Trojan of Things: Embedding Malicious NFC Tags into Common Objects

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Abstract

We present a novel proof-of-concept attack named Trojan of Things (ToT), which aims to attack NFC-enabled mobile devices such as smartphones. The key idea of ToT attacks is to covertly embed maliciously programmed NFC tags into common objects routinely encountered in daily life such as banknotes, clothing, or furniture, which are not considered as NFC touchpoints. To fully explore the threat of ToT, we develop two striking techniques named ToT device and Phantom touch generator. These techniques enable an attacker to carry out various severe and sophisticated attacks unbeknownst to the device owner who unintentionally puts the device close to a ToT. We discuss the feasibility of the attack as well as the possible countermeasures against the threats of ToT attacks.

1 Introduction

Today, we use a smartphone not only for accessing to the various Internet services, but also for interacting with the networked devices around us, e.g., wireless headphones, fitness devices, smart home devices, connected cars, and contactless payment systems. To communicate with these networked devices, modern smartphones are shipped with various networking interfaces such as cellular networks, Wi-Fi, Bluetooth, and NFC. This trend has made smartphones getting more and more connected to our life – Anywhere, Anytime and with Anything.

Given the pervasive network connectivity of smartphones, we propose a new proof-of-concept attack named Trojan of Things (ToT). ToT attacks target the NFC-enabled mobile devices such smartphones. The key idea of ToT attacks is to covertly embed maliciously programmed NFC tags into common objects (“things”) routinely encountered in daily life such as banknotes, clothing, or furniture, which are not considered as NFC touchpoints. NFC tags are passive devices that can communicate with active NFC devices, e.g., NFC-equipped smartphones. An NFC tag comprises a thin processor chip and an antenna. It is small enough to be embedded into a business card.

The threat of maliciously programmed NFC tag has been reported in the past [24, 23, 27, 22, 28, 9]. An attacker can leverage an NFC tag to trigger risky actions; e.g., opening a malicious URL in a browser without user approval [22] or forcing a smartphone to pair with a rogue Bluetooth device [27, 22]. What distinguishes ToT from prior work is its stealth; instead of actively prompting victims to touch a point such as a smart poster where a malicious NFC tag was embedded, ToT passively waits for victims to approach a malicious NFC tag that is embedded within ordinary objects so that victims will not even realize that their devices may engage in NFC communication with these tags. That is, a ToT aims to carry out an attack without being perceived by the victims.

To fully explore the threat of ToT attacks, we develop a ToT device, which is used to mount sophisticated ToT attacks. It consists of a processor, communication interface such as Wi-Fi, and an NFC-tag emulator, which is a device that makes use of the NFC card emulation mode and can act as multiple NFC tags. The standard operation of a ToT device...
is as follows. It first presents a malicious URL to the victim device. The ToT device works with a web server behind the URL. The web server fingerprints the victim device and conveys the type of the device to the ToT device. The ToT device uses this information to tailor additional tags to be sensed by the victim device.

Although malicious NFC tags can induce a victim device to do certain low-risk actions such as opening a URL without prompting the user, higher-risk actions such as pairing with a Bluetooth device do require user confirmation. To deal with this problem, we develop several alternative techniques to deceive the user into confirming the prompt. In addition, we develop a new technique named Phantom touch generator, which aims to deceive victim devices into sensing phantom touch events in their touch screens by applying strong electromagnetic field at a specific frequency to trigger capacitive coupling. These techniques enable an attacker to carry out various attacks without being noticed by the device owner who unintentionally puts the device close to the installed ToT.

We make the following contributions:

- We present a novel class of attacks that we call ToT, which injects malicious functionalities into common objects (Section 3).
- We develop the two effective techniques; “ToT device” (Section 4) and “Phantom touch generator” (Section 5).
- We demonstrate the feasibility of ToT attacks using 24 smartphones for the NFC reading experiments and 7 smartphones for the Phantom touch generator experiments (Section 6).
- We provide possible countermeasures against the threats of ToT attacks (Section 7).

2 Background

In this section, we provide background information on the two key technologies used in our attack, NFC and capacitive touchscreen, which are widely used in smartphones.

2.1 NFC

Near-Field Communication (NFC) is a short-range wireless communication technology widely used in many applications, e.g., contactless payment systems, transit passes, smart posters, and smartphone apps. According to Ref. [16], the number of smartphones equipped with NFC is drastically increasing year by year. Roughly two-thirds of all smartphones shipped in 2018 are expected to be equipped with NFC.

NFC makes use of magnetic inductive coupling to communicate between two devices. NFC devices can be classified into two types: active and passive NFC device. An active NFC device has its own power source and acts as an NFC reader/writer. A passive NFC device, e.g., NFC-equipped IC card or NFC tag, does not have its own power source. When an active NFC tries to read data from a passive NFC device, it emits a weak magnetic field to induce electric current in the passive NFC device. Given the electric current, the passive NFC device encodes data and generate a magnetic field to induce electric current in the active device. While the theoretical working distance of NFC is up to 20 cm, the practical working distance is a maximum of about 4 cm.

NFC is a communication protocol that can exchange data just by bringing NFC compatible devices close to each other. In many NFC applications, communication is established without going through user interaction; e.g., mobile payments are completed just by placing the two devices at a close distance. This design leads to high usability. However, the high usability of NFC raises several security issues. Although the NFC communication range is limited to only a few centimeters and tags can be configured to be read-only, the NFC service can be easily exploited by a simple attack replacing the existing NFC tag with a malicious NFC tag. Several studies have reported the threats of malicious NFC tags [24][23][27][22][25][19]. We will summarize these studies in Section 8. Wall of Sheep, an organization that makes people aware of security risks, recommends that people should not trust NFC tags created by third parties and take precautions [28].

