

# mQRCode: Secure QR Code Using Nonlinearity of Spatial Frequency in Light

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# Outline

**Motivation**

Basic Idea

Spatial Frequency

Encryption Scheme

Against Attacks

Evaluation

Conclusion

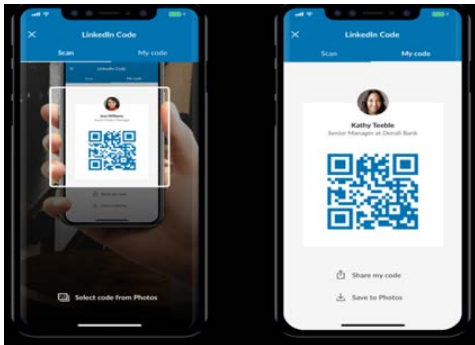
# QR Code

**Quick Response Code:** a near-field comm method.

- Rapid readability for any handheld device with a camera.
- Applications: retail, transportation, advertisement, social contact, gaming, access controlling, and etc.



**Social E-cards**



**Mobile Payment**



**Electronic Tickets**

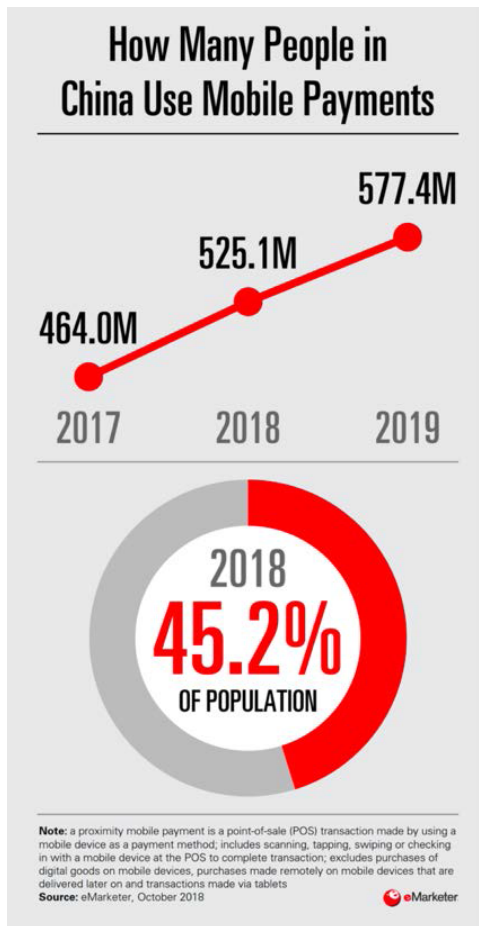


**Access Control**

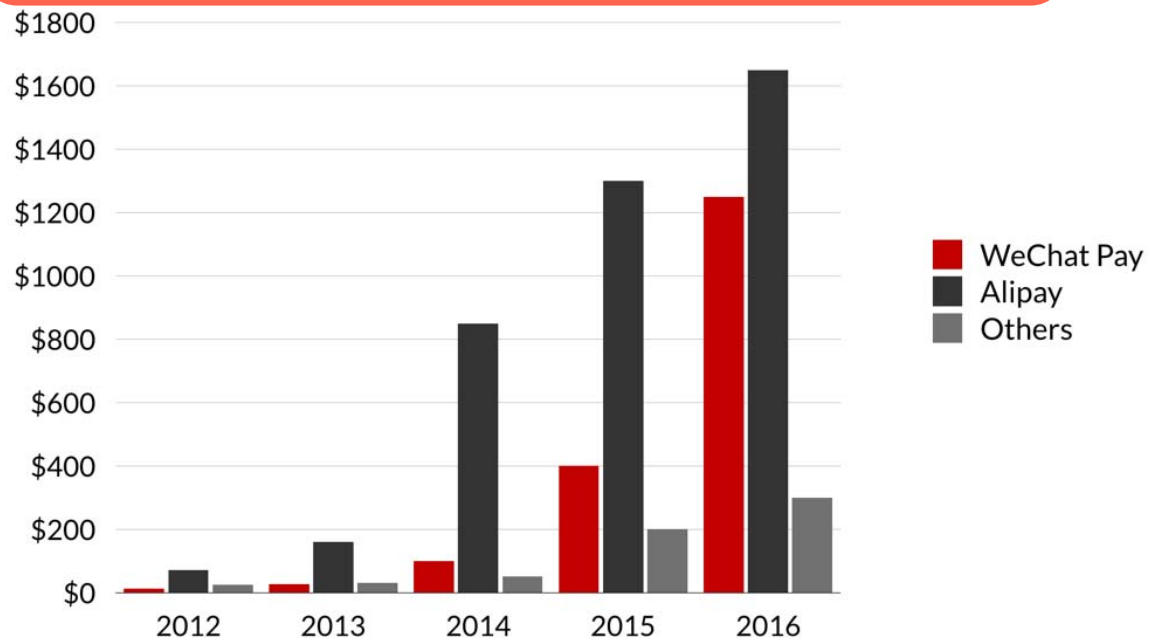


# Motivation

## QR Code is Popular



> 3100 Billion USD via QR Code Payment in 2016.



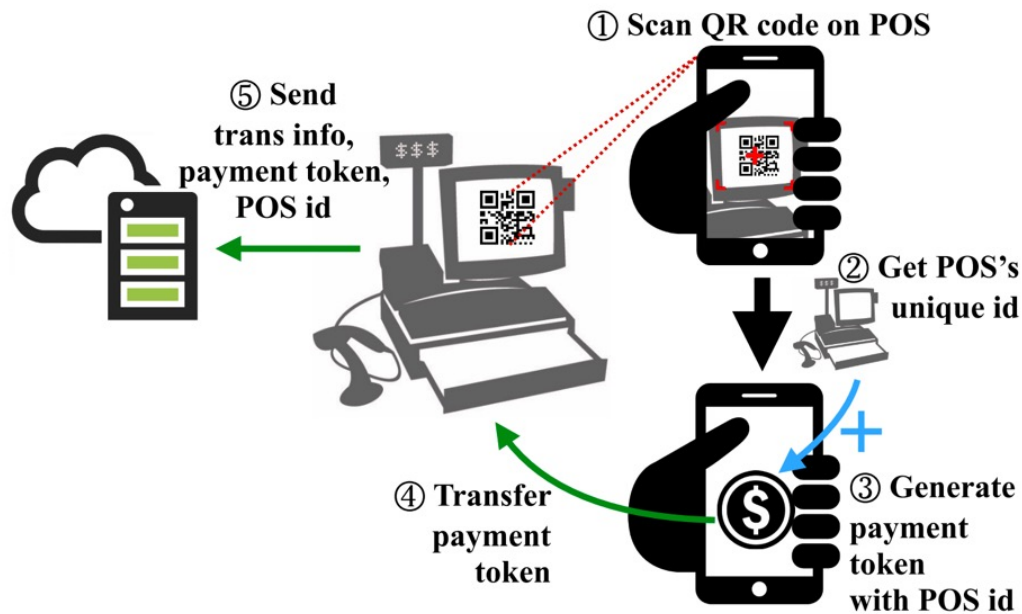
# Motivation

## QR Code is INSECURE

[USENIX Security' 17] Picking Up My Tab: Understanding and Mitigating Synchronized Token Lifting and Spending in Mobile Payment.

