A Novel Remote Visualization of Screen Images Against High-Resolution Display With Divided Screens Focusing on the Difference of Transfer Function of Multiple Emanations

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***Abstract*—Electromagnetic (EM) remote visualization of screen images attacks (RVSIAs) is among the most actively researched topics in hardware security. Target displays are being developed daily; for example, recently developed high-resolution displays have multiple divided areas on the screen, and each area transmits different pixel information. In this case, it is difficult to reconstruct the screen using the conventional methods because the target screen information is leaked by multiple lines at the same frequency and timing, and multiple screen information is mixed into the EM waves. By contrast, in this article, we propose a novel RVSIA method that focuses on the difference in the transfer functions of multiple emanations from a high-resolution display. Considering the structure and signal transmission method of recent high-resolution displays, the proposed attack method observes leaked EM waves from multiple observation positions and alters the receiving frequencies of the receiver. For the first time, we have been able to separate multiple screen information contained in leaked EM waves using an independent component analysis method. In the experiments, we applied the proposed method to an actual laptop PC that divides the screen into multiple areas. As a result, it was possible to reconstruct screen information using the proposed attack method. Thus, the proposed method enables successful attacks against recent high-resolution displays. Furthermore, the measurement equipment employed remains similar to those utilized in the conventional attacks.**

***Index Terms*—Electromagnetic (EM) information leakage, hardware security, independent component analysis (ICA), remote visualization of screen images.**

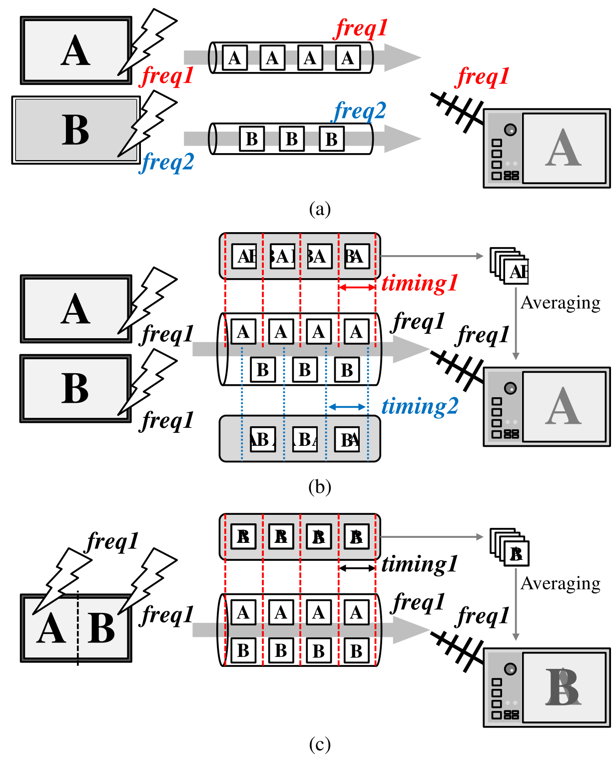

Fig. 1. RVSIA against leaked EM wave, including multiple screen information. (a) Conventional attack focused on the difference in the leakage frequency. (b) Conventional attack focused on the difference in the leakage timing. (c) Conventional attack cannot be applied to the display divided screen because the screen information contained in the leaked EM waves have the same leakage frequency and leakage timing.

I. Introduction

To ENSURE the security of a highly sophisticated information-oriented society, the information being processed and transmitted inside a device and on a network is protected using cryptographic techniques. Meanwhile, when people intervene in an information system, the encrypted information is decrypted and becomes recognizable. Therefore, there is a risk of information leakage when a malicious attacker attempts to eavesdrop on information in the decryption phase. Attacks that acquire information at the stage where a human perceives information are known as remote visualization attacks, which eavesdrop on information through electromagnetic (EM) emanations leaked from input/output (I/O) devices [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19]. Recently, the extent of such attacks has broadened

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from the conventional cases discussed in military and diplomatic circles to civilian products (or consumer electronics) owing to the miniaturization and enhancement of the equipment used for remote visualization attacks [4].

Previous works [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13] focused on video display units (VDUs) among various I/O devices as targets of EM remote visualization attacks because they process sensitive information. Additionally, with the development of VDUs and changes in their usage environments, novel remote visualization of screen images' attacks (RVSIAs) and countermeasures have been proposed in [10], [11], [12], and [13].

