Lightweight Display-to-device Communication Using Electromagnetic Radiation and FM Radio

ZHICE YANG, ShanghaiTech University and Hong Kong University of Science and Technology
JIANSONG ZHANG, Alibaba Group
ZEYU WANG, Hong Kong University of Science and Technology
QIAN ZHANG, Hong Kong University of Science and Technology

This paper presents Shadow, a novel display-to-device communication system working in radio frequency. It leverages Electromagnetic Radiation (EMR) signals emanating from displays to transmit information. Specifically, Shadow modulates the high-frequency electric signals flowing in the display interface and makes the leaked EMR signals fall into the FM band. In this way, nearby mobile devices can receive information from the display through FM receivers. Compared with other display-to-device communication approaches, Shadow does not rely on cameras, and is thus more lightweight and requires fewer user actions. Furthermore, Shadow's transmissions do not incur any degradation in the display quality, as they only take place in the Blanking Interval, which will not be shown on the display panel. Shadow requires no modification to existing hardware. The prototype is implemented with commodity display systems and mobile devices. Results show that it can achieve 1.5 kbps at distances of up to 20 cm from the display panel.

CCS Concepts: •**Hardware** →**Displays and imagers; Wireless devices;** •**Human-centered computing** →*Mobile devices;*

Additional Key Words and Phrases: Display; Electromagnetic Radiation; Mobile Devices; Blanking Interval;

ACM Reference format:
Zhice Yang, Jiansong Zhang, Zeyu Wang, and Qian Zhang. 2018. Lightweight Display-to-device Communication Using Electromagnetic Radiation and FM Radio. *PACM Interact. Mob. Wearable Ubiquitous Technol.* 2, 1, Article 49 (March 2018), 19 pages.
DOI: 10.1145/3191781

1 INTRODUCTION

It is well known that the human brain recalls pictures more easily and frequently than text concepts [23]. This probably explains why there are more and more displays showing appealing images and video clips everywhere, for the purpose of quickly attracting people's attention and delivering information − displays are becoming the primary source for people to receive information. The side effect of this efficient visual-based information delivery fashion is that, usually we also need a device to receive additional (usually text) content when we are attracted by some visual content on displays. For example, we may want to learn detailed product information or item/place introductions when we are attracted by video/image ads, but this (text) content is too bulky to show on displays and also too dense to remember for viewers.

DOI: 10.1145/3191781

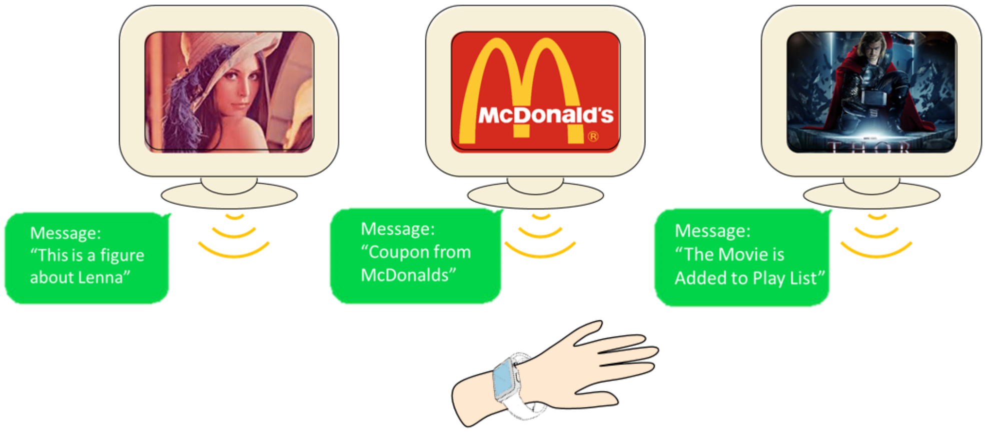


Fig. 1. **Display to Device Communication.** We envision an ideal way to fetch information from displays should follow such a path. The display keeps broadcasting the information related to its visual content, and the user receives the information when he/she takes a simple action to get his/her device close to the display panel. There are no cumbersome actions, and no special hardware requirements.

Devices today mainly rely on the display-to-camera channel to receive information from displays. Specifically, the display content reserves an area for device-friendly content, *e.g.*, the QR code, and the device uses its camera to capture that area and decode for a redirect link, *e.g.*, a URL. The URL in turn is used to fetch additional content from an external source, *e.g.*, the Internet.

However, despite its popularity, display-to-camera channels actually require complicated user actions, *i.e.*, from taking a phone out of a pocket, launching certain Apps, aiming the phone at the code area, to holding the aiming posture for a while. Some are even cumbersome, for example, scanning QR code requires the user to aim a camera at the QR code and adjust the distance/orientation in a fine-grained manner to match different code sizes/types as well as lighting conditions. These complicated actions incur unfriendly barriers for interaction and potentially discourage the elderly, the visually impaired and many other people from using the related applications. Moreover, since display-to-device channels rely on cameras, many popular devices without a camera such as wearables are not able to use them.

In our vision, as Figure 1 shows, an ideal display-to-device channel should be lightweight and have the following properties. First, *convenient to use*. It should involve fewer user actions. Being able to approximately point the mobile receiver to the display is more convenient than accurate aiming. Invoking wearables like wristbands and smart watches to receive is far more convenient than having to take a phone out of a bag or pocket to receive. Second, *easy to deploy*. It should avoid hardware modification to displays and also be compatible with most mobile devices. Third, *invisible*. Since the most important functionality of a display is the visual viewing, its communication ability should not degrade/affect the display quality. As for the most stringent requirement, the communication should be entirely invisible.

Installing a Bluetooth or Wi-Fi transmitter on displays to broadcast the content seems a potential solution. However, since we may expect the additional content is to be related to, or even highly coupled with the visual content, *e.g.*, synchronized audio tracks or subtitles, there is no ready solution to bridge the radio and the display content. Further, upgrading existing displays to have radio abilities also means considerable cost.

To this end, we propose a novel display-to-device communication system called Shadow. Shadow's communication channel is based on the basic property of electric current – *changing electric current generates ElectroMagnetic Radiation* (EMR). Shadow leverages the EMR signals emanated from the display cable and the VGA interface as the radio source to wirelessly convey information. Importantly, Shadow modulates the EMR signals in a way that can be received by the Frequency Modulation (FM) radio, which is widely available in mobile devices.

Shadow satisfies all the above properties for a lightweight display-to-device communication method. First, Shadow is convenient to use. It only requires the user to move his/her device close to the display, then the device can automatically receive the additional content from the display. Shadow can even be compatible with wearable devices because FM radio is integrated in most Wi-Fi and Bluetooth chips [2]. Second, Shadow is easy to deploy. It does not require any hardware modification to displays or mobile devices, and can be deployed with a software upgrade. Third, Shadow's communication is truly invisible, because it only makes use of the display signals in the *Blanking Interval*, which will generate EMR signals but will not be shown on the display panel.

Shadow represents a complete communication system. In this paper, we first conduct systematic studies on the feasibility of establishing FM communication between displays and devices with the EMR signal (§3.1). Results reveal special communication challenges in handling interference from severe harmonics. Then, to solve these problems, instead of using legacy FM modulation, we propose a modulation scheme, called Frequency Over Shift Keying (FOSK), to fully realize Shadow's communication idea in practice (§3.2). To ease the deployment of Shadow in today's display systems, we develop a middle layer to manage the communication function in the current display stack (§3.3).

We implement Shadow's transmitter with commodity PCs and develop receiver Apps for both smart phones and smart watches. To sum up, we have made the following contributions:

- We design a novel display-to-device communication method based on modulating EMR signals for FM receiving. To the best of our knowledge, we are the first to realize this in commercial devices without modification to device hardware or original display content.
- We conduct thorough feasibility studies of using display EMR signals for communication. The prototype system demonstrates that it can achieve 1.5 kbps at a distance of up to 20 cm.
- We propose a truly invisible display-to-device channel by modulating the display signals in the Blanking Interval. Shadow is the first work that introduces the Blanking Interval for wireless transmission.

2 OVERVIEW

In this section, we first introduce the basis of Shadow's design, including the display interface EMR, and the FM radio of a mobile device. After that, we introduce the idea of Shadow.