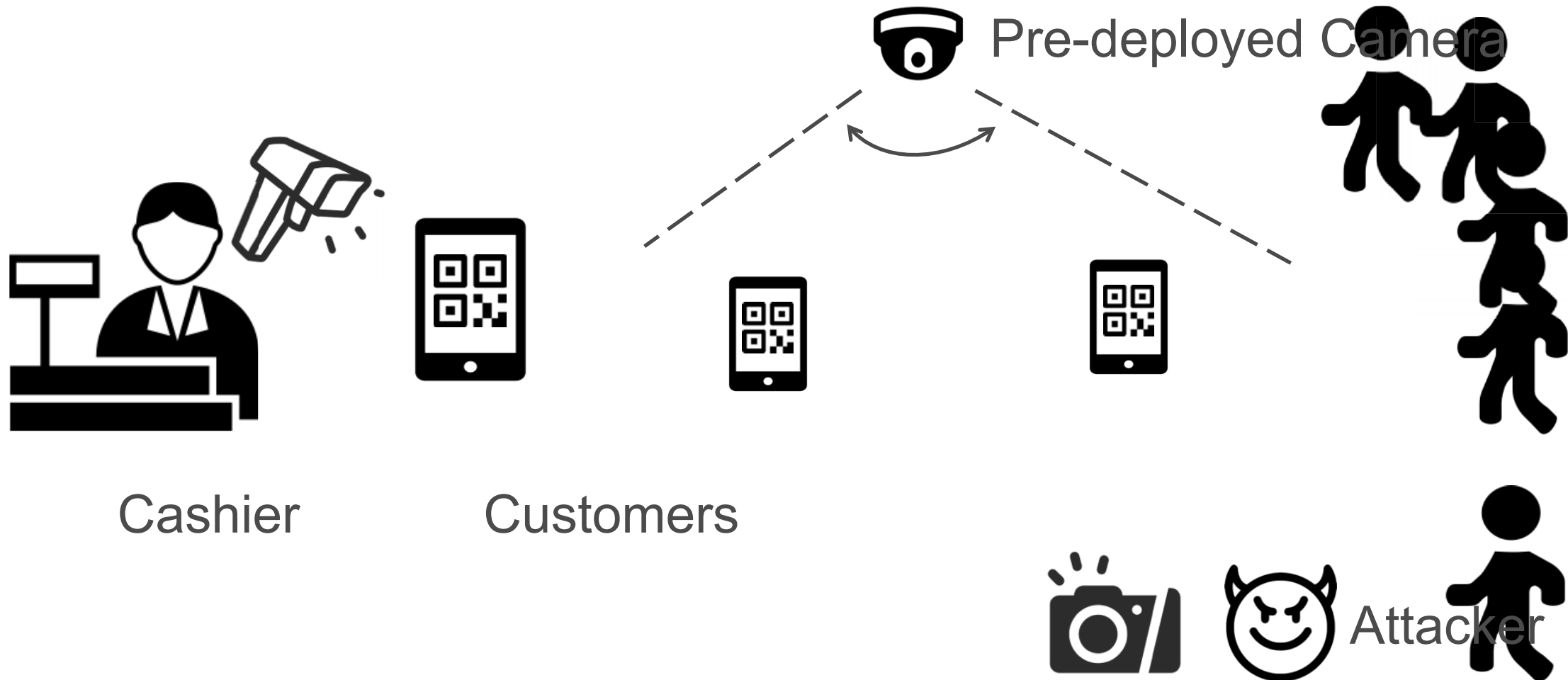
[NEWS' 19] QR code scams rise in China, putting e-payment security in spotlight.