In [10] and [11], an environment with multiple devices was assumed to be similar to the office environment. Under this assumption, an RVSIA was conducted against multiple displays connected to PCs. These studies assumed that different models of displays and PCs were installed, and that the leaked EM waves, including screen information leaked from them, have different frequencies. Consequently, an attacker can reconstruct the screen information by changing the receiving frequencies and observing the leaked EM wave for each target device, as shown in Fig. 1(a).

In [12] and [13], a harsher attack scenario was assumed by placing multiple displays and PCs of the same model in the same room. In this situation, it is difficult to reconstruct the information displayed on each screen by changing the receiving frequency because the leakage frequencies containing the screen information from the same model are the same. However, even if the same models are installed, there is a difference in the leakage timing of the EM emanation from each device because there is a slight deviation in the clock signal that transmits pixel information. Therefore, first, the attacker profiles the leakage timing precisely from EM emanations, including screen information for each device. Next, the screen image is reconstructed by applying the image averaging process using multiple frames while synchronizing the timing for the target device. EM emanations, including screen information other than the target, have different timings and become noise in the reconstructed image, as shown in Fig. 1(b).

As mentioned, recently, RVSIA have been studied considering the actual usage environment, which makes it possible to reconstruct certain screen information from multiple leaked EM waves. In these conventional methods, the attackers reconstruct screen information by focusing on the differences in leakage frequency or leakage timing associated with the deviation of clock signals.

However, recent display screens are divided into multiple areas to achieve a higher resolution [20]. Each divided area on the screen has a different transmission line and transmits unique pixel information. Therefore, the attackers receive EM waves containing multiple screen information even if only one device is targeted because the information of each divided screen is leaked simultaneously, which is similar to an RVSIA targeting multiple devices. However, attackers cannot reconstruct certain screen information against multiple leaked EM waves from a single device using the conventional RVSIA because these EM waves have the same leakage frequency and timing, as shown in Fig. 1(c). In such cases, reconstructing the information becomes difficult because the number of pixels from the divided screen is always mixed in the reconstructed image.

To address this problem, we propose a novel RVSIA method that focuses on the difference in the transfer function between emanation sources and the antenna caused by receiving EM waves at multiple observation positions and multiple receiving frequencies. Even if the EM emanation containing multiple screen information has the same leakage frequency and timing, the proposed RVSIA is capable of reconstructing the screen information. In the proposed method, we separate multiple screen information, including the leaked EM wave, using independent component analysis (ICA), which is a signal processing technique of blind source separation (BSS). BSS separates each signal source from a mixed signal from multiple unknown signal sources. ICA separates by using the independence of each signal source in multiple inputs. In the proposed method, we apply ICA to multiple signals obtained by receiving the leaked EM wave at multiple positions and receiving frequencies to change the transfer function and make it possible to separate the mixed screen information. For the first time, using the proposed RVSIA, it is possible to reconstruct the entire screen information of a display that transmits pixel information while dividing the screen, which is difficult to reconstruct using the conventional methods.

The rest of this article is organized as follows. An overview of the target display and the methodology of the proposed RVSIA are presented in Section II. In Section III, the proposed attack is verified by applying it to a laptop PC. Finally, Section IV concludes this article.

II. Proposed RVSIA Using Difference of Transfer Functions

In the proposed method, to separate screen information included in EM waves leaked from a target, we observe multiple leaked EM waves of different intensities by focusing on the difference in the transfer functions from the leak source to the antenna. The multiple observed signals are then separated using ICA to reconstruct the image of the display across multiple areas.

In this section, we first provide an overview of a high-resolution display, which is the focus of this article. We then explain the phenomenon that multiple screen information are superimposed on the EM waves leaked from such displays. Then, a measurement method is described focusing on the difference in the transfer functions of the leaked EM waves, including the images leaked from multiple screen areas. Next, we describe the ICA algorithm used to separate multiple screen information contained in the measured EM waves.