2.1 EMR from Display Interface

EMR is a common phenomenon of electric circuits. Basically, changing electric current generates electromagnetic signals which radiate out into nearby space. EMR causes interference to nearby electric circuits, therefore should be avoided if possible. However, despite various circuit techniques (*e.g.*, shielding, coupling [4]) developed for eliminating EMR interference, EMR is not entirely avoidable with practical constraints of electrical devices such as cost, form factor, *etc.* In practice, the industry relies on regulations and Electromagnetic Compatibility (EMC) tests to prevent the severe impact of EMR [4].

The design proposed in this paper is based on two observations: first, *the EMR from the display interface can be detected within a certain distance.* Display panels rely on the display interface including VGA, DVI, *etc.* to receive display content generated by graphics modules. The high frequency electric current conveying the color information of each pixel of the display panel flows through cables and connectors. The corresponding EMR, though largely attenuated by EMC means, still results in a detectable leakage within tens of centimeters or even meters away. Figure 2 shows the EMR around a normal display panel. Similar observations have also been reported in the literature. For example, [26] reports an eavesdropping technique which snoops on display content by analyzing the EMR from the display interface.

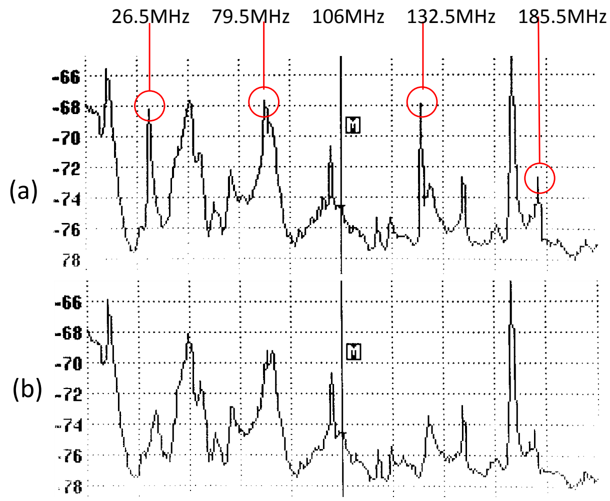


Fig. 2. **Spectrum of EMR from the Display Interface.** The horizontal axis is in units of 20 MHz and its center is at 106 MHz. The vertical axis is in units of 2 dBm. Results are measured 20 cm in front an LCD with a VGA interface. When the display content shows black-white striped vertical lines, 2 pixels in wide, its spectrum (a) shows obvious RF power peaks in certain frequencies compared with the case showing a full-screen black figure (b).

The second observation is that *the EMR from the display interface and the display content are highly correlated.* As a general rule of industrial standard, an image frame with a 2D matrix of values representing the intensity of the pixels is transmitted to the display panel serially with the raster scan order (see the arrows in Figure. 3)[1]. As Figure 3 shows, a greyscale image frame (a matrix of intensity values I_{ij}) to be displayed is first serialized to a data sequence I_k according to the raster scan order, and then transmitted to the display panel through the display interface. In VGA interface [2], I_k is amplitude modulated, *i.e.*, the voltage of the signal $d(t_k)$ is linearly related to the intensity I_k. Importantly, since the EMR is emanated by $d(t)$, it can be determined by the display content I_k.

From the viewpoint of communication, the display interface converts a sequence of digital values I_k to an analog signal $d(t)$, which is exactly what a Digital-to-analog Converter (DAC) does in an RF transmitter. Therefore, by considering how fast I_k are transformed into analog signals, we can flexibly generate $d(t)$ and its EMR signals with appropriate display content I_{ij}.

2.2 Frequency Modulation Radio

FM broadcasting is a popular way of broadcasting audio (*e.g.*, music, news.). As the name suggests, FM broadcasting uses frequency modulation (FM) to modulate RF signals. Frequency modulation linearly maps the instant amplitude of a message signal $m(t)$ to the frequency deviation of the carrier wave $\cos(2\pi f_c t)$:

$$\texttt{fmmod}(m(t), f_c) = \cos(2\pi \int_0^t (f_c + f_\Delta m(\tau))d\tau) \tag{1}$$

On the contrary, an FM receiver obtains $m(t)$ by mapping the frequency deviation of the received signal to the amplitude (Figure 4).

Due to the simplicity of decoding and many beneficial functionalities, the FM receiver has been widely used in vehicles and the home for decades. It is also widely integrated in modern wireless transceivers [2] and most

[1]For a chromatic image, the value of a pixel contains the intensity of red, green and blue.

[2]DVI and HDMI use different encoding schemes. Nevertheless, their EMR is also related to the display content. More details are discussed in section 7.

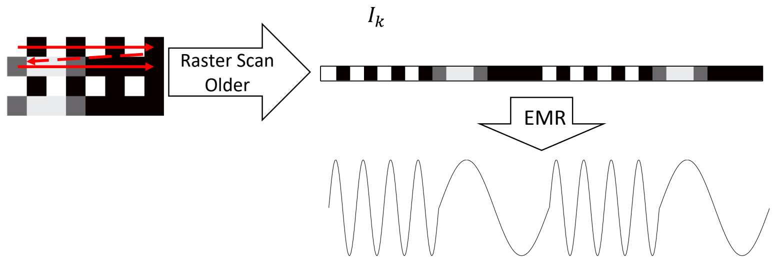


Fig. 3. **Display EMR and Display Content are Highly Correlated.** Consider transmitting 8 Pixels × 4 Pixels to a "mini" screen through VGA interface. The intensity of the display EMR is linearly correlated to the intensity of the display content. As a result, pixels with different black-white spacing generate EMR signals with different frequencies.

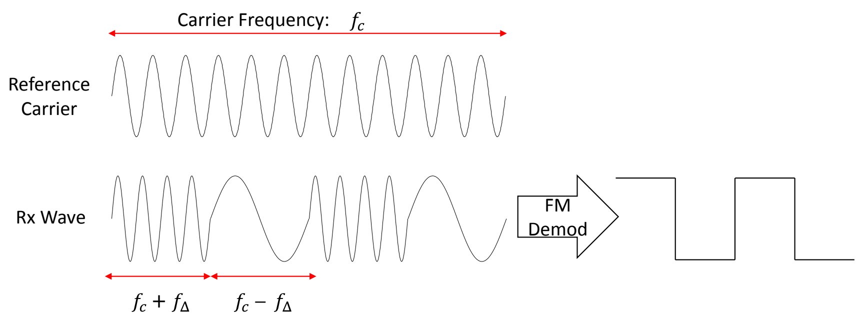


Fig. 4. **Decoding the FM Signal.** The FM decoder maps the frequency deviation f_Δ from the carrier frequency f_c to the amplitude of its output signal.

of our mobile devices such as smart phones (iPhone 6s [8]) and wearables (Apple Watch, Google Glass [6], *etc.*) have the hardware to decode FM radio [3].

2.3 Shadow – the RF Solution for Display-to-device Communication

Shadow's design is based on the fact that the display EMR can be controlled by the display content and mobile devices can receive FM signals. The idea is obvious when jointly considering Figure 3 and Figure 4. We can modulate the display EMR to an FM channel through well-organized display content. Mobile devices can then extract information from the EMR signals through their FM receivers.

Let us look at an example, if we want to transmit a "1010" message from the display to the mobile device, the corresponding image frame for display is shown on the left-hand side of Figure 3. In real displays, which have much denser pixels, the transmitted EMR wave is able to convey sufficient information like a URL. Note that Shadow can also change the display content dynamically to deliver information continuously, *e.g.*, play an audio stream.

One concern is that modifications to display signals may also modify the original display content and degrade the viewing experience. Shadow eliminates this side effect by only modifying a special period in the display signals – the Blanking Interval, which will generate EMR but will not be visually displayed.

[3]In some phone models, the FM ability is hidden, but it can be deliberately enabled.