Android OS has supported NFC technology from version 2.3. Note that Android smartphones can
Table 1: Android OS operations that can be launched by reading an NFC tag.

| operation                              | requests user approval |
|----------------------------------------|------------------------|
| open a specified URL                    | No                     |
| launch a specified app                  | No                     |
| send an Intent to an NFC-enabled app    | No                     |
| launch an Instant app (new)             | No                     |
| send email to specified address         | Yes                    |
| with specified subject and body         |                        |
| connect to specified Wi-Fi AP           | Yes                    |
| pair with specified Bluetooth device    | Yes                    |

work as either a passive or an active NFC device. In the following, we focus on the characteristics of Android smartphones as an active NFC device. When an Android device is held over an NFC tag, Android OS can perform various operations by reading the data recorded in the NFC tag. Table 1 lists the operations that can be launched by reading an NFC tag. Recently, Google announced a new technology called Android Instant Apps [5]. It allows a user to use apps without downloading/installing them. Android Instant Apps can be accessed via a web link or an NFC tag containing the web link. Thus, reading an NFC tag can launch a new app that has not been installed on the smartphone.

2.2 Capacitive Touchscreen

Majority of the current mobile devices such as smartphones and tablets are equipped with touchscreens. While there are various technologies for sensing touch, mutual capacitive sensors are widely used for smartphones as they have high durability, fast response, and multitouch support [6].

As shown in Figure 1, a mutual capacitance touchscreen controller consists of transmitter (TX) electrodes and receiver (RX) electrodes, which are mutually coupled, e.g., \( C_0 \) in the figure. The grid of TX and RX electrodes is used for sensing touch events. As the human body has a capacitance, it can act as a capacitor. When a finger approaches to the screen surface, it passes electric charge onto the touchscreen sensors through mutual capacitance (\( C_f \) in the figure). Thus, the touchscreen controller can detect touches by measuring the changes in electric current that flows into the RX electrodes; the current changes are caused by the changes in capacitance between the TX and RX electrodes. The pair of TX and RX electrodes for which the changes are detected is used to locate the area of touch.

It is known that a touchscreen controller in a smartphone can malfunction due to noise signals leaked from the smartphone’s battery charger or screen [11]. Touchscreen controller manufacturing companies have developed countermeasures against the electromagnetic interference (EMI) caused by noise signals, which are relatively weak. However, when a stronger noise signal is intentionally applied to a touchscreen controller, false touch events can be
generated. As some hobbyists have reported [25]7, it is known that false touch events occur when a smartphone is brought close to a commercial plasma ball, which is powered by an oscillator and a high-voltage transformer circuit producing a large alternating voltage, typically 25 kV at around 30 kHz [3]26. The strong electric field generated by the electric circuit of the plasma ball causes capacitive coupling with the touchscreen sensors; the coupling causes changes in electric current flowing into the RX electrodes and the changes are detected as random touch events.

3 Trojan of Things

In this section, we present the overview of ToT attacks. We first describe our threat model. We then introduce several attacks using malicious NFC tags. Finally, we present examples of ToT implementations and their implications.

3.1 Threat model

In this work, we assume an attacker has embedded a malicious NFC device into a targeted thing in advance. If the target is a small and portable thing such as banknote or clothing, the attacker embeds a malicious NFC tag into it. This device can carry out a simple attack. If the target is a large and stationary thing such as a table, the attacker can embed several components, e.g., an NFC-tag emulator, a single-board computer, and high-voltage transformer, in it. This is what we call a ToT device, which is used to carry out sophisticated attacks.

We also assume the victim has an Android smartphone equipped with NFC. The victim unintentionally places the smartphone close to a ToT, and the smartphone automatically reads a malicious NFC tag/emulator when it is unlocked and not in the sleep mode. The validity of this assumption will be discussed in Section 7. After reading the NFC Data Exchange Format (NDEF) records stored in the malicious NFC tag/emulator, the smartphone will execute a corresponding operation used for attacks, which will be described in the next subsection.

As triggering high risk actions such as connecting to Wi-Fi AP requires user approval by displaying a dialog box with a confirmation message, we develop two techniques to evade the user approval process. The first is to mislead the user into approving the dialog box by different ways of manipulating the UI such as showing a deceptive message or dimming relevant parts of the display (Section 4). The second technique is an attack on the touchscreen named Phantom touch generator (Section 5). Figure 2 summarizes the types of ToT, possible attacks, and the system components.

3.2 Attacks using the malicious NFC tags

As shown in Table 1, two types of operations can be invoked via NFC: operations that require user approval and operations that do not. The latter will be automatically executed if an NFC tag is brought close to a smartphone. We call an attack that makes use of such operations as a single-shot attack. A representative example of a single-shot attack is opening a malicious URL in a browser; such a malicious website can trigger download/installation of a malware on the smartphone [28].

By combining multiple single-shot attacks, we can create more sophisticated attacks, which we call combination attacks. ToT device is a system that implements combination attacks. Combination attacks enable an attacker to establish device fingerprinting. As shown in Section 4, device fingerprinting is useful to infer the language used for the device; the infor-
mation can be used to display a dialog box with a deceptive message to the victim. The fingerprint information can also be used for displaying a dialog box with a suitable message, which needs to be adaptive to the vendor-specific customization of confirmation message strings.

Operations that require user approval can be used for high risk attacks. For instance, by forcing a device to connect to a malicious Wi-Fi AP, the attacker can establish the man-in-the-middle attack. Or, the attacker can even take complete control of the smartphone by forcing the device to pair with a Bluetooth mouse, which can be used as a remote control. Thus, evading the user approval process is a key success factor of the attacks. One way to evade the use approval process is to display a dialog box with a deceptive message, as we discussed above. Actual examples of composing such a deceptive message will be described in Section 4. Another way is to employ the new attack we developed, Phantom touch generator, which will be described in Section 5.

3.3 Examples of ToT implementation

In order to let a victim accidentally scan a malicious NFC tag/emulator on his/her smartphone, a malicious NFC tag/emulator should be embedded in a thing that has many opportunities to come close to a smartphone. In this section, we present two examples of a simple ToT and an example of a ToT device.

Figure 3 presents an implementation of a simple ToT in a banknote. We embedded a malicious NFC tag into a toy banknote imitating a one dollar bill. The NFC tag is embedded into an area indicated by a circle, as shown in the figure. We placed the bill in a wallet and the wallet in the pocket. When an unlocked smartphone was placed in the pocket, the smartphone read the data from the malicious NFC tag. Thus, the ToT attack is easy to deploy and feasible. The implications of such a ToT attack are as follows. The most notable feature of banknote is that it physically circulates from person to person. Therefore, by embedding a malicious NFC tag in a banknote, several smartphones can be attacked one after another. In addition, since many people may carry their wallet and smartphone together in their pockets or bags, there are many opportunities for the ToT to attack an individual smartphone. We also note that it is not easy to track the attacker once a mobile ToT is disseminated into the real world.