A. *High-Resolution Displays and Their Signal Transmission Methods*

Displays are tending toward higher resolution, larger display size, and increased color depth. Additionally, the bandwidth of the signals that transmit screen information is expanding. Inside many displays, screen information is transmitted from the display controller to the liquid crystal display (LCD) by employing low-voltage differential signaling (LVDS). In LVDS, the display is divided into multiple areas to increase the bandwidth, and multiple transmission lines are used in each area to transmit video signals [20].

For example, LVDS transmits red–green–blue color and clock signals for synchronization using four transmission lines; however, in a high-resolution display, these four transmission lines are doubled, and a total of eight transmission lines are used to display the left and right sides of the display. By dividing the display into multiple areas, it is possible to increase the degree of parallelism in drawing, thereby increasing the bandwidth involved in drawing the display.

B. Measurement Method for Leaking EM Waves Mixed With Multiple Screen Images Leaking From a High-Resolution Display

This section explains the measurement method for executing an RVSIA on a high-resolution display, as described Section II-A. In a high-resolution display, as already explained in Section II-A, a line transmits information for each drawing area in the display; therefore, the pixel information transmitted by multiple lines is superimposed on the leaked EM wave. In addition, each transmission signal is synchronized to display pixel information on the screen at exact timing, and the EM waves leaking from each of them will have the same leakage frequency and leakage timing. Therefore, it is difficult to reconstruct the screen information using a method that focuses on the differences in leakage frequency and timing as in a conventional RVSIA. In this section, we discuss the measurement method focusing on the difference in transmission characteristics from the leakage source to the receiving antenna.

In the LVDS system, signals are transmitted by differential transmission, and previous studies [9], [12] have investigated the mechanism of information leakage arising from such a differential transmission system. Furthermore, the EM interference (EMI) of TVs, where LVDS is used, has been investigated in detail [21], [22]. From these studies reported, it was indicated that the dominant source of EMI is common-mode noise excited in the cables and connectors connecting the main board to the LCD display. Here, slight differences in the physical structure of the cables and transmission lines on the board cause differences in the intensity of the common-mode noise, resulting in different frequency characteristics of the EMI, as indicated in [21], [22], and [23]. Therefore, it can be regarded that if the lines along which the drawing information is transmitted differ, it will propagate through slightly different coupling paths to the unintentional antenna structure and radiate outside the equipment with different transfer functions.

In the proposed method, in addition to the above, we also focus on the following:

1) the observation position where the leaked EM waves are received;
2) the receiving frequency at which the leaked EM waves are received.

Then, multiple screen information increases the difference in the transmission characteristics to the antenna of the leaked EM wave, which facilitates separation by ICA, as discussed in Section II-C.

C. Screen Information Separation Method Using ICA

In this section, we describe a separation method for multiple screen information contained in an EM emanation. We adopt the ICA technique, which separates each signal source from multiple unknown signal sources. In ICA, it is possible to separate multiple inputs with different transfer functions based on the independent nature of each signal source.

We assume that the target display for attacks divides the screen into 1/*N* and transmits the screen information simultaneously; $s_1(t),\ s_2(t), \ldots,\ s_N(t)$ are the amplitudes of EM emanations, including information from each screen, where N is the number of emanations, including screen information, which denotes the number of divided areas of the screen. In this situation, using the attacker's antenna, we observe a signal $x(t)$ mixed with $s_j(j\ =\ 1,\ 2, \ldots, N)$. However, because each EM emanation has different transfer functions and propagates to the attacker's antenna, the observed signal $x(t)$ is as follows:

$$x\ (t) = \sum_{j=1}^{N} a_j s_j\ (t) \tag{1}$$

where a_j is the transfer function of each EM emanation. The observed signal $x(t)$ depends on the transfer function, and therefore by changing the transfer function, we obtain

$$x_i\ (t) = \sum_{j=1}^{N} a_{ij} s_j\ (t)\quad i\ =\ 1, 2, \ldots, M \tag{2}$$

where $a_{ij}(i\ =\ 1,\ 2, \ldots, M,\ j\ =\ 1,\ 2, \ldots, N)$ is the transfer function for *M* times the change, as shown in (1). In addition, using the vector form, (2) can be expressed as

$$\boldsymbol{x}\ =\ \boldsymbol{A}\boldsymbol{s}. \tag{3}$$

When we obtain the observed signals $\boldsymbol{x}$, it is possible to easily separate EM emanation sources $\boldsymbol{s}$ if the transfer functions $\boldsymbol{A}$ are already known and have an inverse matrix. However, because it is difficult to derive and measure the transfer functions $\boldsymbol{A}$ between the emanation source and antenna, we must find the EM emanation sources $\boldsymbol{s}$ under the condition that the only observed signals $\boldsymbol{x}$ are available.