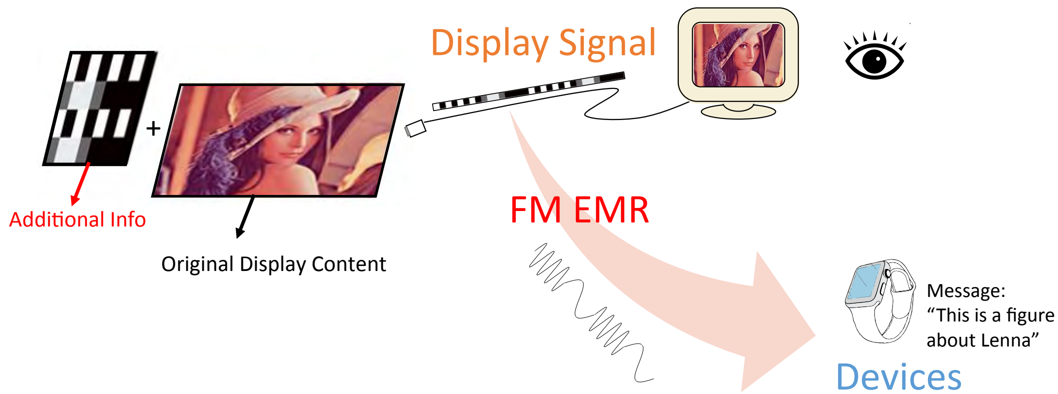


Fig. 5. **Shadow Enables Lightweight Display-to-device Communication with EMR from Display Interface**. Shadow transmitter modulates display signals to generate EMR signals in an FM channel. User devices including wearables can receive information from the display by simply approaching the display and decoding the EMR signals with their FM radio. To keep the original display quality, the modification on the display signals only happens in the *Blanking Interval*, which will not be shown on the display panel.

In this way, Shadow enables a new form of display-to-device communication. As shown in Figure 5, when people with their mobile phones or wearables approach the Shadow-enabled displays, additional information can be delivered to their devices. Moreover, as the signals for communication will not be shown, the display system maintains the original display quality.

3 SHADOW DESIGN

This section introduces Shadow's design to realize the above idea. The first subsection introduces our study on leveraging the display EMR for communication. Several interesting properties of the special communication channel are investigated and discussed. In the second subsection, we introduce our approach to hide the communication in the Blanking Interval. We identify the interference problem and propose our solution – FOSK modulation. The third subsection describes how we incorporate Shadow into current computer systems through a middle layer in the display stack.

3.1 Basic Communication Model

We first consider the general case that a message or a baseband signal $m(t)$ is to be transmitted from the display to the mobile device through the EMR signal $y_0(t)$. The information $m(t)$ can be carried by the EMR signal $y_0(t)$ via Frequency Modulation according to equation (1):

$$y_0(t) = \texttt{fmmod}(m(t), f_c). \tag{2}$$

To generate the EMR signal $y_0(t)$ through the display interface, the corresponding display content I_k should be filled into the display buffer of the graphic module. According to §2.1, I_k can be thought as time-domain samples of $y_0(t)$:

$$I_k = y_0(t_k) = y_0(k/f_s), \tag{3}$$

where k is the index of the sample, and f_s is the sampling rate. In the display interface, f_s represents how fast each pixel is transmitted. It is a parameter determined by the display mode, *i.e.*, the display resolution and the

	Meaning	Typ.
w_t	total pixels per line	1904
w_r	visible pixels per line	1440
h_t	total pixels per column	932
h_r	visible pixels per column	900
f_l	line refresh rate	55.9 kHz
f_r	frame refresh rate	60 Hz
f_s	transmission rate of pixel	106.5 MHz
f_c	frequency of FM carrier wave	18 MHz
F_c	frequency of FM channel	88.5 MHz
f_Δ	Maximum frequency deviation of FM	75 kHz
f_B	Baud rate of Tx	$f_{rx}/20$
f_{rx}	Rx sampling frequency	44100 kHz

Table 1. Table of Notations

refresh rate. f_s can be calculated as: $f_s = w_t \times h_t \times f_r$. Then, with correct f_s, I_k can be calculated through equation (3). Filling I_k into the display buffer with raster scan order will generate $y_0(t)$ in the display interface.

Note that if the carrier frequency f_c of the EMR signal is tuned to one of the commercial FM channels, *e.g.*, F_c = 88.5 MHz, the FM receiver of a mobile device can receive $y_0(t)$ and decode for $m(t)$. As the output from the FM decoder, $m(t)$ is sampled by the device's audio Analog-to-Digital Converter (ADC) and recorded as digital samples like a normal audio signal.

In general, $m(t)$ can be any waveforms. When $m(t)$ is a binary signal like Figure 4, *i.e.*, it holds high/low voltage for a period of time $1/f_B$ to represent symbol "1"/"0", the corresponding EMR signal $y_0(t)$ has the simple form:

$$\texttt{symbol\_0}(t) = \cos(2\pi(f_c - f_\Delta)t) \tag{4}$$

$$\texttt{symbol\_1}(t) = \cos(2\pi(f_c + f_\Delta)t). \tag{5}$$

A high-frequency sine EMR signal (5) is used to transmit bit "1" and a low-frequency sine EMR signal (4) is used to transmit bit "0".

3.1.1 Raising Carrier Frequency with High-order Images. In practice, the sampling rate f_s spans in a wide range under different settings of resolution and refresh rate. For example, f_s in 1920×1200 60 Hz is 193 MHz, f_s in 1440×900 60 Hz is 106 MHz, In the latter case, f_s is not enough to represent the wave in FM band (87 MHz-107 MHz), because $f_s < 2f_c$.

We handle this problem by noticing that there is no low pass filter in the display interface like normal RF radios do. As a result, the analog signal generated by the DAC of the display interface is not smoothed and contains high frequency images of $y_0(t)$ [7, 10]. These aliases or images are shifted and reflected copies of the original signal $y_0(t)$. The frequencies of the images are $N \cdot f_s \pm f_c$, where N is a positive integer. A real example can be referred to Figure 2(a), where f_s=106 MHz and f_c=26.5 MHz. The frequency of $y_0(t)$ is f_c. The DAC result of I_k shows three images of $f_0(t)$ at $f_s - f_c$ = 79.5 MHz, $f_s + f_c$ = 132.5 MHz, and $2f_s - f_c$ = 185.5 MHz.

One beneficial property of the images is that they inherit the frequency modulation of the original signal. For example, if the frequency of $y_0(t)$ is increased by f_Δ, the frequency of the images with positive f_c will increase f_Δ and the images with negative f_c will decrease f_Δ. The negative cases can be treated as the positive ones with a negative sign. Therefore, if the baseband signal $m(t)$ is frequency modulated to $y_0(t)$, we can safely use one of the images of $y_0(t)$ to demodulate for $m(t)$.

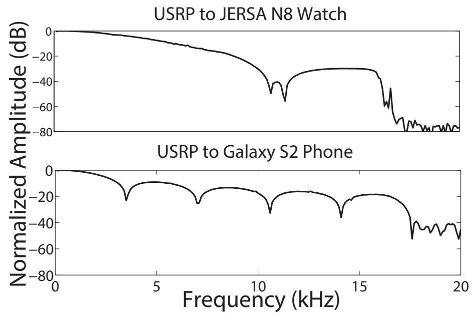


Fig. 6. **Frequency Response of FM Receivers.** In this test, $m(t)$ is a single tone. Its frequency keeps increasing and is shown in the x-axis. The response of the receiver at each frequency is shown in the y-axis.

Shadow leverages this property and uses the high-order images from the DAC output as the carrier wave for FM communication when f_s is not high enough. Shadow transmitter can always find a pair of f_c and N to let one image of $y_0(t)$ locate at a certain FM channel, *i.e.*, $F_c = N \cdot f_s \pm f_c$, to enable receiving on mobile devices.

3.1.2 Channel Properties. Shadow's display-to-device channel has different properties from existing discussions about acoustic channels and data communication over FM. In theory, the bandwidth of the baseband signal $m(t)$ is first limited to 22 kHz by the audio ADC. In practice, the bandwidth is also limited by the low pass filter in FM receivers. For mono FM audio, the passband is around 15 kHz. In addition to that, FM receivers leverage a deemphasis filter to suppress the high frequency components [20, 21], which further reduces the gain in high frequencies.

Figure 6 shows the channel response when receiving tones with different frequencies, *i.e.*, $m(t)$ is a sine signal with different frequencies. Note that the -3 dB power level is around 1 kHz to 2 kHz, which indicates high attenuation in frequencies higher than 2 kHz. According to this fact, we choose the baud rate $f_B = f_{rx}/20$, *i.e.*, around 2 kHz, for the baseband signal $m(t)$.

3.2 Hiding in the Blanking Interval

In the previous subsection, we assume that the entire display signal or all the available pixels are used to generate EMR for communication, which results in full-screen weird textures in the display panel and occupies space for normal display content. In this subsection, we introduce our method to eliminate this drawback.