Figure 4 presents an implementation of another simple ToT in a pair of trousers. A malicious NFC tag is embedded into an area surrounded by a circle shown in the figure, i.e., on the back of the pocket. Since clothes may be washed in a washing machine, sewing a durable (e.g., laminated) NFC tag is suitable for this attack. When an unlocked smartphone was placed into a pocket with a malicious NFC tag, the smartphone successfully read the data from the malicious NFC tag. The implications of such a ToT attack are as follows. The target can be extended to various clothing items such as clothes displayed at a clothing retailer, rental clothes, laundry being dried outdoors, or a suit hanging on a chair. Since clothing is personal, it can also be used for a targeted attack. By embedding a malicious NFC tag in a part which has a high possibility of being close to a smartphone, such as a chest pocket, a trouser pocket, or the end of a sleeve, we can increase the opportunities for a smartphone to read the malicious NFC tag.

Finally, Figure 5 presents an implementation of ToT device using a desk. In this implementation, an NFC emulator, a single-board computer, and other
Fig. 6: Overview of ToT device.

4 ToT Device

In this section, we first provide an overview of ToT device. We then present combination attacks, which can be established using the ToT device.

4.1 Overview

Figure 6 presents an overview of the ToT device. It comprises the two primary components, an NFC tag emulator and a single-board computer with a Wi-Fi controller installed. The ToT device works with a web server, which can be set anywhere connected to the Internet, e.g., a cloud server. We note that the attacker also needs to install a power source. As an NFC-tag emulator, we used Sony RC-S380 for our experiments. By using the NFC-tag emulator, we can dynamically switch the NFC tags according to the attack scenario.

We now describe how the ToT device works using the example shown in the figure.

1. The NFC tag emulator acts as an NFC tag with a URL data recorded and waits for a victim to approach.
2. When the victim’s smartphone comes close to the ToT, it reads the tag and launches a browser to open the URL.
3. The browser then connects to the website specified by the recorded URL.
4. The website employs device fingerprinting by using JavaScript to collect information about the victim’s device.
5. The website sends the device fingerprinting information to the computer onboard the ToT device. We assume that the computer has Internet access.
6. Upon receiving the device information, the computer determines the tag suited for the victim’s device and rewrites the NDEF record of the NFC tag emulator.
7. Finally, the victim’s smartphone reads the new NDEF record from the tag and gets attacked again. Note that the smartphone will read a new record after the emulator is turned off (which implies that the old tag went away) and turned on again.

4.2 Combination attacks

As we have shown, the framework of software-defined malicious NFC tags enables an attacker to employ the device fingerprinting. By using the device fingerprinting information, the attacker can further perform a targeted attack, which leverages the intrinsic features of the mobile devices, e.g., language setting, vendor customization, and the noise tolerance characteristics of the touchscreen controllers, etc. In the following, we present the two applications of the combination attacks – deceptive message trap and exploiting installed apps. Both attacks aim to deceive a victim into touching a button, which establishes the attack, e.g., connecting to a malicious Wi-Fi AP that employs the man-in-the-middle attack.

4.2.1 Deceptive message trap

To make the descriptions easy to follow, we first describe a case where the attacker does not use the device fingerprinting. We then describe a case where
the attacker needs device fingerprinting.

The deceptive message trap is an attack that aims to deceive a victim into touching a button that establishes the attack. We focus on the scenario of a Wi-Fi attack as a representative example. In this scenario, the goal of the attacker is to deceive a victim in touching the “CONNECT” button when a modified message pops up after reading the malicious NFC tag with the WiFiConfig record.

In the Android OS, as of February 2017, the format of the confirmation message invoked by the WiFiConfig NFC record is defined in the file named, `android/platform/packages/apps/Nfc/res/values/strings.xml`. Figure 7 summarizes an excerpt of the main part. Here, the strings shaded with gray are replaced with the service set identifier (SSID) value specified in the WiFiConfig NFC record. SSID is an identifier for a Wi-Fi AP. Since the maximum length of the strings used for specifying a SSID is set to 32 bytes and the SSID encoding scheme allows the use of the UTF-8 charset, the attacker can tweak the SSID strings to deceive a victim.

We show an attack scenario using this trick. The attacker creates a malicious NFC tag with the SSID of WiFiConfig record set to “again”. When the victim’s smartphone approaches to the ToT device with the malicious NFC, the following confirmation message pops on the screen:

```
Connect to network again?
```

When the victim notices this message popping up, she/he may think that the Internet connection is lost and the smartphone is asking to reconnect to the previously connected network, and will touch “CONNECT”. Thus, the man-in-the-middle attack is established. Note that a single-board computer can work as a malicious Wi-Fi AP. Along this line, the attacker can create various deceptive messages such as

```
Connect to network to prevent the data lost?
```

Such a message will threaten the victim into touching the “CONNECT” button, which again will connect the smartphone to the malicious Wi-Fi AP.

We now turn our attention to the case where the attacker needs device fingerprinting. As the format shown in Figure 7 represents the case for uncustomized Android with the language configured to English, the attacker may want to customize the message according to the language used by the victim and the model of the smartphone. Through the analysis of 24 Android smartphones equipped with NFC, we found that several vendor customizations use different formats for the confirmation messages. For reference, we summarize the result in Table 3, 4, and 5 (Appendix). To cope with such differences, the attacker can use the information obtained from device fingerprinting, which was presented in Section 4.2.