ICA separates signal sources under the condition that signal components are independent of each other; each signal follows a non-normal distribution. Therefore, we assume that signal separation is established when the non-Gaussianity of the signal, after separation from the observed signals, is maximized.

In this article, we adopt the fast ICA method among various ICA algorithms [24]. The fast ICA method assumes the separation matrix $\boldsymbol{W}\ = (w_1, w_2, \ldots, w_n)^T$ against $\boldsymbol{z}$ of the observed signals $\boldsymbol{x}$, where $\boldsymbol{z}$ is the matrix that results from performing a whitening transformation on $\boldsymbol{x}$. The matrix $\boldsymbol{z}$ consists of noncorrelated elements and has a variance of one. Then, it outputs the separation signal $\boldsymbol{y}\ =\ \boldsymbol{W}\boldsymbol{z}$, where the separation matrix $\boldsymbol{W}$ is the coefficient matrix used to estimate the transfer functions $\boldsymbol{A}$.

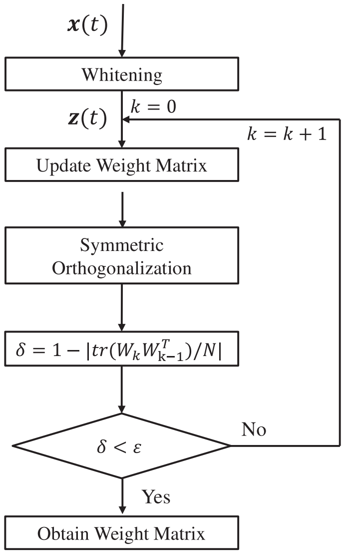

Fig. 2. Flowchart of fast ICA.

The update equations of the separation matrix are as follows:

$$\boldsymbol{w}_i^+ \leftarrow \mathrm{E}\left\{\boldsymbol{z}\mathrm{g}\left(\boldsymbol{w}_\mathrm{i}^\mathrm{T}\boldsymbol{z}\right)\right\} - \mathrm{E}\left\{\mathrm{g}'\left(\boldsymbol{w}_\mathrm{i}^\mathrm{T}\mathbf{z}\right)\right\}\boldsymbol{w}_\mathrm{i} \tag{4}$$

$$\boldsymbol{W}^+ \leftarrow \left(\boldsymbol{W}\boldsymbol{W}^T\right)^{-1/2}\boldsymbol{W} \tag{5}$$

where $\boldsymbol{W}^+$ and $\boldsymbol{w}^+$ denote the update variables, and

$$g\ (x) = \tanh(x) \tag{6}$$

$$(g(x))' = g'\ \ (x) = \ 1 - \tanh^2(x)\,. \tag{7}$$

Fig. 2 shows the flowchart of the fast ICA method used in the proposed method, where k is the number of updates, and ε is a constant for convergence determination. In the proposed method, we use $\varepsilon = 0.0001$, where the separation matrix is assumed to be sufficiently converged.

Using the ICA method, even if the transfer functions $\boldsymbol{A}$ between the emanation sources and antenna are unknown, it is possible to separate the observed signals $\boldsymbol{x}$ into EM emanation sources $\boldsymbol{s}$ by changing the transfer function multiple times.

III. Validation of the Proposed Method

In this section, we verify the proposed method, as shown in Section II, using a laptop PC with a display divided into multiple areas; the high-resolution display is considered the attack target. To observe multiple leaked EM waves with different transfer functions, the observation position or center frequency is changed. We demonstrate that the ICA using multiple leaked EM waves can reconstruct the entire screen information of a high-resolution display. In the ICA, we use in-house code with MATLAB [25].

A. Measurement Setup and Conventional Screen Image Reconstruction Result

Fig. 3 and Table I present the experimental setup. A laptop PC is set up in an anechoic chamber, and a log-periodic antenna is set up 3 m from the laptop PC to measure the leaked EM waves.