The solution of Shadow is based on the observation that our additional information has no need to be visually shown for cameras to receive. Therefore, any signals that generate EMR but are not displayed should work. Interestingly, there indeed exists a special period in standard display signals that satisfies our requirements – *the Blanking Interval.*

As shown in Figure 7. Between the end of one line and the start of the next line, there is a period of time, during which the data signal is blank. It is called horizontal blanking interval (HBlank). Similarly, there is a vertical blanking interval (VBlank) between the data signal of two consequent frames. The Blanking Interval exists in different protocols such as VGA, DVI and HDMI. This is because it is reserved for historical reasons. In the past, it is mainly used to wait for the retrace of the electron beams in cathode ray tube (CRT) monitors. In modern digital monitors like LCD, the Blanking Interval is still transmitted but is not displayed. Therefore, modifying the signal in the Blanking Interval will generate EMR but will not result in any visual content.

3.2.1 The Windowing Interference Problem. In practice, as the VBlank is used to transmit configurations for display panels in some cases [18], we only consider the signals in HBlank. HBlank normally occupies 20% – 30% of the signal for one line [18]. If we only fill $y_0(t)$ into HBlank and let the remaining normal display signals

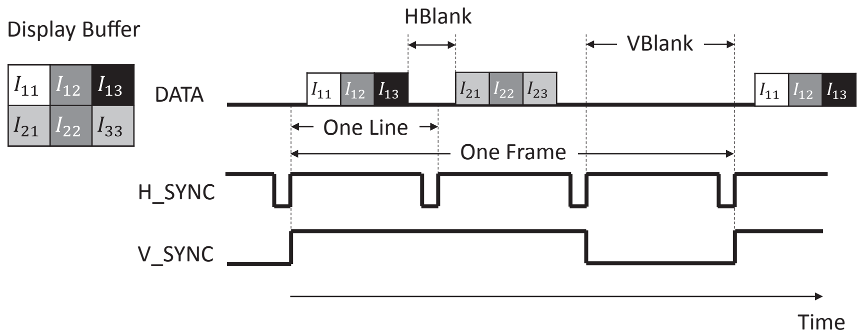


Fig. 7. **The Blanking Interval**. This example shows how a 3 pixels×2 pixels image frame is transmitted in VGA protocol. There exist blank intervals between successive lines (HBlank) and frames (VBlank).

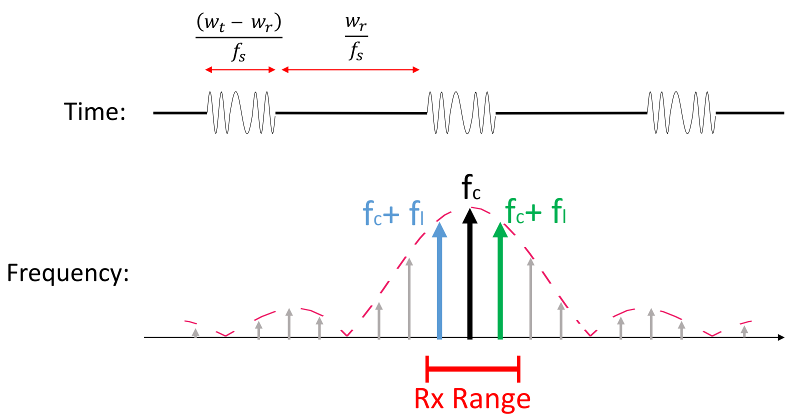


Fig. 8. **The Windowing Interference**. When we only use the display signals in the Blanking Interval for transmissions, this figure shows the time and frequency domain of the EMR signal from the view point of an FM receiver. Since FM receivers use very narrow input filter (to eliminate interchannel interference), only signals with frequencies close to the FM channel are left for FM demodulation. Normal display signals tend to have arbitrary frequencies, so are mostly filtered. As a result, the received signal looks like being windowed by a periodic square wave. Unfortunately, the harmonics caused by the windowing effect fall into the receiving range and cause interference.

unchanged, as shown in Figure 8, the EMR signals viewed from the FM receiver is noncontinuous in the time domain. It can be modeled as a product of $y_0(t)$ and a periodic square wave function:

$$y_1(t) = y_0(t) \cdot \texttt{square}(f_l, \frac{w_t - w_r}{w_t}). \tag{6}$$

$\frac{w_t - w_r}{w_t}$ and f_l are the duty cycle and the frequency of the periodic square wave respectively.

From the viewpoint of the FM receiver, as the frequencies of the normal display signals will not exactly fall into the narrow FM channel (around 200 kHz), the received EMR signals are almost blank except the portions in the Blanking Intervals, whose frequencies are modulated to the FM channel.

One side effect of the windowing function is the harmonics. According to the Fourier Transform, the spectrum of $y_1(t)$ consists of repeated copies of $y_0(t)$ at frequencies $f_c \pm N \cdot f_l$ with a sinc envelope, as shown in Figure 8. The harmonics cause interference when receiving with commercial FM receivers. In Figure 8, the interval between the harmonics is the line refresh rate f_l, which ranges from 30 kHz to 100 kHz in common resolution

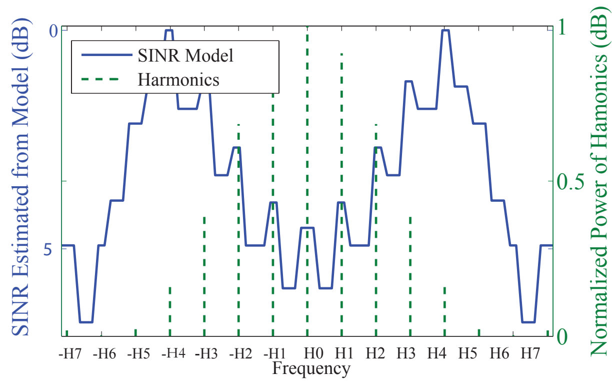


Fig. 9. **FM SINR Model**. A pure sine tone is transmitted in HBlank at frequency H_0. P_{H_i} is calculated with 1:6 duty cycle and f_l = 55.9 kHz. P_{Noise} is set to 10% of P_{H_0} according to our measurement. In this example, the frequency with the highest receiving SINR is around $\pm H_4$.

and refresh settings. However, the receiving range of FM receivers is around 200 kHz. Thus, there will be multiple harmonics fall into the receiving range. Recall that FM demodulation maps frequency deviations to amplitudes (§2), when multiple harmonics/frequencies occur, the FM decoder is confused to match multiple frequencies to one output amplitude.

3.2.2 Frequency Over Shift Keying. We model the impact of the harmonics according to their frequencies and intensities. When commercial FM receivers receive multiple FM stations, they handle the interchannel interference by estimating and recovering the strongest one [35]. Therefore, in the FM receiving range, we model the strongest harmonic as the one to be decoded by the FM module, and the others are treated as interference.

We use f_{H_i} to denote the frequency of harmonics: $f_{H_i} = f_c + i \cdot f_l$. The corresponding power is P_{H_i}. When receiving at frequency $f_\Delta + f_c$, the harmonics that the receiver can capture are: $H(f_\Delta) := \{H_i | f_c + f_\Delta$–100 kHz$< f_{H_i} < f_c + f_\Delta$+100 kHz$\}$. Then, we can define the FM receiving SINR at the receiving frequency f_Δ as:

$$SINR(f_\Delta) = \frac{\max_{k \in H} P_k}{P_{Noise} + \sum_{k \in H} P_k - \max_{k \in H} P_k} \tag{7}$$

We plot the SINR model in Figure 9.

The following observations can be obtained from the SINR model. First, a counterintuitive fact is that the best frequency for FM receiving is not at f_c, where the Tx signal has the maximum power. This is because the sinc envelop is relatively flat at the center, so the interfering harmonics are also strong. Second, in the regions having the highest SINR, the signals for FM decoding are not contributed by the nearest harmonics. For example, when receiving at H_4, the receiver only decodes harmonic H_3 since it has the highest power in the receiving range $[f_{H_4}-100$ kHz, $f_{H_4}+100$ kHz$]$.

To improve the FM receiving SINR under the windowing interference, one option is to receive at frequencies having the highest SINR, *e.g.*, at H_4 in Figure 9. However, as the real effective Rx signal H_3 is located at the margin of the receiving range $[f_{H_4}-100$ kHz, $f_{H_4}+100$ kHz$]$, the frequency deviations of the FM signals are quite limited (to prevent the signals from falling out of the receiving range). As a result, since the frequency deviation in FM is mapped to the amplitude of the baseband signal $m(t)$, the limited range in frequency deviation, in turn, limits the signal strength and also the SNR of $m(t)$.