4.2.2 Exploiting Installed Apps

This attack leverages the apps installed in the victim’s smartphone. For this attack, the attacker specifies “Android Application” in the NDEF record of a malicious tag. After reading the application tag, Android OS will automatically execute the application specified in the record without requiring user approval. There are two variations of this attack. The first variation aims to make the deceiving message look real by intentionally creating a context. The attacker first sets an Application NFC tag that launches a popular SNS app such as Facebook. Subsequently, the Facebook app appears on the screen of the victim’s smartphone. The attacker then sets the WiFiConfig NFC tag using the technique described in the previous subsection. The message popping on the screen appears as follows:

```
Connect to network ? Facebook app is requesting.
```

Since the dialog box of this message appears on top of the Facebook app, it looks as if the message is originated from the Facebook app. Some Facebook users may touch the “CONNECT” button, never knowing that the message is for connecting to a malicious Wi-Fi AP. Note that to create this message, we set the following text string as the SSID: “\u202E.gnitseuqer si ppa koobecaF“, where ‘\u202E’ is a Unicode character known as RIGHT-TO-LEFT OVERRIDE.

Another variation is to make use of a utility application that adjusts the brightness of the screen, e.g., “Screen Filter” [12], which has been installed by more than 5 million users as of February 2017. Since the aim of such applications is to reduce eye stain
while using the smartphone during nighttime, the users usually adjust the brightness level lower than the default setting. Therefore, when the app is executed, the screen gets darker, which makes the characters displayed on the screen difficult to read during daytime. The attacker first sets an application tag that executes such an app. If the victim’s smartphone comes close to the tag, the screen automatically becomes darker. The attacker then switches the tag to the Wi-Fi tag mode. A pop-up message that is difficult to read during daytime automatically appears on the dark screen. The users may accidentally click the “CONNECT” button in such a situation.

We provide screenshots of the attacks described above in the appendix.

5 Attacks to Touchscreen

In this section, we will first describe the new attack, named Phantom touch generator, which aims to alter the selection of a button on a screen; i.e., while a victim thought that she/he touched the button “A”, the attack can scatter the recognized touched position and make the operating system recognize another button “B” touched. We then present another attack to the touchscreen; an attacker installs a circuit board on top of the table/desk, which can directly cause touch events at an arbitrary position.

5.1 Phantom touch generator

5.1.1 Overview

Phantom touch generator is an attack that aims to scatter touch events around the original touch area; i.e., even though a victim touches a “CANCEL” button, which should cancel the request to connect to a malicious Wi-Fi AP, the attack make the operating system recognize the event as a touch of another button, “CONNECT,” in a probabilistic way. Thus, the attack can trick the user, with a certain success rate. In the following section, we aim to present the basic mechanism of Phantom touch generator and reveal the conditions that are needed to establish the attack.

The key idea of Phantom touch generator is to intentionally cause the malfunction by injecting intentional noise signals from the external. As we discussed in Section 2, a touchscreen controller mounted on a smartphone can cause a malfunction due to the noise signals. The malfunctions include three types: (1) “false touch,” which reports touches at positions where no touch is present, (2) “no-touch,” which reports that a touch does not exist when a finger touches the area, and (3) “jitter,” which reports the coordinates distributed around the true touch point.

As we had hints from the experiments of toy plasma balls, we found that we can intentionally cause the malfunction by generating an electric field near the capacitive touchscreen controller, using an electric circuit that can produce large alternating voltage. Applying such signals using a metal plate can create a capacitive coupling with the capacitive sensors of touchscreen controllers. As we showed in Section 2, the capacitive coupling causes the changes of capacitance between the TX and RX electrodes of the touchscreen controller, and the changes will be detected as the (false) touch events.
5.1.2 Experiments

To study the conditions that can cause the “false touches,” we conduct several experiments using the touchscreen controller that provides raw data collected from the capacitive sensors. In the following, we first describe our experimental setup. Second, we attempt to specify the intrinsic frequency of injected noise signal to maximize the false touches. We then analyze the spatial patterns of the false touch events on the screen with a noise injected at a specific frequency. Finally, we study how an actual touch event by a user affects the spatial patterns of the false touch events. This final experiment will reveal the mechanism of Phantom touch generator.

Experimental setup Figure 8 shows our experimental setup. Our objective is to measure the effect of noise signals on the behavior of touchscreens. For this experiment, we use the Raspberry Pi 7-inch Touchscreen Display. As an intentional noise signal, we use the sine-wave signal generated by a function generator. We set a copper sheet parallel to the touchscreen controller. This copper sheet is used to create a capacitive coupling with the capacitive sensors. The distance between the sheet and controller was set to 7 cm. We note that the attack can be applied from the rear side of a touchscreen controller, i.e., the rear side of a smartphone.

Effect of the frequencies and voltage values
We generate sine-wave noise signals with different frequencies and voltage values. We record raw capacitance values and touch events using the software we developed. Since the touchscreen has 264 capacitance sensors, which consists of a $12 \times 22$ matrix, we can obtain 264-dimensional time-series data. This setup enables us to analyze the spatial patterns of the generated touch events.

To measure the interference intensity on the touchscreen, we introduce a metric, $\Delta$, defined as follows.

$$\delta_i = x_i - \bar{x}_i$$
$$\Delta = \max_i (\delta_i) - \min_i (\delta_i),$$

where $x_i$ ($i \in \{1, \ldots, 264\}$) is a measured value for each sensor and $\bar{x}_i$ ($i \in \{1, \ldots, 264\}$) is a measured value for each sensor when noise is not injected, respectively. We note that $x_i$ is variable of time; our capacitance logger sampled the raw values at the rate of 7 times per second. In contrast, $\bar{x}_i$ was set as a static value, which was collected when no signal was injected. If no noise signal is applied, $\Delta$ becomes roughly 20 when there are no touch events on the screen and $\Delta$ becomes greater than 250 when a finger touches the screen. Thus, the metric $\Delta$ can measure the impact of noise interference.

We measured $\Delta$, applying noise signal to the copper sheet with three different voltages (20 Vpp, 70Vpp, and 120Vpp) and frequencies, ranging from 5 kHz to 300 kHz. Figure 9 shows the results. We first notice that there are clear peaks at the frequency of 90 kHz. This result indicates that there is a characteristic frequency of noise that can affect the touch controller. As we will study in the next section, this frequency differs for different models of touchscreen controllers. So, specifying the model of the target is crucial to succeeding in the attack. As we have seen, the device fingerprinting technique can be used.
Spatial distribution of the false touch events
We now study the positions of the touch events caused by the noise signals. In this experiment, nothing touches the screen. Using our monitoring software, we record touch positions for 30 seconds with the sampling rate of two samples per second. The touchscreen has an 800×480 resolution and supports a 10-point multi-touch. The touchscreen controller is capable of reporting up to 10 positions per sample. Note that the touch events are collected from the outputs of the touchscreen controller, not from an operating system.