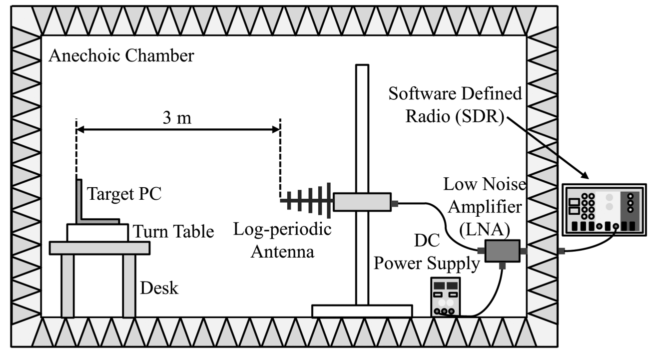

Fig. 3. Experimental setup. The experiment is conducted in the chamber. The distance between the target PC and log-periodic antenna is set to 3 m.

TABLE I
Measurement Equipment

Equipment	Model
Antenna	Schwarzbeck USLP D-69250
LNA	COSMOWAVE LNA270WS
SDR	National Instruments PXIe-5840

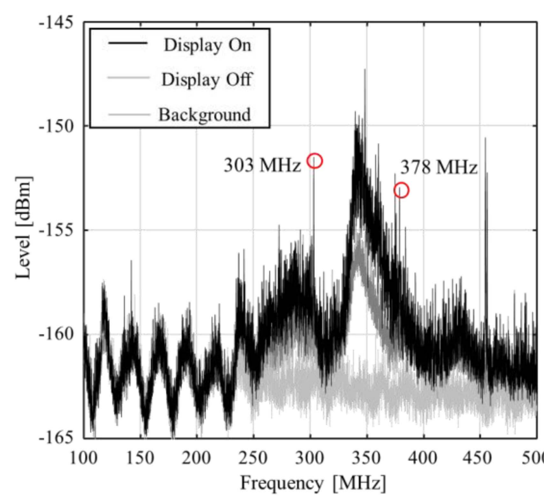

Fig. 4. Frequency spectrum of the leaked EM waves from the target PC. We measure for cases where the display is turned ON and OFF and the target PC is turned OFF (background). The resolution bandwidth is 100 kHz.

The EM waves received by the antenna are amplified through a low-noise amplifier (LNA) and measured using a software-defined radio (SDR).

Fig. 4 shows the frequency spectrum of the EM waves leaked from the target laptop PC. The intensity of the frequency spectrum changes when the display is turned ON and OFF and the target PC is turned OFF (background noise). In particular, in the vicinity of 303 and 378 MHz, we are able to confirm EM emissions containing screen information.

Fig. 5 shows an image displayed on the target laptop PC. In this article, our target is a static document where multiple colors were not used because most of the crucial information are described in such a document. We select the colors that offered stronger leakage than the background color of white and the character

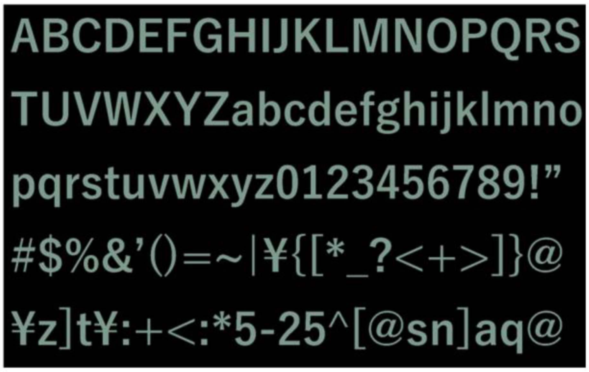

Fig. 5. Screen image on the target display. The screen is divided into two areas: left and right sides.

Fig. 6. Reconstructed image with the conventional RVSIA. Because of the multiple screen information contained in the leaked EM wave, the pixels of the left and right sides of the screen information are overlapping. From this reconstructed image, it is difficult to recognize all characters.

color of black for good reproducible evaluation based on the previous work [26].

