference. The possibility of missing the maximum value of the interference is another way to describe one case of increasing the signal-to-noise ratio. The value of μ_{P2} is the difference between the gain of the desired field strength and the gain of the interference signal. The estimation equation provided in [6] is:

$$\mu_{P2} = \begin{cases} G_w - 6dB, & if\ 6dB \leq G_w \leq 12dB \\ 6dB, & if\ G_w > 12dB \end{cases} \quad (4)$$

For high frequency antenna design, the gain for the wanted field strength is generally higher than 10 dBi, so the value for μ_{P2} is expected to be at least 4 dB according to (4).

D. μ_{P3}

Although in the worst case scenario it is difficult for a mobile service to immediately adjust its signal-to-noise ratio when it encounters interference, it still has the ability to improve transmission by moving away from the source of the interference. Moreover, mobile services are not always placed at the edge of the service area. As suggested in the literature [6], the average rather than the worst case should be used in the limit line extraction, so that the value of μ_{P3} is 3 dB, as per the standard.

E. μ_{P4}

The margin between the average interference signal and the current FCC limit line is calculated as μ_{P4}. The interference signal varies considerably in different devices. The data set was built by measurements and simulations. The measurement cases contain 155 different data center devices. The simulations use a simplified 3D model of the actual router system based on Monte Carlo simulations of an array of optical modules pairs with random phase distribution [26]. The simulations are performed for different number of line cards, from 1 to 15 line cards, with 2000 random phase distributions in each case. Only the cases of 10.31 GHz, 12.78 GHz and 25.78 GHz were simulated depending on the radiated emission frequency of the optical module. Fig. 6 and Fig. 7 show the measured and simulated radiated emission data.

Since simulated and measured data are not available for all cases, if only simulated or measured data is available, the available data is used to calculate the final value, called μ_x, and if both simulated and measured data are present, the average data are used for μ_x. If both simulated and measured data are present, both are weighted equally.

$$\mu_{P4} = 60 - \mu_x \quad (5)$$

where μ_x is the value derived from the measurement and simulation data.

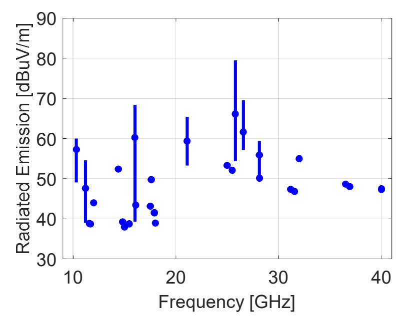

Fig. 6. 155 samples of measured data distribution from 10 GHz to 40

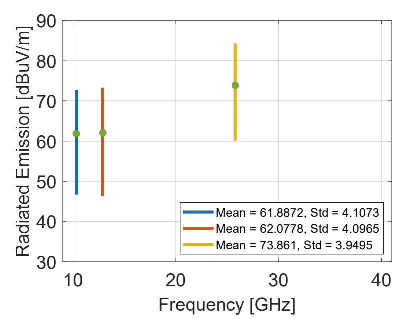

Fig. 7. Simulation data distribution at 10.31 GHz, 12.89 GHz and 25.78 GHz.

The final μ_{P4} used for each frequency as the margin between the average interference signal and the current FCC limit line is calculated by (5). Since the relationship between μ_{P4} and μ_x is linear, σ_{P4} is the same as the standard deviation of the collected data.

F. μ_{P5}

This factor considers the effect of the specific bandwidth of the interference signal on the wanted signal. The calculation in [6] involves three terms: the bandwidth of the wanted signal (B_{want}), the bandwidth of the interference signal (B_{noise}), and the bandwidth of the measurement receiver (B_{meas}). Although the

interference signals generated by the line card can be as low as 10.31 GHz and as high as 53 GHz, the bandwidth is much smaller than the desired field strength at each frequency. Also, the bandwidth of the interference signal is smaller than the bandwidth of the measurement receiver, which is typically 1 MHz. Therefore, this factor should be considered separately at each frequency, and the following case should be considered.

$$B_{meas} > B_{noise} \text{ and } B_{want} > B_{noise}$$

The relationship among B_{noise}, B_{meas} and B_{want} indicates that the disturbance signal from data center equipment is considered to be a narrowband emission. Therefore, apply 0 dB for μ_{P5} for all the frequency points.

G. μ_{P6}

This factor refers to the positional correlation between the actual distance and the measured distance. Note that this factor considers only the distance. The transmitter and receiver gain and frequency are considered among other factors.

$$\mu_{P6} = 20log_{10}\frac{r}{d} \tag{6}$$

where r is the actual distance between the disturbance source and the victim, d is the measurement distance in RE test.

Since the distance are considered as the protection limit, it can also be applied to the factor of location correlation for the distance between the aggressor and victim. Use d = 3m as the RE measurement distance and apply all three BS types (LA, MR, WA) and do average, the factor for location correlation is derived as 7.42 dB from (6).