We used three different voltages (20 Vpp, 70 Vpp, and 120 Vpp) and the following two representative frequencies: 60 kHz as a frequency not affecting ∆ and 90 kHz as a frequency affecting ∆ the most. As expected, the touchscreen does not report any touch events with the 60 kHz frequency. In the followings, we omit the results of 60 kHz frequency. Figure 10 shows the results for 90 kHz frequency. First, we notice that the touchscreen controller did not recognize touch events when the voltage was set to 20 Vpp. We also see that higher voltage signals cause false touch events more frequently. Second, we see intrinsic spatial patterns of touch events, i.e., they linearly spread out on the screen. We also see that many touch events are focused on the top or bottom edges of the screen panel. These observations indicate that even if an attacker waits for a long time, it seems unlikely that a false touch is fired at target coordinates with a high probability, given the skewed spatial distribution.

Limiting the dispersion with a real touch event
After several trials, we found that touching on a screen can fix the skewed spatial distribution of false touches. Although not conclusive due to the “black box” nature of the touchscreen controllers, we conjecture that the touching with a finger stabilizes the area of capacitive coupling. The good feature of this phenomenon is that while touching on a screen makes the distribution focused on a certain area, it still keeps scattering the touch events; thus, it can create false touch events in a more predictable way.

We repeated the similar experiments but added a finger touch this time. Figure 11 shows the experiment results. Under the low voltage signal of 20 Vpp, the false touch events occur only if a finger touches the screen. More importantly, we can see that the positions of the false touches are centered on the line where the true touch point is located. These are desirable characteristics because usually, GUI buttons are aligned in a row: e.g., CONNECT/CANCEL, YES/NO, or OK/CANCEL. Therefore, an attacker can expect that a touch event will be scattered on a wrong button, with a probability of 1/2, with an assumption that the touch events are uniformly scattered along a line. We note that screen orientation also matters. If a screen is in portrait mode, scattered touch events along the vertical line may not produce a touch on the targeted button. As we show in Section 6, the direction of scattered touch events

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As we will see in the next section, the direction of the spread patterns differs for different models of touchscreen controllers; i.e., horizontal spread or vertical spread.
Figure 10: Coordinates of the touch points reported by the touchscreen controller. The injected signals had three different voltage values. The frequency was set to 90 kHz. **Left:** 20 Vpp, **Center:** 70 Vpp, **Right:** 120 Vpp

Figure 11: Coordinates of the touch points reported by the touchscreen controller. While the experiment a finger keeps touching the point centered on the screen. **Left:** no signal is applied. **Right:** a signal with 20 Vpp and 90 kHz is applied.
5.2 Electrical touch

So far, we have assumed that the NFC controller is mounted on the rear side of the smartphone, and Phantom touch generator attacks the touchscreen from the rear side. However, there are several smartphones/tablets that mount the NFC controller on the front side of the devices; e.g., Nexus 10, Xperia XZ, and ZenFone 3 Deluxe. These mobile devices read NFC tags on the same side with its touchscreen.

For this type of devices, an attacker can trigger arbitrary touch events by directly touching the screen when a victim puts the device on a table-type ToT with the touchscreen down. An attacker installs a simple circuit with plate electrodes on the surface of ToT – embedding the circuit in the table top. We implemented such a circuit as shown in Figure 12.

The circuit works as follows. The plate electrodes on the circuit capacitively couple with the TX electrodes of the touchscreen when the circuit gets close enough to the touchscreen. The capacitance between one of the electrodes on the circuit and TX electrodes becomes low when the circuit electrodes are disconnected from anywhere and becomes high when the circuit electrodes are grounded or connected to an object that has large electric capacitance. By systemizing this mechanism, an attacker can virtually touch an arbitrary position by relaying a corresponding electrode to the ground or the object with a large capacitance.

The circuit shown in Figure 12 has a 1-cm² of square plate electrode. If we implement several plate electrodes that are placed 0.5 cm away from each other, the resolution of touch becomes 1.5 cm. The area of plate electrode of the circuit is proportional to the capacitance between the electrode of the circuit and touchscreen. Therefore, plate electrodes that are too small cannot create enough change of capacitance by grounding it. However, an attacker could obtain finer resolution by using circuits used for active styluses, which actively interrupt field coupling between the electrodes of the touchscreen.

An attacker can make use of this attack as follows: An attacker first employs the device fingerprinting to know that the device has the NFC controller at front side. Using the website, the attacker can obtain the information about the device orientation using the web API interface. Using the position of the used NFC tag and the orientation information, the attacker can estimate the area of the touchscreen. Finally, an attacker can pinpoint the position of the button for establishing the attack and make the electrical touch by grounding the corresponding plate electrode.

6 Feasibility Studies

To demonstrate the feasibility of ToT devices, we performed two empirical studies. The first study aims to
verify that NFC tags embedded inside a thing can be actually read by smartphones. For this study, we use 24 Android smartphones/tablets, which are manufactured by the 12 different vendors. We summarize the list of devices we used in Table 3 (Appendix). The second study aims to verify the success of Phantom touch generator attack. For this study, we use 7 Android smartphones/tablets listed in Table 2.

6.1 Maximum NFC Reading Distance

We study the maximum NFC reading distance of the smartphones to demonstrate the validity of the idea of embedding malicious NFC tags in a thing. A NFC tag is attached to the backside of the wood board of the walnut material. We read the tag using the smartphones placed on the backside. We measured the maximum communicable distance by changing the thickness of the wood board at intervals of 5 mm and recording the success of reading the tag. We found that the maximum NFC reading distance was 3.4 cm in average. The maximum and minimum of the measured distance were 5.0 cm and 2.0 cm, respectively. The full result is summarized in Table 3 (Appendix). If we consider the thickness of common objects such as a table top or a wallet, we can conclude that the measured maximum distance is large enough to establish the attacks by ToToT.