<https://www.jianshu.com/p/b9657161933a>



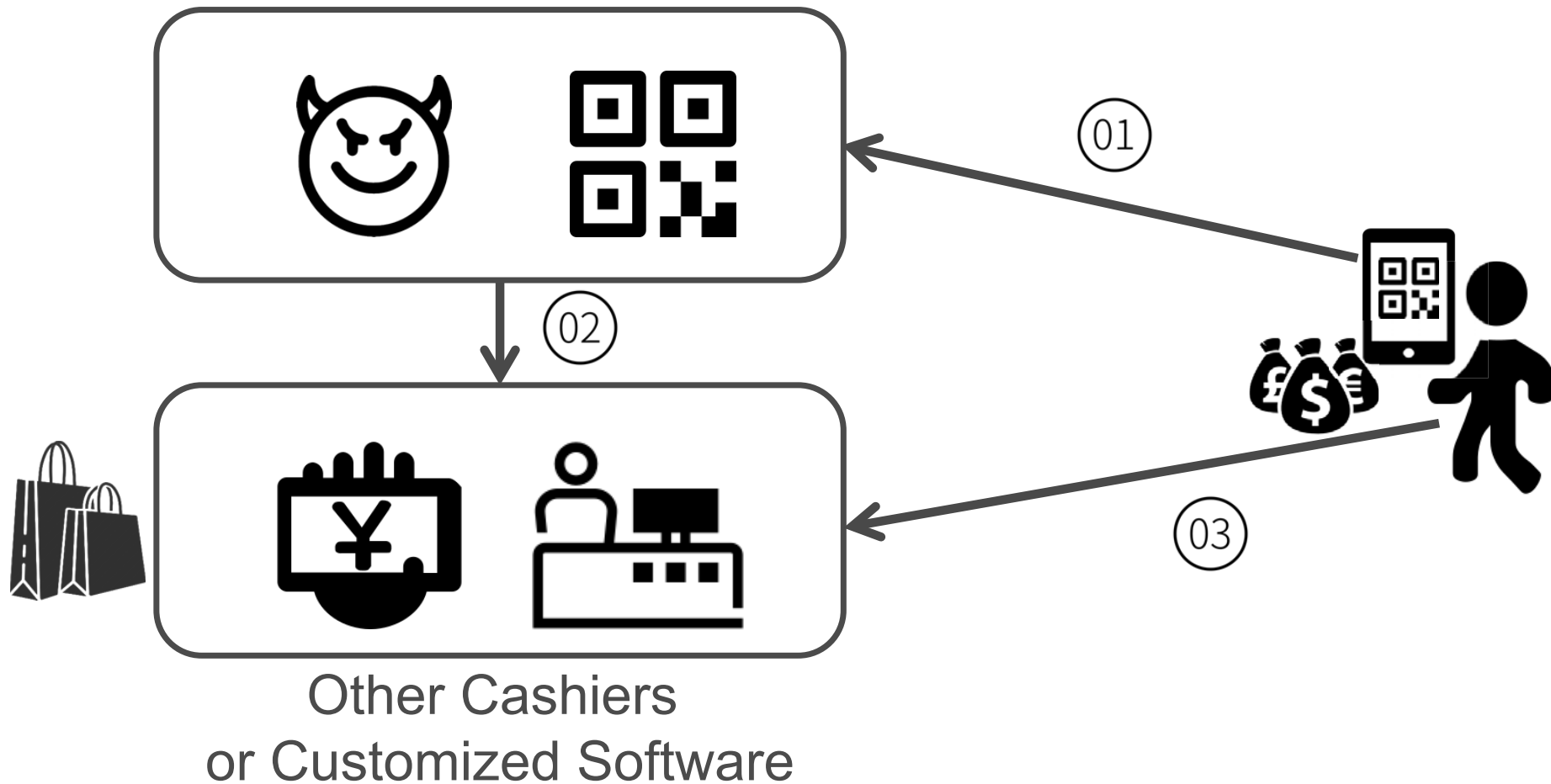
# QR Code Attack

## Replay Attack in a Mobile Payment Scenario



# QR Code Attack

## Replay Attack in a Mobile Payment Scenario



# QR Code Attack

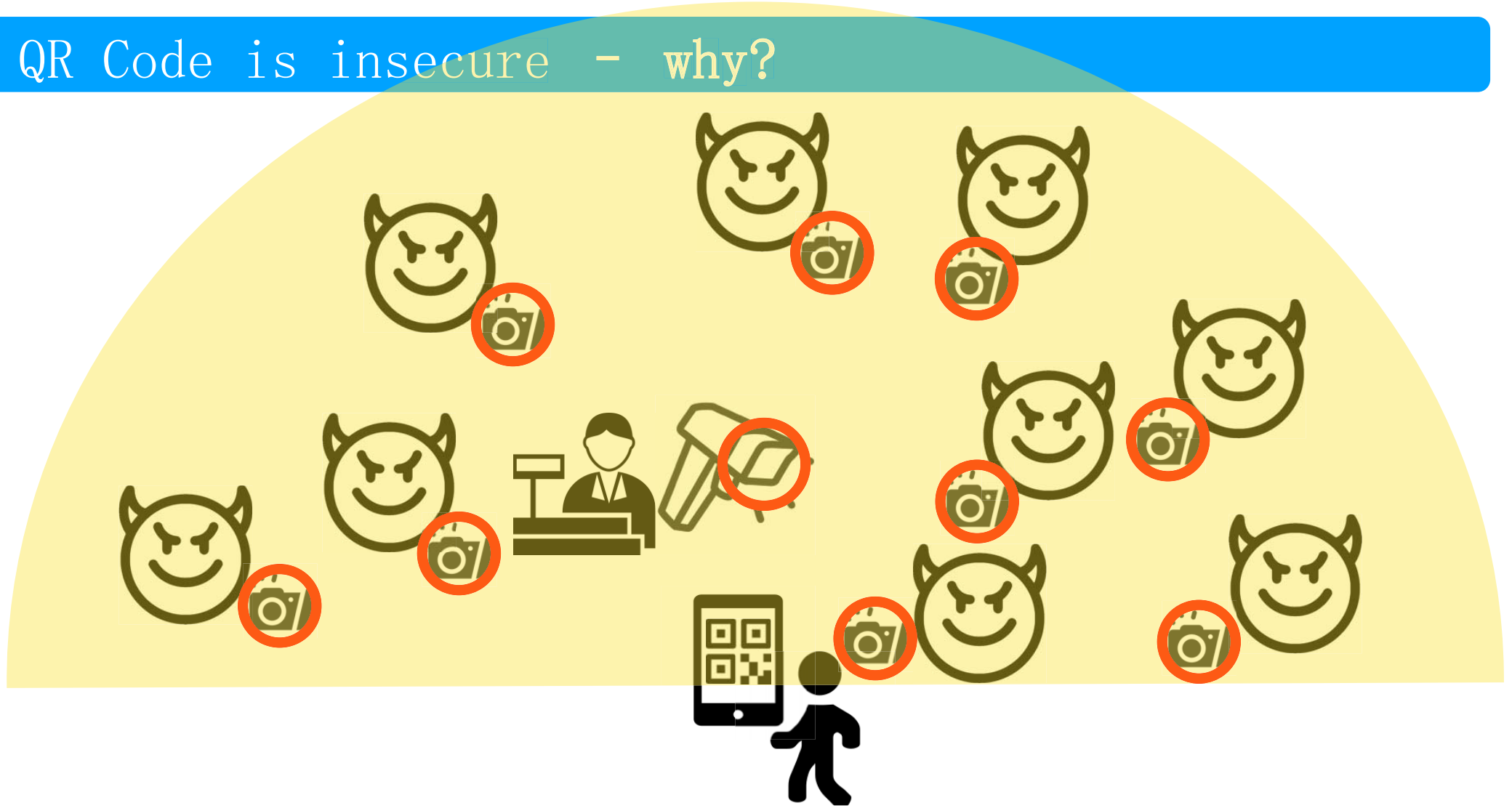
## Replay Attack in a Mobile Payment Scenario



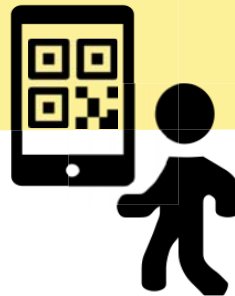


# QR Code Attack

QR Code is insecure - why?