H. μ_{P7}

This factor describes the building and environmental losses. Building losses consider the general materials of the building, such as glass and concrete walls, to provide an estimated average value. Environmental losses consider foliage losses and atmospheric losses.

1) Building loss:

The building loss described in [18] summarizes different models under several scenarios. Using the building penetration loss model, the loss for each material can be calculated. An alternative parabolic model in (7) is provided for comprehensive building penetration loss analysis regarding different frequencies and materials.

$$\mu_{P7} = 10log_{10}(A + B \cdot f^2) \tag{7}$$

where A = 5 and B = 0.03 for low loss buildings as the worse case analysis.

2) Environmental loss:

Both foliage loss and atmosphere loss count for the environmental loss. Both factors are analyzed in [18].

a) Foliage loss: The loss can be higher than 4 dB per 5 m depth, which is roughly the loss of one tree. However, Foliage is not considered to be always applicable to the emission test scenario.

b) Atmosphere loss: Reference [18] shows the value of atmosphere loss to be less than 1 dB/km. Since even in wide area case the distance between the disturbance source and victim under consideration is less than 100 m, the atmosphere loss can be neglected compared to other factors.

As a result, only building loss is considered for μ_{P7} following (7).

IV. Extracted Limit Line and Discussion

Applying all the factors discussed above, the limit lines can be extracted by fitting methods. The least square fitting method was used to provide fitting results from 10 GHz to 40 GHz. The extracted points and the fitted limit lines for each frequency are shown in Fig. 8.

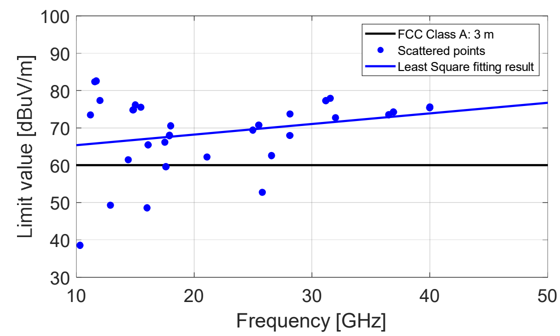

Fig. 8. Extracted limit line points at each frequency and the fitting limit line based on lease square method.

The extracted limit line shows a rising line starting at 65.4 dBμV/m at 10 GHz and reaching 73.9 dBμV/m at 40 GHz. The least square fit method provides a proper regression analysis taking into account the approximation of the growing trend between the frequency and RE limit lines. The fit results indicate a limit value of 76.8 dBμV/m at 50 GHz, which can be used as a reference when the EMI analysis is transferred to optical module transceivers and SerDes systems at 53 GHz or higher.

This extraction of aggressors based on data center equipment provides a new reference for limit line upgrades above 10GHz from a new perspective. Data center equipment is considered to be one of the most important devices in Class A, showing a representative extraction result. However, there are several points to discuss depending on the general extraction method.

1. Diversity of datasets. The measurement data contains 155 samples. The numerical analysis is based on the comprehensive modeling for the specified models from standard and technical reports. The 3D full-wave simulations contain as much the line card number and iterations as possible. And the literature studies in more than 12 papers provide various analysis perspectives for the dataset. The diversity of resources ensures that the statistical analysis on aggressors and victims is not heavily biased by any potential problems, thus increasing the confidence level of the extracted limit lines.

2. Scope of applications. Although the number of measurements may be insufficient, all applied values are derived from published standards and detailed models that have been validated with sufficient data. The standard deviation of the

desired field strength (σ_i) was not considered in the extraction process. Therefore, the extracted limit lines can be considered as a relatively strict reference compared to the ultimately desired limit lines.

3. Special "outliers". Some points are far from the regression line, such as the point at f = 10.31 GHz. However, these "outliers" are not considered as exceptions to the limit line analysis. Each individual frequency point in Fig. 8 does not indicate that the RE at a particular frequency should be limited below the level, but rather is a reference for the entire limit line fit. The formula for the extraction of the limit line is derived from a mathematical statistical model. Nevertheless, more data points can be used to compensate for large variations.

V. Conclusion

In this paper, limit line from 10 GHz to 40 GHz is extracted for data center equipment and the trend of limit lines above 40 GHz is proposed. The extraction method follows the mathematical statistical approach described in [6]. The factors for limit line extraction were collected from various methods, including measurements, numerical analysis, simulations, and other studies. Data points were extracted according to the frequency of the aggressor and the least squares method was used to derive the regression line as the proposed potential limit line. increasing trend in the proposed potential limit line shows that higher limit lines are expected for higher frequency devices. The method requires more data points to increase the confidence level. In addition, if the numbers of devices at some frequencies are significantly greater than at others, then the expected weights for those frequency points will be higher. A new limit line extraction method that can balance the weights of different radiated emission results is a potential future topic.

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