6.2 Conditions of the successful Phantom touch generator attacks.

Using the smartphones that have the NFC controller on the front side, we empirically study the conditions for the successful attacks. Unlike the experiment using a Raspberry Pi 7-inch touchscreen display, we need higher voltage to establish Phantom touch generator attack. As our amplifier is not capable of generating voltage greater than 150 Vpp, we used a high-voltage transformer taken out of a plasma ball, which costs about 6 USD.

Figure 13 shows the setup of the experiments. The smartphone and the copper sheet are insulated with the polycarbonate plate of 5 mm thick. Following the procedure that is shown in Section 5.1, we first identify the characteristic frequencies for the smartphones to cause the malfunctions. For the smartphones that had caused malfunctions, we will further test the following tasks. We will create a NFC tag that requests the Bluetooth pairing. The smartphone will pop up a dialog message after reading the tag. We then touch the button of “NO.” Before the smartphone reads the tag, we have applied Phantom touch generator. We will see whether the actual touch becomes “YES” (attack succeeded) or “NO” (attack failed).

Sometimes, we do not see any responses even though we touch the button due to the noise injection. In such cases, if there are no responses back after the five consecutive touches, we count it as a
failure of the attack. Also, if the patterns of the touch scattering for a device has a horizontal/vertical direction, we set the orientation of the device to portrait/landscape.

Table 2 summarizes the results. For the 5 out of 7 models, we specified the characteristic frequencies and voltage values that can cause malfunction, i.e., “false touch.” Of the 5 models that cause malfunctions, 3 models succeeded the attack with probabilities distributed around 1/2; i.e., the OS detected the touch for a wrong button and the device was paired with a Bluetooth device. The rest of 2 models worked as follows. For Nexus 9, the detected touch events were biased to a specific area, which was not close to the buttons; thus, the attacks failed. For AQUOS ZETA SH-04F, when a finger touched somewhere in the right/left half of the screen, the false touches appeared on the left/right half on the screen; thus, the attacks failed. Thus, the patterns of false touches depend on the models.

There were two models that did not generate false touch events; the one that the detected touch events lag behind the finger’s touch (Galaxy S 6 edge) and the one that does not recognize the touch at all (ARROWS NX F-05F). In addition the malfunctions mentioned in Section 5.1 we found the following malfunction patterns: Even when the noise injection is stopped, the device stops reacting to the touch until it goes to sleep mode, the monitoring application is abnormally killed, and the operating system restarts, etc.

7 Discussion

In this section, we discuss the feasibility of ToT attacks and possible defenses against them.

7.1 Feasibility

Our threat model makes three assumptions about a victim’s smartphone: (1) It is an Android smartphone equipped with NFC, (2) the NFC functionality is enabled on the smartphone, and (3) the screen of the smartphone is unlocked when the smartphone is brought close to a ToT. We now discuss the feasibility of ToT attacks in light of these three assumptions.

The first assumption limits the scope of target devices. In fact, although iOS supports NFC technology, it has not supported reading NFC tags as of February 2017. Still, we conjecture that the threat of ToT attacks is potentially pervasive in future because of the following two reasons. First, it has been forecasted that the shipments of Android NFC-enabled smartphones will reach 844 million in 2018 [16], indicating that the potential target of ToT attacks is increasingly becoming ubiquitous. In addition, there is a possibility that Android Instant Apps [5] accelerates the adoption of NFC. We note, however, that the naive use of the new technology has potential security risks such as launching a fake browser, etc. Second, many financial technology companies have recently launched mobile payment services using NFC technology; this trend will continue to grow and push the adoption of NFC-empowered smartphone services.

The second assumption limits the opportunities of successful attacks; i.e., the attack will not succeed unless the NFC functionality is enabled on the victim’s smartphone. To verify the second assumption, we manually investigated 24 smartphones listed in Table 3 (Appendix). We found that the NFC functionality is enabled in the factory setting in 16 out of 24 models. Interestingly, in more recent models, the NFC functionality is enabled in the factory setting. The results of our survey are summarized in the appendix (see Table 3). As we already have discussed before, we also conjecture that the number of users who enjoy NFC services on their smartphone (thus, will enable NFC) will keep on increasing.

Finally, the third assumption also limits the opportunities of successful attacks; i.e., even if a smartphone approaches a ToT, the attack will fail if the smartphone’s screen is locked: Android OS will not invoke functionalities recorded in the NDEF record when the screen is locked. To verify the attack feasibility, we analyzed two types of ToT, a simple ToT and ToT device. Since a simple ToT can be disseminated as a small thing with an NFC tag attached, the attacker can easily produce a large number of ToTs with a reasonable cost. Thus, a simple ToT has high affinity with mass attack; producing more ToTs will
Table 2: Results of the Touch scatterer attack. The direction of the scattering patterns is defined when a screen is set in portrait mode.

| Device             | Manufacture | Success false touches | Frequency [kHz] | Voltage [Vpp] | Success attack rates | Scattering patterns |
|--------------------|-------------|-----------------------|-----------------|--------------|----------------------|---------------------|
| Nexus 7            | ASUS        | ✓                     | 128.2           | 40.0         | 18/30                | vertical            |
| ARROWS NX F-05F    | FUJITSU     | —                     | —               | —            | —                    | —                   |
| Nexus 9            | HTC         | ✓                     | 280.9           | 490.0        | 0/10                 | horizontal          |
| Galaxy S6 edge     | SAMSUNG     | ✓                     | —               | —            | —                    | —                   |
| Galaxy S4          | SAMSUNG     | ✓                     | 384.5           | 70.4         | 13/30                | horizontal          |
| AQUOS ZETA SH-04F  | SHARP       | ✓                     | 202.0           | 700.0        | 0/10                 | horizontal          |
| Xperia Z4          | SONY        | ✓                     | 218.0           | 340.0        | 20/30                | horizontal          |

increase the expected number of successes even if the probability of each attack is small.