Therefore, instead of using traditional frequency modulation, Shadow introduces a novel modulation scheme – Frequency Over Shift Keying (FOSK) to take advantage of the harmonics with high FM receiving SINR and

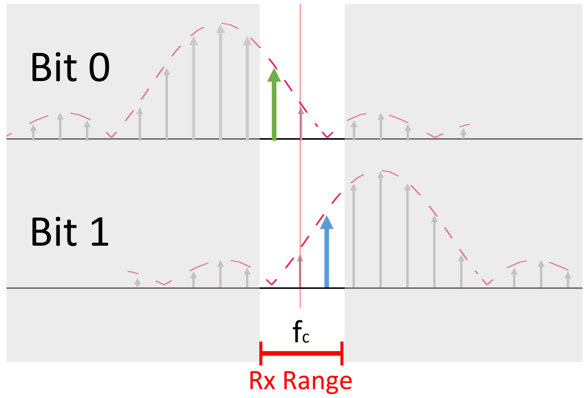


Fig. 10. **Illustration of FOSK**. Instead of using small frequency deviations of the FM carrier wave to convey information. Carrier wave in FOSK is over shifted so that the harmonics with the highest SINR can be used to represent symbols.

also keep the frequency deviation as large as possible. The example in Figure 10 is used to explain FOSK. The receiver is still receiving at f_c. We first obtain the frequency f_Δ^b which has the highest FM SINR from model (7). Instead of shifting the carrier wave with small deviations, the carrier wave is shifted by f_Δ^b to represent symbol "1". Note that when the carrier wave is shifted by f_Δ^b, the strongest signal in the receiver's range is the harmonic $-H_2$, so the receiver falsely believes the harmonic is deviated from f_c, so the output amplitude is $f_c - 2f_l - (f_c - f_\Delta^b) = f_\Delta^b - 2f_l$. Similarly, we shift the carrier wave by $-f_\Delta^b$ to represent symbol "0", and its frequency deviation is $2f_l - f_\Delta^b$. The frequency difference between "1" and "0" is $2(f_\Delta^b - 2f_l)$, which is normally more than half of the Rx range and brings good SNR in $m(t)$.

The FOSK scheme can be summarized as below:

$$\texttt{symbol\_0}(t) = \cos(2\pi(f_c(t) - f_\Delta^b)t) \tag{8}$$

$$\texttt{symbol\_1}(t) = \cos(2\pi(f_c(t) + f_\Delta^b)t) \tag{9}$$

Compared with traditional frequency modulation (4)(5), the carrier wave in FOSK is over shifted (f_Δ^b is normally 3 or 4 times larger than f_Δ). But due to the existence of the harmonics, the real deviation is $f_\Delta^b - i \cdot f_l$, which is still within the FM receiving range. FOSK makes use of the harmonics to reduce the interference caused by the harmonics.

3.3 Decoupled Communication Plane

As there is no API in the current display stack to write in the Blanking Intervals. In this subsection, we first explain our method to control the signal in Blanking Interval. Then we present the *Blank Plane* in the display stack for accessing to the Blanking Interval. In this way, Shadow can be easily deployed in current display systems.

Our method basically relies on the difference in the working mechanisms of display controllers and monitors. Monitors determine the start and the end of the display content in the display signals according to the frequency of H_SYNC and V_SYNC signals (see Figure 7). When the frequency of H_SYNC is fixed, the start and the end of the display period are also fixed. On the other hand, the display controller can actually output data before and after the standard start and end of the display period. We take advantage of the flexibility of the display controller to modify signals outside of the standard display period, *i.e.*, to modify signals in the Blanking Intervals.

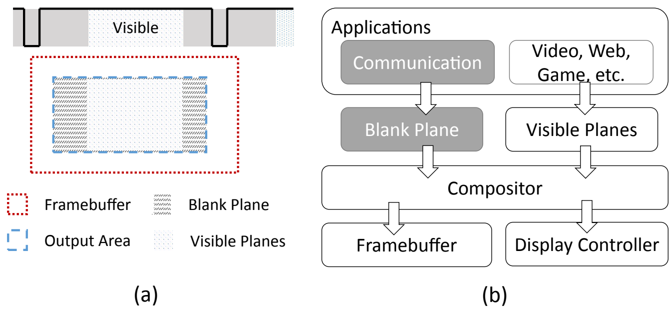


Fig. 11. **Blank Plane in the Display Stack**. Shadow uses the Blank Plane in the display stack to manage the access of the Blanking Interval.

Obviously, handling the above actions is cumbersome for normal applications. We abstract the access to the Blanking Period to a dedicated display plane called the Blank Plane, so that every application can access the Blanking Period as easy as “display something on the screen”. As shown in Figure 11, the Blank Plane abstracts a part of the display framebuffer. The compositor manages the whole framebuffer and allocates portions around the normal display area for the Blank Plane. These portions can be directly mapped to the Blanking Interval during the transmission of display content. The compositor takes care of the isolation between the Blank Plane and normal planes, *i.e.*, the content in the Blank Plane will not be displayed in the normal plane and vice versa. The compositor is also responsible for configuring the display controller to make sure that all the planes will be transmitted and the monitor will only display the normal planes.

The action to access the Blank Plane is the same as other planes. The application first sends a request to the compositor and tells the compositor about the content and the location to be displayed. If the location falls into the Blank Plane, the content of application will be stored to the framebuffer for the Black Plane.

4 IMPLEMENTATION

As an example of implementing Shadow in real display system, we choose Linux-based PCs with VGA-connected monitors. The Blanking Interval is managed through the Direct Rendering Manager (`DRM`) to coexist with desktop display servers such as X server and Wayland. We modified the compositor in Weston (an opensource implementation of Wayland). Specifically, 1. It allocates extra framebuffer for the Blank Plane. 2. It remaps the coordinates of the framebuffer to maintain correct display service for existing programs after introducing the Blank Plane. 3. It adjusts the timing of H_SYNC signal and increases the number of output pixels through DRM Mode Setting API `drmModeSetCrtc()`. 4. It handles the display request for the Blank Plane according to the display coordinates.

We implement an FM EMR encoder with C++. As the waveform of each symbol can be determined according to (8)(9), we store the pre-calculated wave in a looking-up-table (LUT). The data sequence I_k is generated by replacing “0” or “1” with the corresponding waveforms in the LUT.

The packet structure is shown in Figure 12. As we do not use the vertical blanking interval to transmit, the duration of one packet is just the time of one display frame. The preamble is used for packet detection and time synchronization like other communication systems. Its duration is $130/f_{rx}$, *i.e.*, 130 Rx samples. The pattern of the preamble is barker13 code. When the refresh rate of the display is 60 fps, there are 28 symbols in one packet.

We develop the receiver App for Samsung Galaxy S2 smartphone (Dual-Core 1.2 GHz Cortex-A9, 1 GB RAM) and JERSA N8 smart watch (MTK6572 Dual-Core 1.3 GHz, 512 MB RAM). They both run Android 4.4 operating system. Since the official Android API does not provide the interface to access the FM related functions, we

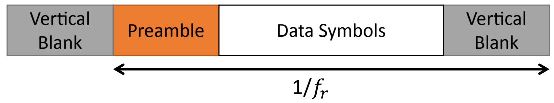


Fig. 12. **Packet Structure**

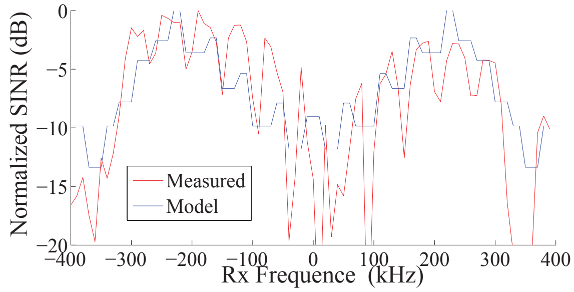


Fig. 13. **SINR Model**

implement our receiver based on third-party resources. For Sansumg Galaxy S2, our implementation is based on an opensource FM receiver [15]. As the JERSA N8 smart watch is based on MTK SoC, which is not supported in [15], we develop its FM receiver by referring to the firmware source code with similar chip model [9]. The decoding takes 7×10^{-6} s of the CPU time of our smart watch. Therefore, it should be is affordable for most mobile devices.