First, we use the conventional RVSIA, which uses a single observation position and a single receiving frequency. Fig. 6 shows the image reconstructed using the conventional RVSIA. The center frequency of the receiver is set to 378 MHz with the strongest leakage. The in-phase and quadrature (I/Q) sampling rate is 100 MHz, and the bandwidth is 80 MHz. Because the display of the target laptop PC is vertically divided at the center of the display, the screen information of the areas on the left and right is radiated and observed to be mixed. Therefore, as shown in Fig. 6, the pixels of the left and right screen information overlap. Because each pixel overlaps, it is difficult to recognize characters. From this result, we confirmed that a conventional RVSIA is difficult to apply to the divided display.

B. Validation of the Proposed Method Using Divided Display

1) Obtaining Different Transfer Functions by Changing Measurement Positions: As the first method, we changed the position between the target PC and the attacker’s antenna to observe multiple EM waves with different transmission characteristics. Fig. 7 shows the measurement setup in which EM waves with different characteristics can be obtained by changing the angle of the turntable. The target PC is always maintained at a distance of 3 m from the antenna, and the angle of the turntable is changed from 0° to 45° in steps of 15°. At this time, we measure up to 45° because the intensity of the leaked EM wave containing screen information decreased significantly when the observation angle is greater than 60°. The center frequency of the receiver is fixed at 303 MHz.

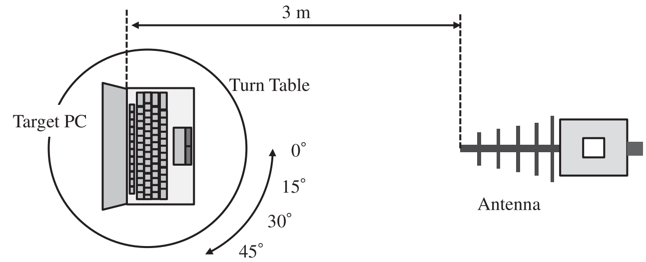

Fig. 7. Obtaining EM waves with different transfer functions by changing the angle between the antenna and the target PC.

Fig. 8 shows the reconstructed images of the screen obtained by separating the screen information. To obtain the reconstructed images, as shown in Fig. 8, two different EM waves from different angles are necessary as inputs of the ICA. A measurement angle of 0° is common for all images, as shown in Fig. 8. Angles of 15°, 30°, and 45° are selected for Fig. 8(a), (b), and (c), respectively. Compared with the image reconstructed by the conventional method, as shown in Fig. 6, it can be seen that the overlapping of the left and right screens is suppressed. In particular, the left side of the screen is clearly reconstructed so that all characters can be recognized. However, it is difficult to recognize the characters in the reconstructed image on the right side of the screen. This is because the leakage EM wave observed at 303 MHz is dominated by the left side of the screen.

In Fig. 8(c), the right side of the screen is recognizable compared with Fig. 8(a) and (b). As can be seen from Fig. 8(c), when EM waves measured at 0° and 45° are used, the difference in transmission characteristics becomes more pronounced, which is more suitable for separation. We found that the input signals with large differences in the transfer function are optimal for separating the screen information in our proposed method.

2) Obtaining Different Transmit Functions by Changing Receiving Frequency: We altered the receiving frequency of the receiver to obtain the difference between the transfer functions of the EM waves. From the results of the frequency spectrum measurements, as shown in Fig. 4, the target PC emits EM waves containing screen information in multiple frequency bands. At this time, we observed leaked EM waves with center frequencies of 303 and 378 MHz where a strong intensity is observed. Each observation position was fixed at 0° from the target PC.

Fig. 9 shows the images of leaked EM waves observed with center frequencies of 303 and 378 MHz as inputs to the ICA. Compared with the image reconstructed by the conventional method, as shown in Fig. 6, it can be seen that the overlapping of the left and right screens is suppressed significantly. It can be seen that the characters in both the left and right sides of the reconstructed screen become more recognizable when compared with the cases where the measurement position is changed (see