In contrast, it will not be easy for an attacker to install ToT device in many places due to the cost issues. The key success factor of ToT devices is attributed to the patterns of human behavior. Many people use smartphones while eating food or drinking coffee. If the attacker installs a table-type ToT device in an eatery or a coffeehouse, the probability of the ToT device encountering a smartphone placed on the table with the screen unlocked is high. There are other situations when a person places a smartphone on a desk or a table without locking the screen. If such a table is installed at a public space such as library, many people will use the table in a day. Of these, there will be several who own NFC-enabled Android phones and place it on the table without unlocking the screen, i.e., the expectation value of the number of successful attacks becomes high. The malicious table will keep waiting for new victims as long as power is supplied. In our future work, we plan to conduct field studies to quantify the correlation between human behavior patterns and the success of an attack.

### 7.2 Countermeasures

We now discuss possible countermeasures against the threat of ToT attacks. We divide the discussion into three groups according to three points of view.

**mobile OS:** The simplest and the most effective defense is to add/improve the user approval processes before the mobile OS launches applications recorded in a tag. For instance, by forcing to request user approval for all NFC-driven operations shown in Table 1, we can eliminate the threats of a simple ToT that leverages the single-shot attack, which targets operations that do not require approval. Even when the attacker uses a ToT device, showing a proper message will decrease the chances of attack success. To this end, mobile OS vendors should change the format of messages associated with NDEF records. By explicitly presenting the reason why an operation is invoked, it is possible to create a message format that makes it impossible to generate deceptive messages.

Making the user approval process more rigorous could sacrifice the usability of NFC-powered services. To solve this problem, we can leverage the context of NFC touch events. This has been explored by Czeskis et al. [4], who developed techniques to achieve context-aware communication for RFID tags and contact-less cards. Their key idea was to leverage the built-in accelerometer, which can be used to implement activity recognition techniques to infer whether or not the holder of the tag physically moves her/his hands, e.g., tap the tag against the reader. We can use a similar technique to distinguish legitimate touch events from the false events generated by a ToT. Smartphones have other sensors that can be used to infer the context of touch events, e.g., proximity sensor and illuminance sensor. If the
smartphone infers that the context is likely an attack, the level of user approval can be increased to give priority to security; otherwise, the level of user approval is decreased to give priority to usability. Likewise, if a smartphone infers from sensor data that it is likely to be inside a pocket, it can automatically lock the screen to prevent the device from reading NFC tags unintentionally.

Smartphone hardware: While conducting the experiments described Section 6, we noted that some touchscreen controllers stopped working when a strong electric field was applied. Although these observations are not conclusive, we conjecture that the manufacturers of these controllers may have installed mechanisms to stop the controllers upon detection of external noises. In fact, as Ref. 18 reported, manufacturers of touchscreen controllers have developed techniques for dealing with the noise that can interfere with capacitive touch sensing. Incorporating such mechanisms will lead to eliminating the threats of touch scatterer. In addition, as Kune et al. proposed in Ref. 19, there are several analog/digital countermeasures against intentional EMI attacks, e.g., a filter that attenuates external noise signals and signal processing to eliminate anomalous inputs. These techniques will also be useful as countermeasures against the threats of Phantom touch generator. In Section 5, we also demonstrated that design of mounting the NFC controller on the front side of the smartphone makes generating false touch attacks easy. To defend against the threat of such attacks, mounting the NFC controller on the back is more desirable.

Things: It is almost impossible to visually detect a ToT because NFC tags are embedded into physical things. However, there may be situations where law enforcement agencies want to inspect tables inside a building to investigate whether a ToT has been installed. An active probe that searches for NFC tags should be developed to make this task easier. For this purpose, it is also possible to build a ToT honeypot that behaves as an NFC-enabled smartphone. The drawback of this approach is that it is not scalable because the practical working distance range of NFC is at most about 4 cm. Further research is needed to shed more light on this problem.

8 Related Work

Attacks using NFC tags: There have been several studies on the threats of attacks using NFC technology [24, 23, 27, 22, 28, 9]. Miller [22] reported that malicious NFC tags can attack browser exploits and NFC stack bugs that existed at the time. Gold et al. [9] demonstrated a phishing attack that uses a smart poster with malicious NFC tag attached. The accessed website prompts users to log in to a fake SNS site. They also demonstrated that an attacker can write a malicious file to the victim’s device by using the peer-to-peer mode of NFC. Wall of Sheep [28] demonstrated the experiment using NFC tags attached to smart posters and buttons at the DEFCON venue. At the venue, they put posters that say “Find a Wall of Sheep button and scan it with your NFC phone for exclusive discounts, tools and surprises every day.” They reported that about 50 attendees scanned the NFC tags that “could” have been malicious tags. These studies assumed that an attacker can come close enough to a victim, or the victim intentionally reads the malicious NFC tag by using posters or other existing facilities. The threat model is different from the one for ToT; an attacker injects malicious NFC tags into common objects.

RFID tags: NFC is a specialized subset within the family of radio frequency identification (RFID) technology. Several researchers have studied the risk of RFID tags that can be attached to various things [2, 17]. Baldini et al. [2] reported the application of RFID tags in the retail sector and discussed associated privacy issues and countermeasures. Juels published a survey paper on the research of privacy and security of RFID [17]. The survey examined the privacy protection mechanisms and integrity assurance in RFID systems. In the paper, Juels mentioned the importance of user perception of security and privacy in RFID systems as users cannot see RF emissions. The indication is closely related the problem we addressed in this paper.
The absence of user perception in RFID systems leads to the “relay attack,” which enables an attacker to set up a link between the reader and the contactless card without the agreement of the owner. Several countermeasures against the relay attack on RFID systems have been studied [14, 4, 8, 21]. As we discussed in Section 7, the techniques used as the countermeasures against relay attack, such as context-aware communication, can be useful to tackle the threats of ToT.

Attacks on touchscreen: There have been many studies on the side-channel attacks on touchscreens (LCDs); Aviv et al. [1] used smudge left on the screen to infer a graphical password, Maggi et al. [29] used the data collected from a surveillance camera to recognize keystrokes of a victim, and Hayashi et al. [13] used electromagnetic emanation to reconstruct a victim’s tablet display. To the best of our knowledge, while these attacks passively steal data from the touchscreen, our Phantom touch generator is the first attack that actively radiates signals toward touchscreen to cause targeted malfunctions.