# QR Code Attack



# Outline

Motivation

**Basic Idea**

Spatial Frequency

Encryption Scheme

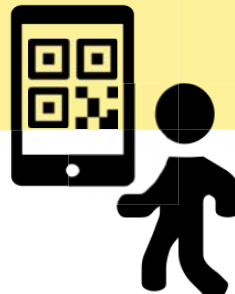
Against Attacks

Evaluation

Conclusion

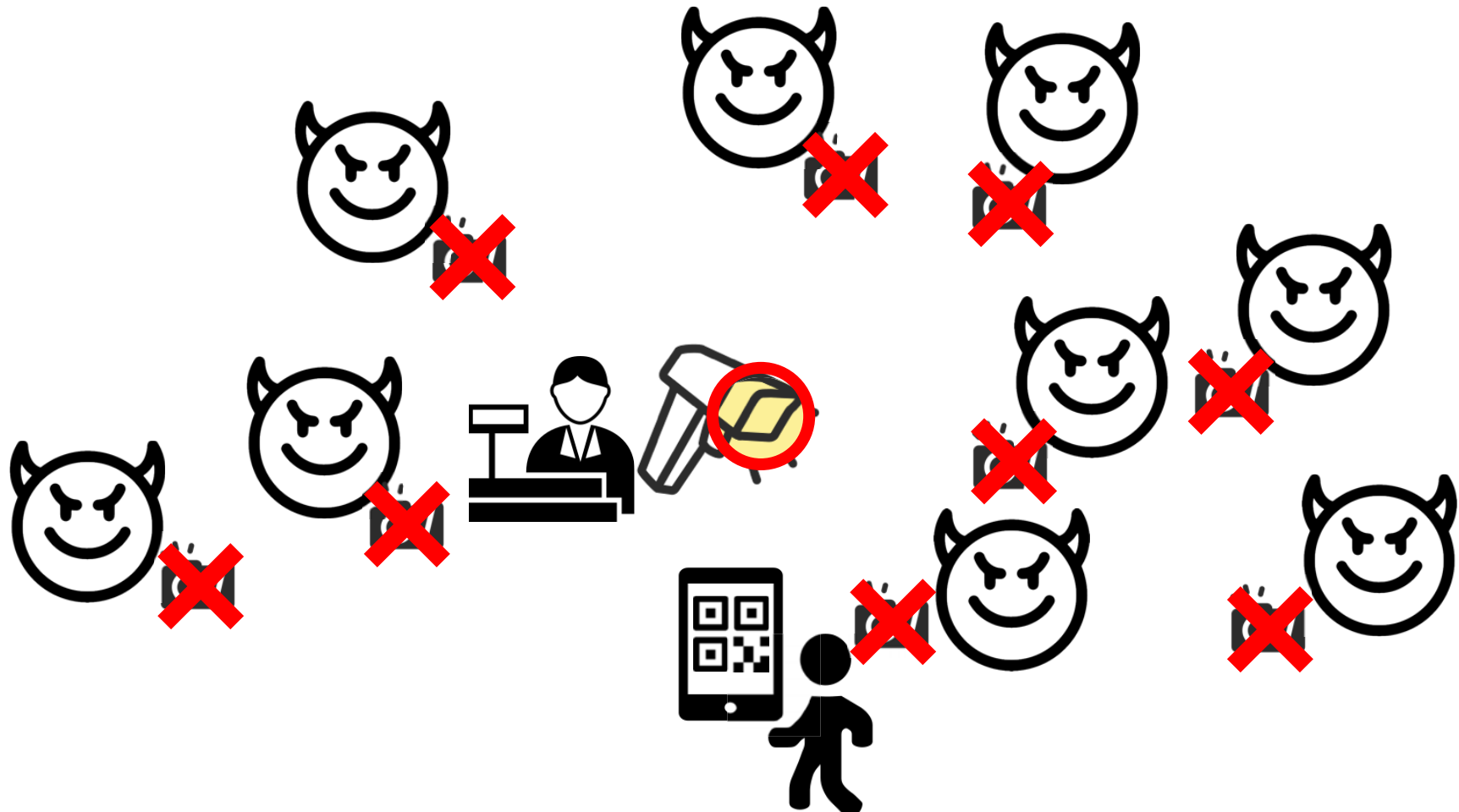
# Basic Idea

Can we reduce the range of attacks?



# Basic Idea

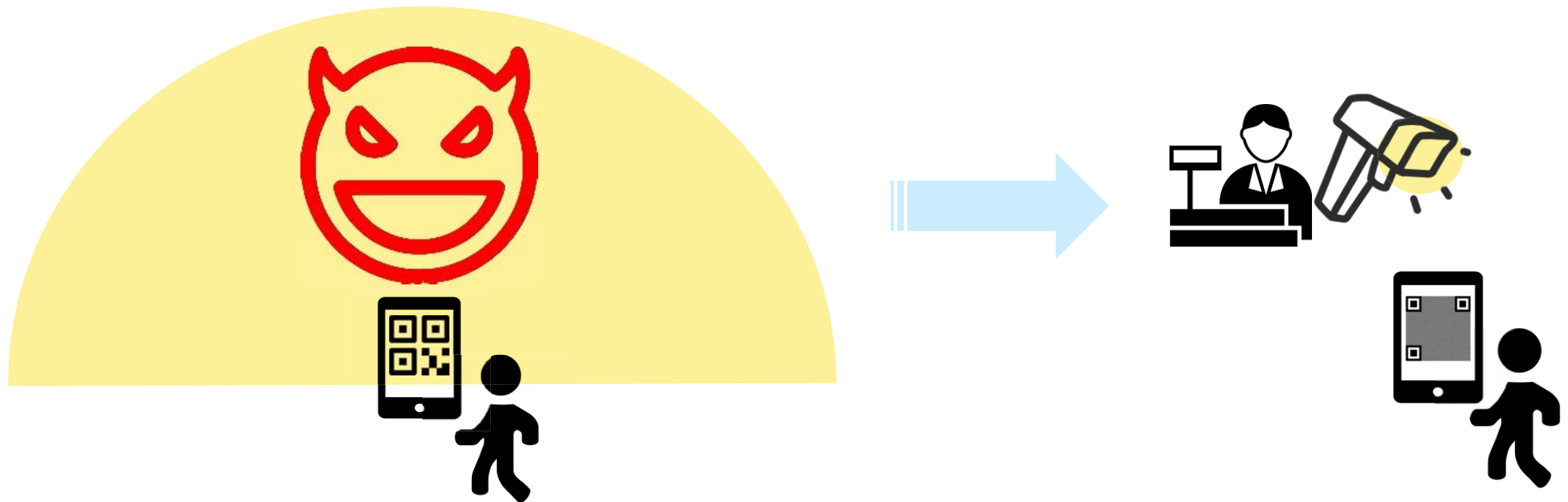
Can we reduce the range of attacks?