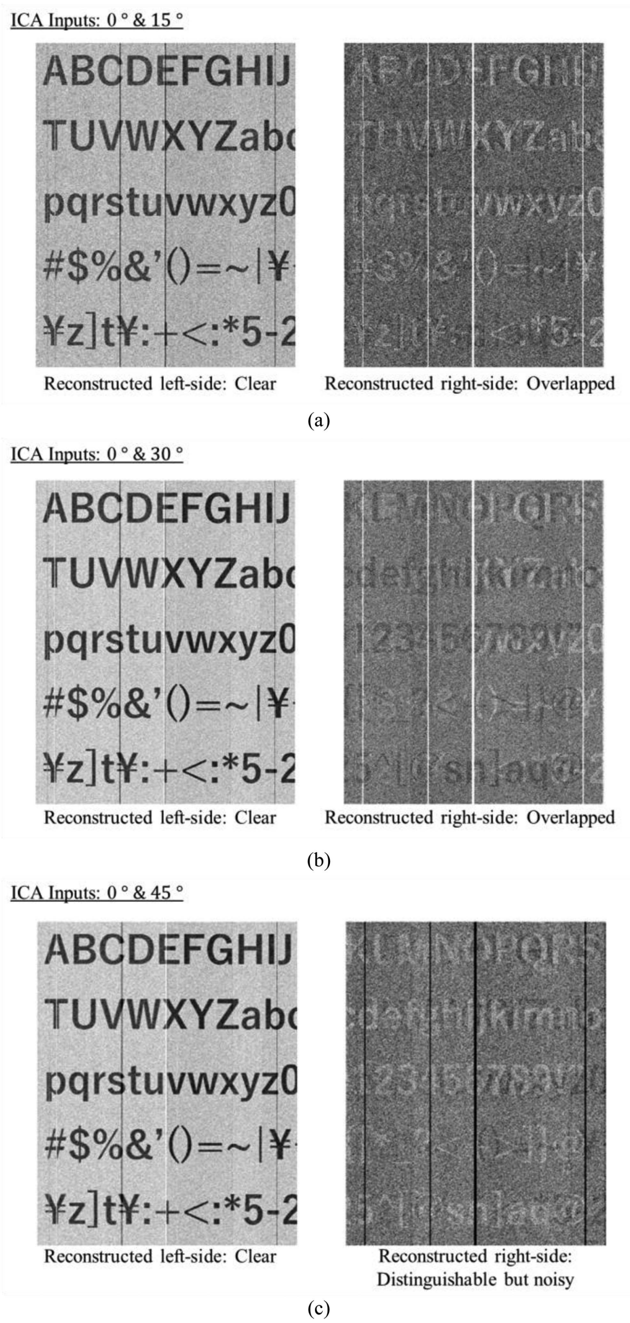

Fig. 8. Separation and reconstruction results using EM waves observed at different angles. The measurement angles are (a) 0° and 15°, (b) 0° and 30°, and (c) 0° and 45°. In (c), the reconstructed right side of the screen becomes distinguishable but there exist noise impacts.

Fig. 8). However, it can be seen that the noise component is included in the entire image even in the reconstructed image after separation by applying the ICA, and the pixels slightly overlap on the left and right side even after separation.

C. Improving Reconstruction Accuracy Using Multiple Input Signals

In the previous sections, we conducted measurements and analyses for two different cases by changing the observation positions and receiving frequencies to obtain the difference

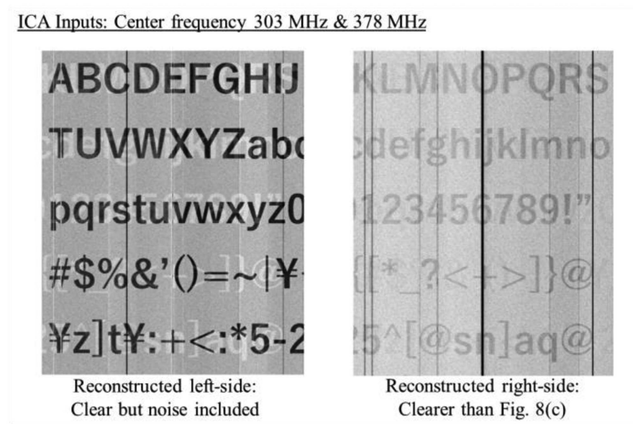

Fig. 9. Separation and reconstruction results using EM waves with different frequencies. Compared with Fig. 8, the right side of the screen is reconstructed more clearly. But there are still noise components included in the reconstructed image.