9 Conclusion

We introduced a novel proof-of-concept attack named ToT, which targets NFC-enabled smartphones. The key concept of ToT is to inject malicious functionalities into common objects, which are not considered as NFC touchpoints. We believe that this concept sheds new light on the security research of mobile/IoT devices. To fully explore the threats of ToT attacks, we developed two effective techniques: ToT device and Phantom touch generator, which enable an attacker to carry out various severe and sophisticated attacks without being perceived by the device owner who unintentionally puts the device close to a ToT. Through the extensive experiments using off-the-shelf smartphones, we demonstrated that the proposed attacks work in practice. Although our attack is a proof-of-concept, we provide possible countermeasures that will thwart the threats. We hope that our paper will be a catalyst to further enhance the security of NFC-powered smartphones.

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A Supplemental data.

In this section, we provide supplemental data that are omitted in the main body of the paper due to the space limitation.
Table 3: Results of Feasibility Studies

| Device               | Manufacture | Android Version | Maximum Reading Distance [cm] | NFC R/W Activated in Factory State | Message Type (Wi-Fi) | Message Type (Bluetooth) |
|----------------------|-------------|-----------------|-------------------------------|------------------------------------|----------------------|----------------------------|
| ONE TOUCH IDOL 2 S   | ALCATEL     | 4.3             | 3.0                           | —                                  | —                    | BT-EN-1                    |
| Nexus 7              | ASUS        | 6.0.1           | 4.0                           | ✓                                  | WI-EN-1              | BT-EN-1                    |
| SAMURAI KIWAMI       | FREETEL     | 5.1             | 3.0                           | —                                  | WI-EN-1              | BT-EN-1                    |
| ARROWS NX F-05F      | FUJITSU     | 5.0.2           | 4.0                           | ✓                                  | WI-EN-1              | BT-EN-1                    |
| Nexus 9              | HTC         | 7.0             | 4.5                           | ✓                                  | WI-EN-1              | BT-EN-1                    |
| INFOBAR A02          | HTC         | 4.1.1           | 2.5                           | —                                  | —                    | BT-EN-1                    |
| Ascend P7            | HUAWEI      | 4.4.2           | 3.5                           | ✓                                  | —                    | BT-EN-4                    |
| TORQUE G02           | KYOCERA     | 5.1             | 3.5                           | ✓                                  | WI-EN-1              | BT-EN-1                    |
| TORQUE G01           | KYOCERA     | 4.4.2           | 3.5                           | ✓                                  | —                    | BT-EN-1                    |
| Nexus 5X             | LG          | 6.0             | 4.5                           | ✓                                  | WI-EN-1              | BT-EN-1                    |
| isai vivid           | LG          | 5.1             | 5.0                           | ✓                                  | WI-EN-2              | BT-EN-2                    |
| DM-01G               | LG          | 5.0.2           | 5.0                           | —                                  | WI-EN-2              | BT-EN-2                    |
| ELUGA P              | PANASONIC   | 4.2.2           | 2.0                           | —                                  | —                    | BT-EN-1                    |
| Galaxy S7 edge       | SAMSUNG     | 6.0.1           | 3.0                           | ✓                                  | WI-EN-1              | BT-EN-5                    |
| Galaxy S6 edge       | SAMSUNG     | 6.0.1           | 2.0                           | ✓                                  | WI-EN-1              | BT-EN-5                    |
| Galaxy S4            | SAMSUNG     | 5.0.1           | 3.0                           | —                                  | WI-EN-1              | BT-EN-5                    |
| AQUOS ZETA SH-01H    | SHARP       | 5.1.1           | 3.5                           | ✓                                  | WI-EN-1              | BT-EN-1                    |
| AQUOS ZETA SH-04F    | SHARP       | 5.0.2           | 3.5                           | ✓                                  | WI-EN-1              | BT-EN-1                    |
| AQUOS SERIE          | SHARP       | 5.0.2           | 3.0                           | ✓                                  | WI-EN-1              | BT-EN-1                    |
| Xperia XZ            | SONY        | 7.0             | 3.0                           | ✓                                  | WI-EN-1              | BT-EN-3                    |
| Xperia Z5            | SONY        | 6.0             | 3.0                           | ✓                                  | WI-EN-1              | BT-EN-3                    |
| Xperia Z4            | SONY        | 6.0             | 4.0                           | ✓                                  | WI-EN-1              | BT-EN-3                    |
| Xperia Z3            | SONY        | 5.0.2           | 3.0                           | ✓                                  | WI-EN-3              | BT-EN-3                    |
| Xperia Z2            | SONY        | 5.0.2           | 2.5                           | —                                  | WI-EN-3              | BT-EN-3                    |

Table 4: List of confirmation messages invoked by the WiFiConfig record

| Type  | Title                  | Message                              | Positive Button | Negative Button |
|-------|------------------------|--------------------------------------|-----------------|-----------------|
| WI-EN-1 | Connect to network    | Connect to network <SSID>?           | CONNECT         | CANCEL          |
| WI-EN-2 | Connect               | Connect to <SSID>?                   | YES             | NO              |
| WI-EN-3 | <SSID>                | Connect to this network?             | CONNECT         | CANCEL          |

Table 5: List of confirmation messages invoked by the BTSSP record

| Type  | Title                  | Message                              | Positive Button | Negative Button |
|-------|------------------------|--------------------------------------|-----------------|-----------------|
| BT-EN-1 | —                      | Are you sure you want to pair the Bluetooth device ? | YES             | NO              |
| BT-EN-2 | —                      | Bluetooth pairing requested. Pair?    | YES             | NO              |
| BT-EN-3 | —                      | Pair with [name]?                    | YES             | NO              |
| BT-EN-4 | NFC pairing request   | Pair with the Bluetooth device ?     | Pair            | Cancel          |
| BT-EN-5 | —                      | Pair the Bluetooth device ?          | YES             | NO              |
Figure 14: Wi-Fi connection dialog box (normal).

Figure 15: Wi-Fi connection dialog box (attacked).

Figure 16: Wi-Fi connection dialog box (dimmed using Screen Filter app).

Figure 17: Wi-Fi connection dialog box (customized for Xperia Z3).

Figure 18: Wi-Fi connection dialog box (attack using Dropbox app).

Figure 19: Wi-Fi connection dialog box (attack using Facebook app).