# Basic Idea

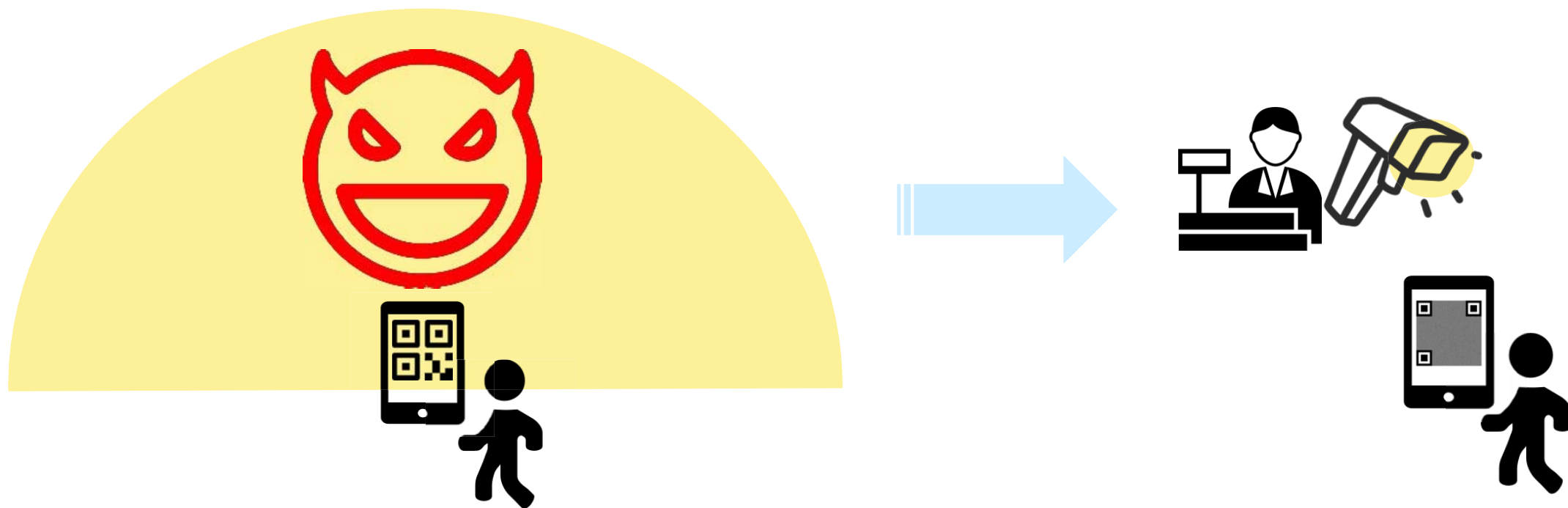
## Design Principle:

Impose the least cost to users  
(e.g., additional hardware or communication channels)



# Basic Idea

Nonlinearity of  
Spatial Frequency



# Outline

Motivation

Basic Idea

**Spatial Frequency**

Encryption Scheme

Against Attacks

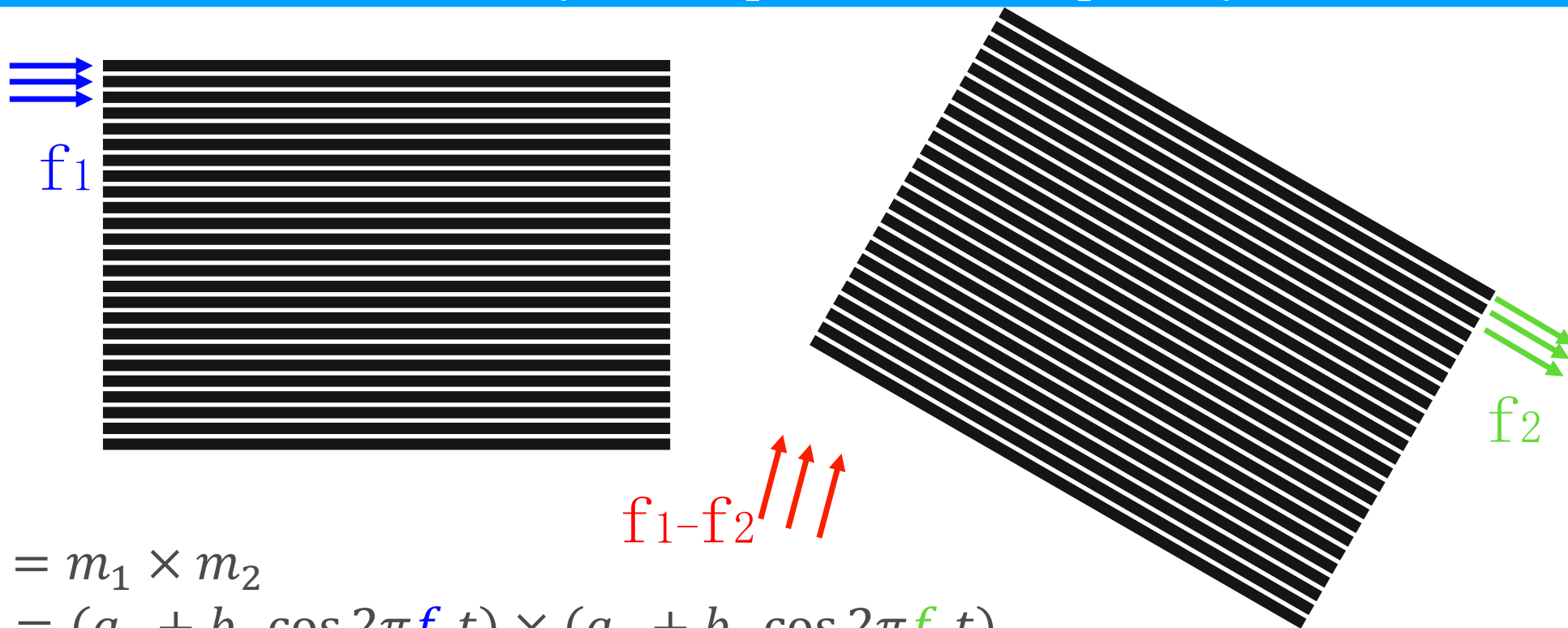
Evaluation

Conclusion



# Spatial Frequency

What is Nonlinearity of Spatial Frequency?