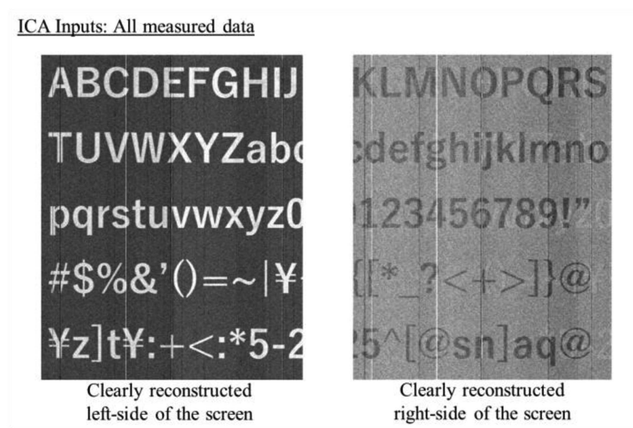

Fig. 10. Separation and reconstruction results using all measurement data; variation of measurement position and measurement frequency. Compared with Figs. 8 and 9, both left and right sides are reconstructed clearly.

in the transfer function. Then, we reconstructed the left and right sides of the screen with two different signals as inputs to ICA. Although the overlapping of the left and right screens was suppressed in each reconstructed image compared with the conventional method, noise components were included, and the left and right could not be completely separated.

Therefore, in this section, we discuss a method to improve the accuracy of separation by applying ICA with three or more EM waveforms with different transfer functions as inputs. From (2), if the screen of the target PC is separated into two, then the input signals required for the separation become two as well. However, by using more EM waves with different transfer functions, it is possible to separate noise components in addition to separating the screens to improve accuracy. Therefore, it is expected that the separation accuracy will be further improved, and the reconstructed image after separation will be a clearer. In this section, the screen information is separated by applying ICA to all the EM waves observed in Section III-B1 and B2.

Fig. 10 shows a reconstructed image of the screen obtained by applying the ICA method using multiple inputs. Compared with Figs. 8 and 9, in Fig. 10, the separation accuracy is further improved and the noise component is significantly reduced. All characters are recognizable and both the left and right images are clearly reconstructed.

Thus, we demonstrated that even when multiple screens are leaked at the same timing and leakage frequencies, it is possible to obtain different transfer functions by conducting multiple measurements at various locations and changing the receiving frequencies. Each screen information can be separated and remotely visualized.

Compared with the conventional RVSIA, the proposed method can separate screen information by increasing the number of measurements with the above operation and applying ICA without a major setup update.

Additionally, we measured and analyzed the situation where the display image used other colors in Fig. 5. Although the leakage intensity differs depending on the display color, we confirmed that the proposed method could be applied similarly to other colors.

IV. Conclusion

In this article, we proposed a novel RVSIA to reconstruct screen information. It utilizes the difference in the transfer function and applies ICA to EM waves by measuring at multiple observation positions and multiple receiving frequencies. By applying the proposed method, we demonstrated that it is possible to reconstruct the entire screen information of a high-resolution display by separating and reconstructing the image for each display area. The proposed method was verified to reconstruct screen information even if the leaked EM wave had the same leakage frequency and the same leakage timing, which is difficult in the conventional RVSIA. As a result of applying the proposed RVSIA to a laptop PC that divides the screen into multiple display areas, we were able to reconstruct the screen information without overlapping the multiple screen information. When using multiple signals by changing the observation position and receiving frequency as much as possible, we were able to reconstruct images without any noise components and overlaps with other screen information. Conversely, the accuracy of the reconstruction decreases when the observed signals exhibit slight differences in the transfer function.

Consequently, our proposed method is valid and useful because it is possible to reconstruct screen information only by changing the observation position and receiving frequency and by applying ICA. Therefore, the proposed method can be utilized without any major measurement equipment update compared with the conventional method. The proposed method expands the RVSIA range that can cover the recent high-resolution displays with divided screens.

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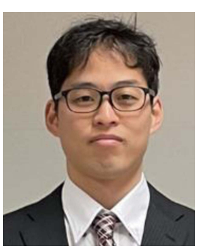

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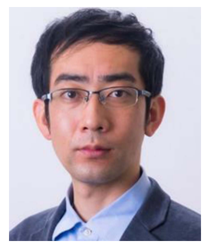

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