5 EVALUATION

In this section, we first validate the SINR model with real experiment and then provide the overall performance evaluation of Shadow.

5.1 The SINR model

Equation (7) models FM SINR at different frequencies shifted from f_c. In Figure 13, we compare the SINR from real measurements with the theoretical results calculated from (7). They have a very similar trend. Importantly, regions with high SINR in the model almost coincide with the real measurements, which indicates that our modulation design based on the SINR model is correct.

5.2 Overall Performance

We evaluate the overall performance of Shadow with settings shown in Figure 14. The smart phone and smart watch are connected to the earphone antenna during the evaluation. As shown in Figure 14 (b), to ease the control of the earphone antenna, we paste the cable of the earphone to a plastic stick. In this way, the orientation and location of the earphone antenna can be controlled through the stick. In Figure 14 (b), we also plot the coordinate system that we used in following descriptions. The display panel is on the y-z plane and the VGA cable is on the x-axis. In Figure 14 (c), we consider the feasibility of receiving with compact FM antenna by making the earphone twisted on the wrist.

The evaluation is designed to show the communication performance of Shadow under different settings. We configure the transmitter to send packets with random payload and increasing IDs. The ID of a packet is also the seed of the packet's random payload. We leverage the ID to help us identify the decoding errors. By default, each packet contains 28 bits, and the maximum throughput is 1.68 kbps.

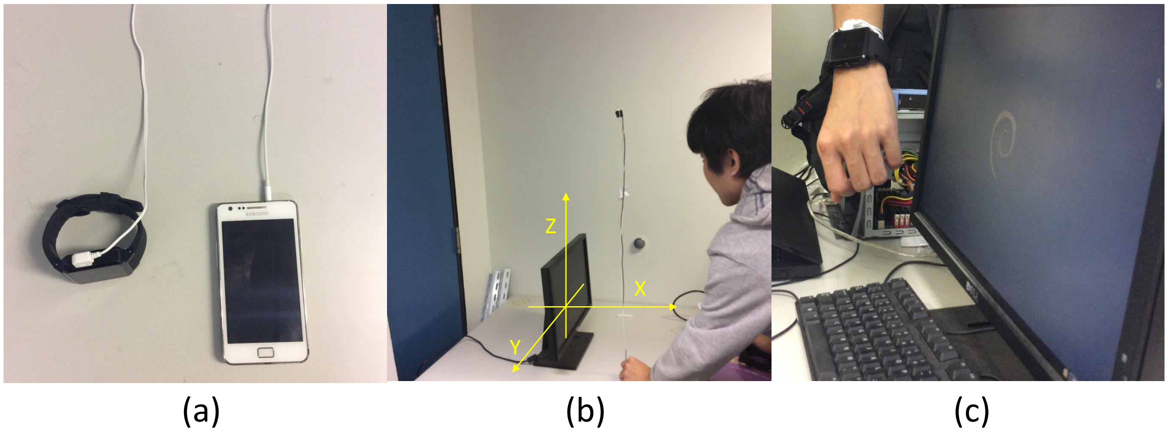


Fig. 14. **Evaluation Settings**. (a) Experiment Receivers. (b) Normal Settings. We use a coordinate system determined by the VGA line and the surface of the screen to describe the location relation. (c) The FM antenna is twisted to show the preliminary feasibility of using a compact FM antenna.

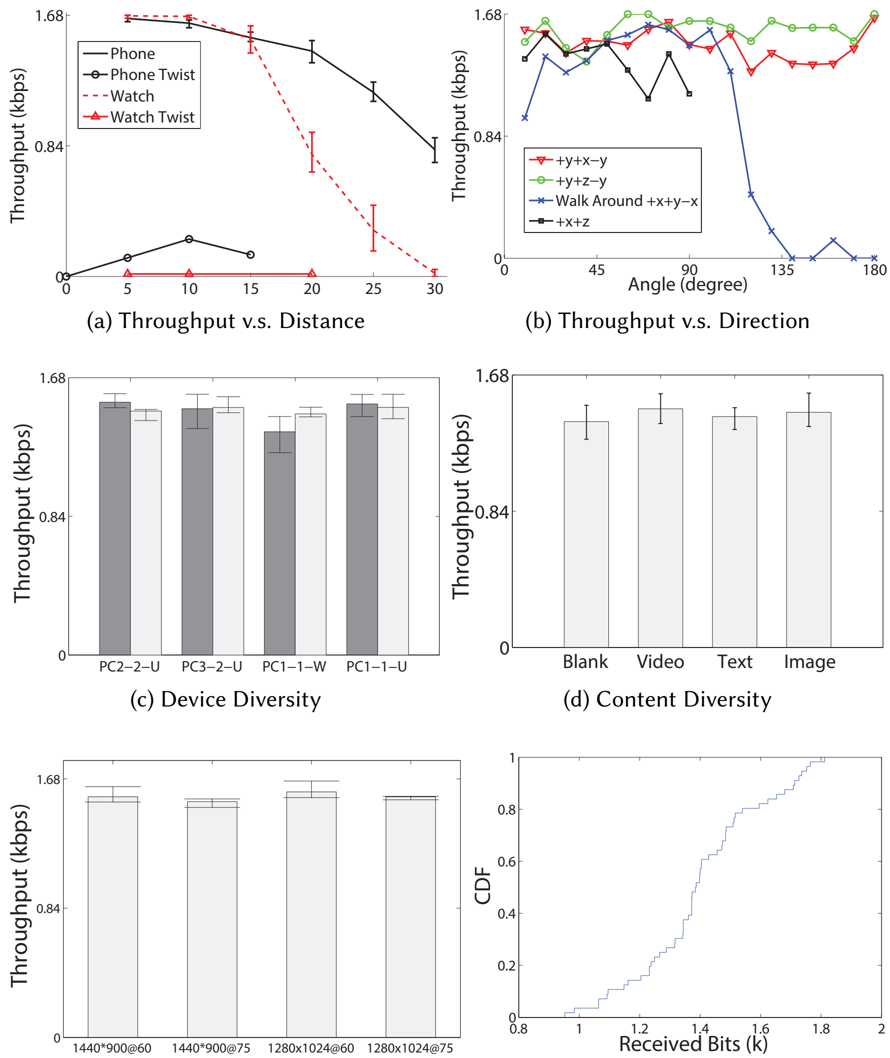
Exp1. Communication Distance. We move the mobile devices to the locations with different distances to the transmitter panel. The movement is in the +x direction in Figure 14 (b). During the movement, we keep the antenna towards the direction +z.

The results are shown in Figure15 (a). In general, the throughput decreases when the distance increases. This is because the EMR signal from the display interface attenuates with distance. Within the distance of 10 cm, both the mobile phone and the smart watch can achieve 1.6 kbps throughput, which is not only enough to transmit short messages such as a URL, but also enough to provide other features such as voice streaming, MIDI music, *etc.* In the range between 15 cm to 30 cm, the throughput of the watch decreases faster than that of the mobile phone. This is possibly caused by the small size of the device, which makes RF design harder than the mobile phone. The maximum communication distance of the watch is 30 cm and the value of the mobile phone is about 50 cm. For radio signals aground 100 MHz, anything less than 50 cm is still in the near field, where RF signal-strength drops much more quickly than in the far-field. Therefore, the distance is limited by the power of the EMR signal. To extend the distance, one direct method is to use more display signals or even the visual parts for communication. According to our measurement, when the entire display signal is used for communication, the distance can reach 1 meter. Therefore, when necessary, the communication distance of Shadow can be easily extended.

Another two curves near the x-axis are the throughput measured through the twisted antenna in Figure14 (c). The low throughput indicates that the FM antenna is a crucial factor for amplifying the FM signal. From the results of mobile phone, we can still observe several valid transmissions. We believe by leveraging professional compact FM antennas rather than our self-twisted one can significantly improve the receiving quality in compact devices (see the discussion in §7).

Exp2. Direction diversity. In real scenarios, users may approach the display from different directions. Even from the same direction, the antenna may have different orientations as well. In this experiment, we quantify the impact of the receiving directions. First, we fix the distance to the display panel to 15 cm and change the direction of the antenna to different directions. Second, we fix the distance to the display panel to 15 cm and walk around the display panel.