$$m = m_1 \times m_2$$

$$= (a_1 + b_1 \cos 2\pi f_1 t) \times (a_2 + b_2 \cos 2\pi f_2 t)$$

$$= a_1 a_2 + a_2 b_1 \cos 2\pi f_1 t + a_1 b_2 \cos 2\pi f_2 t +$$

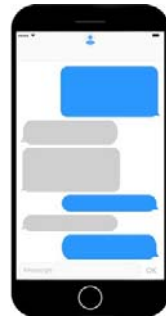
$$b_1 b_2 \cos 2\pi (f_1 + f_2) t + b_1 b_2 \cos 2\pi (f_1 - f_2) t$$

# Observation

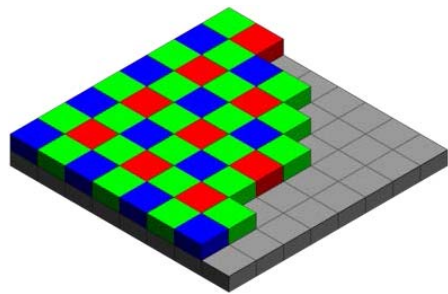
Spatial frequency is everywhere!



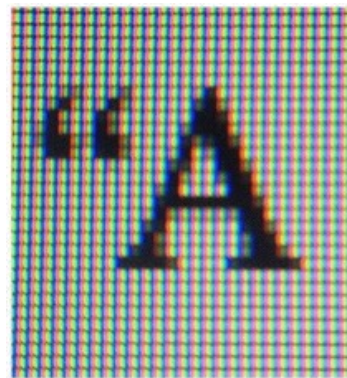
Camera



Display



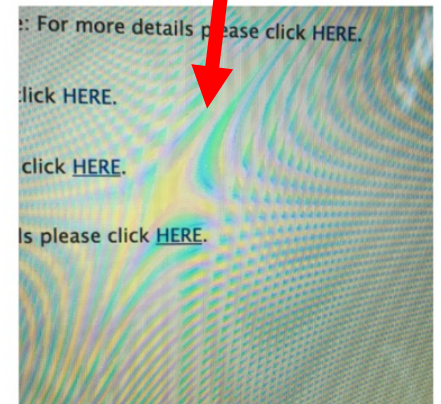
Color Filter Array



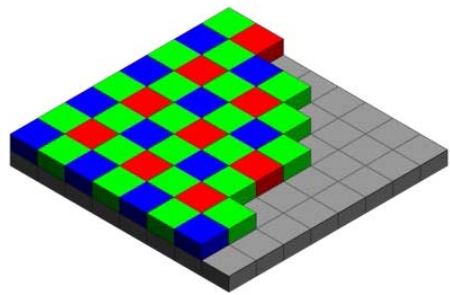
Pixel Array



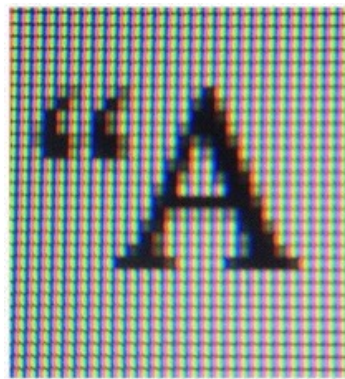
Low-frequency Colorful  
Noise Patterns



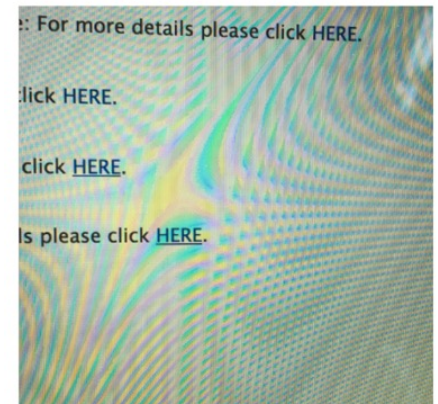
# mQRCode



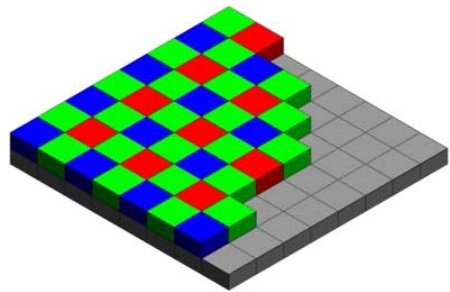
Color Filter Array



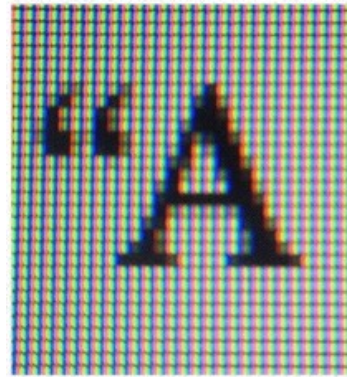
Pixel Array



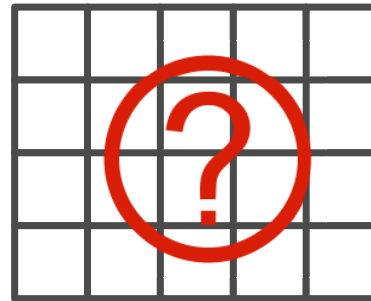
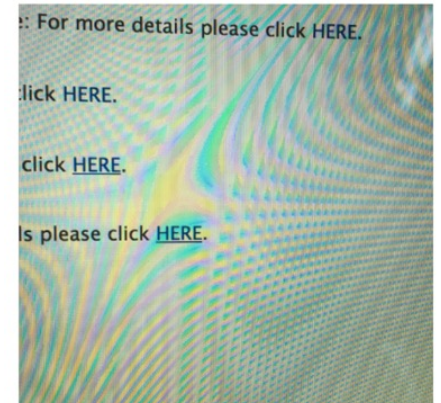
# mQRCode



Color Filter Array



Pixel Array



Random pattern  
to human eyes.



Nonlinear interaction  
results in QR Code.

# Outline

Motivation

Basic Idea

Spatial Frequency

**Encryption Scheme**

Against Attacks

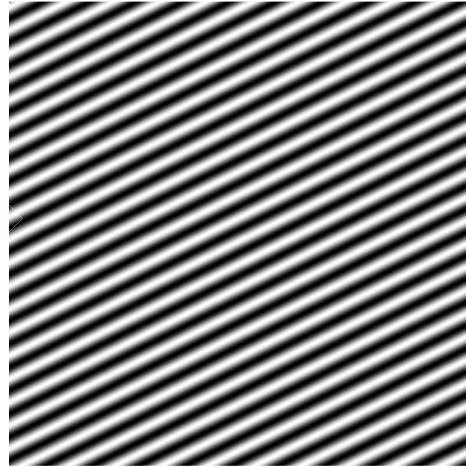
Evaluation

Conclusion

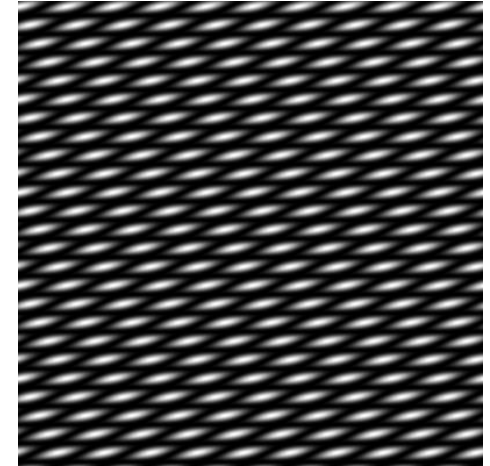
# Encryption Scheme



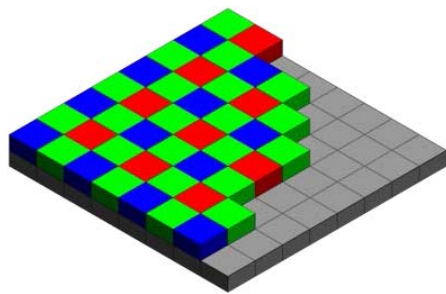
$m_1(x, y)$



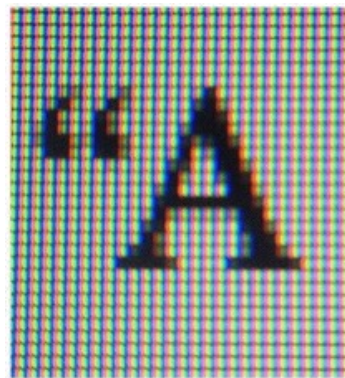
$m_2(x, y)$



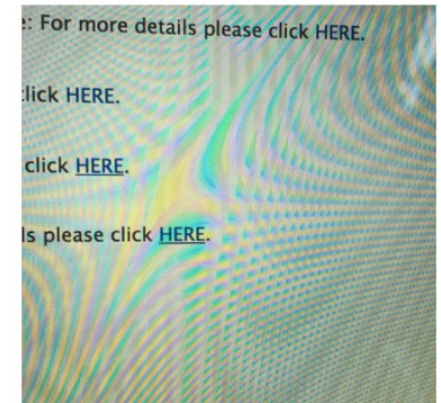
$$m_3(x, y) = m_1(x, y) \times m_2(x, y)$$