The results are shown in Figure15 (b). The axis labels are used to describe the rotation sequence. For example, +y+z-y means the antenna rotates along the x-axis. The three curves cover all the possible directions. The results



(a) Throughput v.s. Distance
(b) Throughput v.s. Direction
(c) Device Diversity
(d) Content Diversity
(e) Settings Diversity
(f) One Action Information

Fig. 15. Shadow overall evaluation

show the throughput of different directions is quite close. It means that we can obtain stable communication performance in front of the display without caring much about the antenna directions. However, when we walk around the display from its front to its back, the throughput decreases dramatically. This is probably caused by the directionality and the polarization of the EMR signals. The results imply that, in some cases, the receiver may not get good performance even the distance is close. In public places, the administrator can adopt multiple displays as transmitters to provide a better coverage.

Exp3. Device Diversity. We use three different PCs as transmitters and two different mobile devices as receivers to evaluate the performance of different devices. In this experiment, we fix the distance between the transmitter and receiver at 15 cm. The antenna's direction is +z.

The results are shown in Figure15 (c). The horizontal labels consist of three parts. The first part is the ID of the PC. The second part is the model of the PC. PC2 and PC3 are of the same model. The third part is the testing OS (U is short for Ubuntu and W is short for Windows 8.1). The two vertical bars represent two Rx devices. We can observe that there is no obvious performance difference between different transmitters and receivers. This is because Shadow is based on the display protocol which is independent of devices.

Exp4. Content Diversity. Different videos and images are used as normal display content to evaluate the impact of their EMR on communication. We choose four samples for display: 1) a full-screen black figure. 2) a random video from youtube. 3) a random wiki page and 4) a random full-screen image. In all the cases, the receiver's direction is unchanged and the distance is 15 cm.

The results are shown in Figure15 (d). There is no obvious difference between the four display samples. This is because the frequency of the normal display content is random, and the FM receiver is only sensitive to the frequencies in a very small range (see §3.2.1). Therefore, the normal display content can hardly affect the communication of Shadow.

Exp5. Diversity in Display Settings. We use different display settings, *i.e.*, resolutions and refresh rates, to evaluate our design. The receiver's antenna direction is unchanged and the distance is 15 cm.

The results are shown in Figure15 (e). We observe no obvious difference under different display settings. We explain it in two cases. First, when the display uses the same refresh rate, different resolutions mean different sampling frequencies f_s. f_s has no impact on the throughput. Second, when the display uses the same resolution, different refresh rates mean different sizes of the packet. This is because the duration of one packet equals to the duration of one frame. Packets from high refresh rate settings have short packet size, but as the preamble occupies a constant number of samples, these packets have more communication overhead. As a result, the high refresh rate setting has similar throughput in Figure15 (e).

Exp6. One Action Throughput. In this experiment, we investigate a typical user action to use Shadow, *i.e.*, the user moves the hand to let the mobile device approach the display and then move back the hand. The action likes fetching something from the display panel. We evaluate how much information can be received by the device with this simple action. 6 volunteers are asked to perform the action. Each action takes about 1 second. Each volunteer repeats the action for 10 times.

The CDF of the received information is shown in Figure15 (f). On average, the "fetching" action can get 1.4k bits, which are enough for short messages, such as URLs or small figures. If we keep the device close to the display panel for a long period rather than taking a single approaching action, as we can see from the other evaluation experiments, the throughput is around 1.5 kbps, which is enough for transmitting highly-compressed human voice or low-rate MIDI music.

6 RELATED WORK

Display-to-device communication. The display-to-camera link is currently the dominant way for devices to receive information from displays. As one of the most common forms, displaying a QR code for scanning is widely used in our daily life for payment [13], authentication [14], conveying side information [12], and so on. Recent research has made considerable effort to improve the display-to-camera communication in various aspects, including but not limited to increasing the data rate [25, 34] and communication distance [28] with improved encoding schemes, improving the capturing reliability [27] with frame synchronization schemes, and so on. Shadow is different from all of them as its communication approach does not rely on a visible channel. Thus, it reduces the action overhead for users to perform. At the same time, Shadow can easily cooperate with any display-to-camera schemes to facilitate display-to-device communication.

One obvious drawback of using displays to transmit is that the information for communication may be visible and thus obtrusive. To eliminate this side effect, recent work either use complementary patterns in nearby pixels and successive frames [37] or change the transparency of a block of pixels slightly [31] to make the communication content less intrusive for human eyes. However, as we use RF signals to communicate, it is not necessary for Shadow to generate any visible signals. This is a fundamental difference in design approaches between Shadow and these related works. This is also why Shadow is able to provide an invisible display-to-device channel, without degrading any display quality.

Today's smart display systems such as smart TVs [3] are able to directly communicate with user's mobile devices through the installed Wi-Fi and Bluetooth modules. However, the communication ability is generally designed and optimized for private communication and control purposes. Setting up links requires cumbersome actions. Importantly, the data path of these wireless modules is logically isolated from the display content. Unlike Shadow there is no ready solution to couple the side information with the display content through these wireless links.

EMR side channel. Sniffing EMR signals to analyze the inside operations of electronic devices has been studied in the security area for years. The electric current in keyboard [36], GPIO port [17], tablet screen [26] and CMOS chip [22] can generate enough EMR signals that can be captured a certain distance away, but most of their approaches require very high-end capturing tools and complicated analyzing methods such as DPA [29]. On the contrary, Shadow is designed for communicating in commercial devices and relies on actively controlling EMR signals.

Using display interface to actively generate EMR for communication was first tried by [30]. Later, an open source project [1] attempted to generate TV broadcasting through a VGA card. Similar attempts to generate FM broadcast have also been verified in [19, 24]. Those work provide evidence to support the basic idea of our design, but they all occupy the full display content and do not consider practical communication issues such as frequency offset and bit rate. In other words, Shadow differs from all of them in providing a complete and practical communication system design.

7 DISCUSSION AND LIMITATION

EMR Regulation and Low Power FM Broadcast. Organizations such as FCC [16] regulate the radio emissions of electronic devices to avoid the radio interference. In our application scenario, we leverage original unintentional devices (VGA interface) as an intentional device (Low power FM broadcast radio [5]). An intuitive question is whether such usage may violate EMR regulations. We may have no direct measurement means due to the strict requirement of EMR testing, but by indirectly comparing, we can safely draw the conclusion that the EMR from the VGA interface is fully compatible with EMR regulations.

According to the regulation for unlicensed operation in 88 MHz-108 MHz, the field strength of any emission within the permitted 200 kHz band shall not exceed 250 microvolts/meter at 3 meters, and the field strength of any emissions radiated on any frequency outside of the specified 200 kHz band shall not exceed 100 microvolts/meter [16]. Note that the above regulating value, 250 microvolts/meter, is for an FM broadcast range of 60 meters [5]. However, according to the evaluation result, our FM receiving device can only hear FM signals from a VGA interface within one meter, which is far less than 60 meters. Thus the field strength of EMR within 3 meters should be far less than 250 microvolts/meter. We can also infer that the interference of the images is less than 100 microvolts/meter and fits the radiation regulation.

FM Antenna. Similar to other wireless signals, receiving an FM broadcast requires an appropriate antenna. Current FM receivers in mobile phones normally multiplex the earphone cables as their antennas. This design is reasonable since FM broadcasting is mainly for human-listening. However, compact FM antennas exist [32] and can be used in portable FM receivers [11]. For wearables, we can even use the human body as the receiving antenna [33].

Frequency Offset. Like other communication systems, there is a frequency offset between the displays and mobile receivers. In practice, we observe a ±30 kHz frequency offset in f_s. This is reasonable since the VESA DMT and CVT standards allow for a +/-0.5% tolerance for the pixel-clock frequency [18]. This can be observed even among PCs of the same model and the same operating system. The main problem of the offset in f_s is that it results in an offset in f_c, which makes the center frequency of the pre-shared FM channel not accurate for receivers. Our solution is to make the symbol appear at every possible frequency during one symbol period, *i.e.*, instead of keeping f_c stable, sweep f_c from $f_c - 30$ kHz to $f_c - 30$ kHz. In this way, receivers can always encounter a period, during which it has good SNR.

Data Communication over FM. Radio Data System (RDS) and Radio Broadcast Data System (RBDS) are used in FM broadcasting to transmit digital information, *e.g.*, an FM playlist. The RDS signal is embedded in a high frequency channel in the baseband signal, where they can be directly decoded by the FM chip. However, due to the interference from the harmonics in our situation, the decoding SNR can hardly satisfy the RDS decoding. This is the main reason we did not consider modulating EMR to generate RDS signals for data communication.

Limitations of VGA implementation. VGA is an old protocol, and even a little bit out-of-date for the newest display systems. It is especially not suitable for high-fidelity and ultra-high-resolution ones. However, in many undeveloped areas or low-end display applications, VGA is still the most popular one for its cost-effectiveness.

The basis of Shadow is the redundancy in the display protocols. For the VGA protocol, the redundancy is the Blanking Interval in display signals. For modern digital display protocols like DVI and HDMI, similar redundancies exist. An instance to leverage the redundancy is the HDMI protocol. HDMI uses the Blanking Interval to transmit audio signals. However, when the audio is not necessary or is not supported in the display, the redundancy returns. We did not show the feasibility of making use of redundancy in these digital display protocols, but we believe there could be some opportunities hidden in the blanking interval, either from the aspect of ubiquitous communication/interaction or security (*e.g.*, side channels).

8 CONCLUSION

This paper presents the design and implementation of Shadow, an RF solution for display-to-device communication. One advantage of Shadow over current camera-based solutions is that it has no requirement for complicated user actions. The transmission is automatically established and finished when the user device gets close to the display. As Shadow relies on no camera, it can also be used in wearables. Moreover, Shadow keeps the original viewing experience as if there is no communication at all. Shadow achieves a broadcast throughput of around 1.5 kbps, which is comparable to current QR codes.

ACKNOWLEDGEMENT

We would like to thank anonymous IMWUT reviewers for their constructive comments. This work was supported in part by the RGC under Contract CERG 16212714, 16203215, Contract ITS/143/16FP-A, in part by the Guangdong Natural Science Foundation No. 2017A030312008, and in part by the ShanghaiTech University Startup Fund under Grant F-0203-17-010.

REFERENCES

[1] 2017. Analog and Digital TV (DVB-T) Signal Generation. http://bellard.org/dvbt/. (2017).
[2] 2017. bmc 11ac chip. https://wikidevi.com/wiki/Broadcom. (2017).
[3] 2017. Easy TV APP. https://play.google.com/store/apps/details?id=com.easy.tv.remote&hl=en. (2017).
[4] 2017. Electromagnetic compatibility. https://en.wikipedia.org/wiki/Electromagnetic_compatibility. (2017).
[5] 2017. FCC PUBLIC NOTICE: Permitted Form of low POWER BROADCAST operation. https://apps.fcc.gov/edocs_public/attachmatch/DOC-297510A1.pdf. (2017).
[6] 2017. google glass spec. http://www.usish.com/english/products_wm_bn_bm_04.php. (2017).
[7] 2017. High Speed, Digital to Analog Converters Basics. http://www.ti.com/lit/an/slaa523a/slaa523a.pdf. (2017).

[8] 2017. iphone spec. https://www.linkedin.com/pulse/20140919151138-5689549-size-doesn-t-matter-speed-does. (2017).
[9] 2017. MTK 6577 Firmware. https://github.com/andr3jx/MTK6577/tree/master/kernel/firmware. (2017).
[10] 2017. Oversampling Interpolating DACs. http://www.analog.com/media/cn/training-seminars/tutorials/MT-017.pdf. (2017).
[11] 2017. Portable FM Antenna. http://www.amotech.co.kr/Eng/KST/Product.asp?ContentsIdx=68&CategoryIdx=4&SubIdx=1. (2017).
[12] 2017. QR code ad. http://www.youscan.me/blog/case-studies/mall-of-america-use-qr-code-to-give-you-1000-shopping-spree-prize/. (2017).
[13] 2017. qrpay. http://www.qrpay.com/. (2017).
[14] 2017. Secure Quick Reliable Login. https://www.grc.com/sqrl/sqrl.htm. (2017).
[15] 2017. Spirit2 FM radio. https://github.com/mikereidis/spirit2_free. (2017).
[16] 2017. Title 47 CFR PART 15RADIO FREQUENCY DEVICES. http://www.ecfr.gov/. (2017).
[17] 2017. Turning the Raspberry Pi Into an FM Transmitter. http://www.icrobotics.co.uk/wiki/index.php/Turning_the_Raspberry_Pi_Into_an_FM_Transmitter. (2017).
[18] 2017. VGA Standard. http://www.vesa.org. (2017).
[19] 2017. VGASIG. http://bk.gnarf.org/creativity/vgasig/. (2017).
[20] 2018. FM deemph: Gnu radio. https://github.com/gnuradio/gnuradio/blob/da0a102e9b076db83fe5a63b3730ac39b588eb92/gr-analog/python/analog/fm_demod.py. (2018).
[21] 2018. Frequency Modulation (FM) Tutorial. https://goo.gl/13pqm8. (2018).
[22] Dakshi Agrawal, Bruce Archambeault, Josyula R. Rao, and Pankaj Rohatgi. The EM Side channel(s). In *Cryptographic Hardware and Embedded Systems - CHES 2002*.
[23] Tim Curran and Jeanne Doyle. 2011. Picture superiority doubly dissociates the ERP correlates of recollection and familiarity. *Journal of Cognitive Neuroscience* 23, 5 (2011), 1247–1262.
[24] M. Guri, G. Kedma, A. Kachlon, and Y. Elovici. AirHopper: Bridging the air-gap between isolated networks and mobile phones using radio frequencies. In *2014 9th International Conference on Malicious and Unwanted Software: The Americas (MALWARE)* (2014-10). 58–67. DOI: http://dx.doi.org/10.1109/MALWARE.2014.6999418
[25] Tian Hao, Ruogu Zhou, and Guoliang Xing. 2012. COBRA: Color Barcode Streaming for Smartphone Systems *(MobiSys '12)*.
[26] Yuichi Hayashi, Naofumi Homma, Mamoru Miura, Takafumi Aoki, and Hideaki Sone. A Threat for Tablet PCs in Public Space: Remote Visualization of Screen Images Using EM Emanation *(CCS '14)*. ACM.
[27] Wenjun Hu, Hao Gu, and Qifan Pu. LightSync: Unsynchronized Visual Communication over Screen-camera Links *(MobiCom '13)*.
[28] Wenjun Hu, Jingshu Mao, Zihui Huang, Yiqing Xue, Junfeng She, Kaigui Bian, and Guobin Shen. Strata: Layered Coding for Scalable Visual Communication *(MobiCom '14)*.
[29] Paul Kocher, Joshua Jaffe, and Benjamin Jun. Differential Power Analysis. In *Advances in Cryptology*.
[30] Markus G. Kuhn and Ross J. Anderson. Soft Tempest: Hidden Data Transmission Using Electromagnetic Emanations. In *Information Hiding*. Springer Berlin Heidelberg.
[31] Tianxing Li, Chuankai An, Xinran Xiao, Andrew T. Campbell, and Xia Zhou. Real-Time Screen-Camera Communication Behind Any Scene *(MobiSys '15)*.
[32] Abraham Loutridis, Kansheng Yang, Matthias John, and Max Ammann. A Compact Printed Spiral FM Antenna. *Session 3P0* (????), 1830.
[33] Francis Rajesh Martin, Patrick Clement, Sameer Bidichandani, and Frederic Castella. 2012. Virtual FM antenna. (Feb. 21 2012). US Patent 8,121,662.
[34] Samuel David Perli, Nabeel Ahmed, and Dina Katabi. PixNet: Interference-free Wireless Links Using LCD-camera Pairs *(MobiCom '10)*. ACM.
[35] Tippure S Sundresh, Frank A Cassara, and Harry Schachter. 1977. Maximum a posteriori estimator for suppression of interchannel interference in FM receivers. *Communications, IEEE Transactions on* 25, 12 (1977), 1480–1485.
[36] Martin Vuagnoux and Sylvain Pasini. Compromising Electromagnetic Emanations of Wired and Wireless Keyboards *(SSYM'09)*.
[37] Anran Wang, Zhuoran Li, Chunyi Peng, Guobin Shen, Gan Fang, and Bing Zeng. InFrame++: Achieve Simultaneous Screen-Human Viewing and Hidden Screen-Camera Communication *(MobiSys '15)*.