Color Filter Array

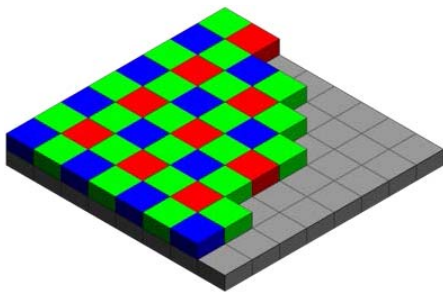


Pixel Array



# Encryption Scheme

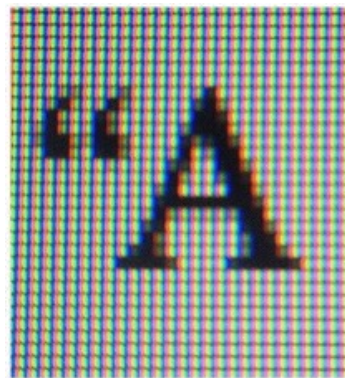
$m_1(x, y)$



Color Filter Array



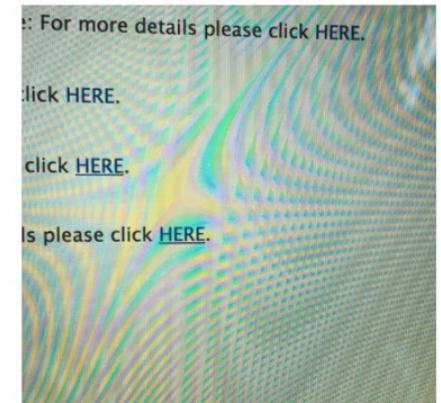
$m_2(x, y)$



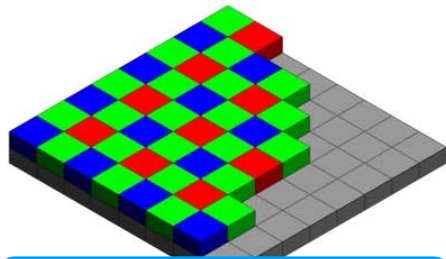
Pixel Array



$m_3(x, y) =$   
 $m_1(x, y) \times m_2(x, y)$

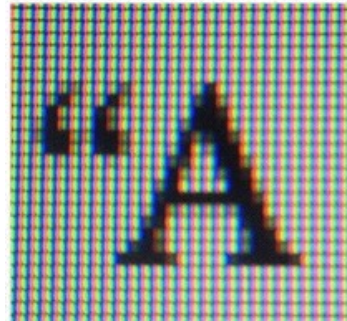


# Encryption Scheme



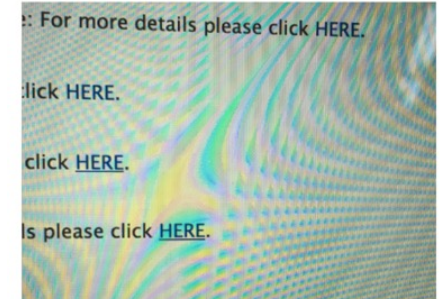
Known

$m_1(x, y)$



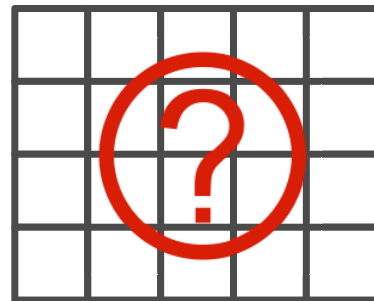
Computed

$m_2(x, y)$



Known

$m_3(x, y) = m_1(x, y) \times m_2(x, y)$



mQR Code





# Outline

Motivation

Basic Idea

Spatial Frequency

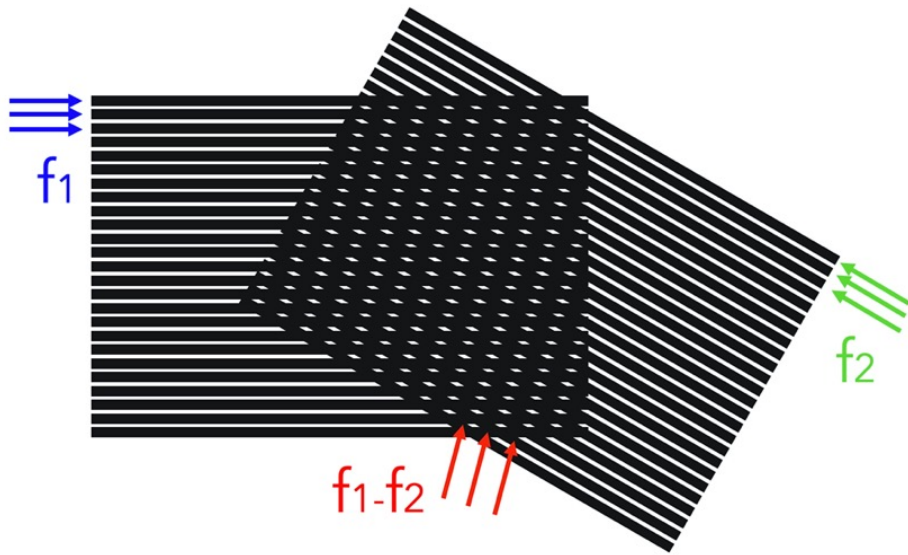
Encryption Scheme

**Against Attacks**

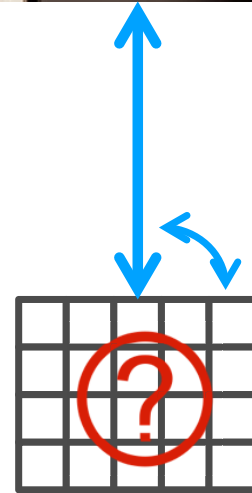
Evaluation

Conclusion

# Why Using Nonlinearity



$$b_1 b_2 \cos 2\pi(f_1 - f_2)t$$

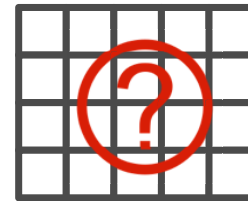
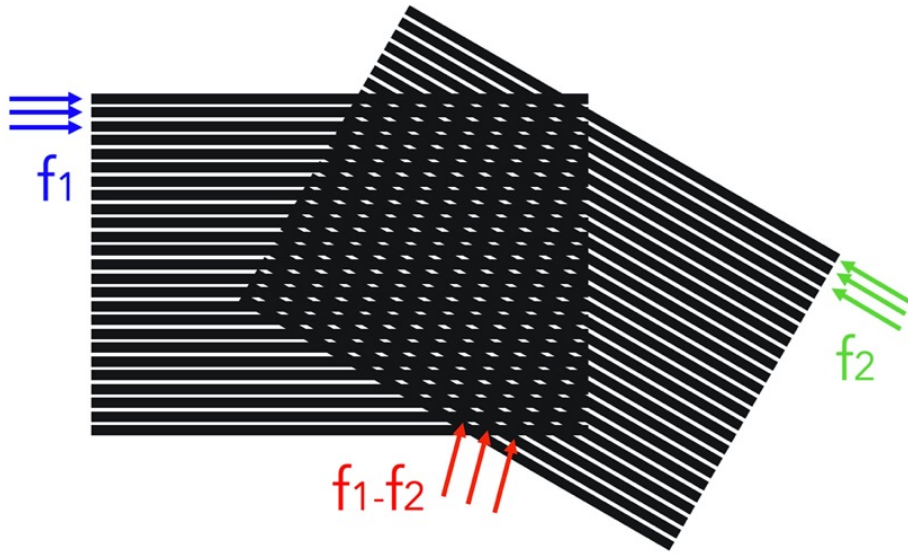


$$|f_1| \cong |f_2|$$

$f_1 - f_2$  is evident

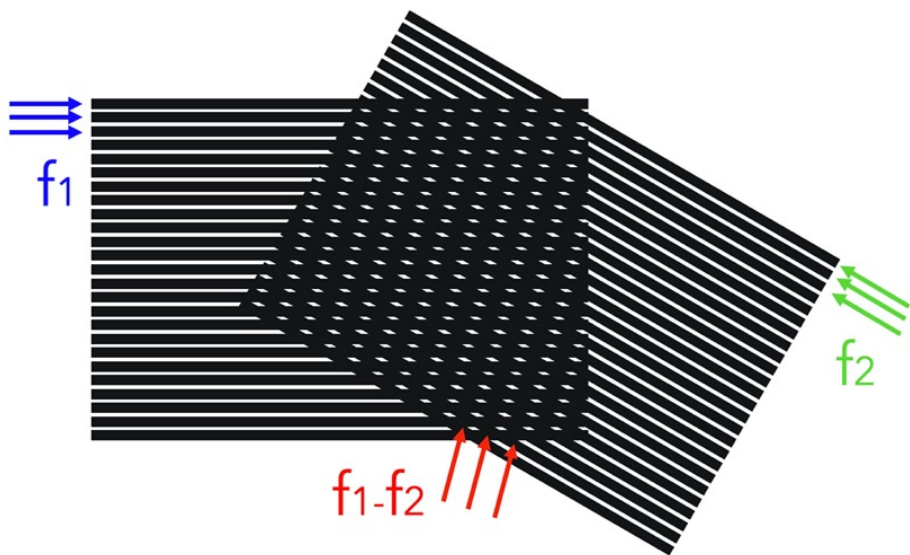


# Why Using Nonlinearity



$$b_1 b_2 \cos 2\pi(f_1 - f_2)t$$

# Why Using Nonlinearity

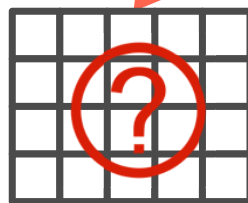


$$b_1 b_2 \cos 2\pi(f_1 - f_2)t$$

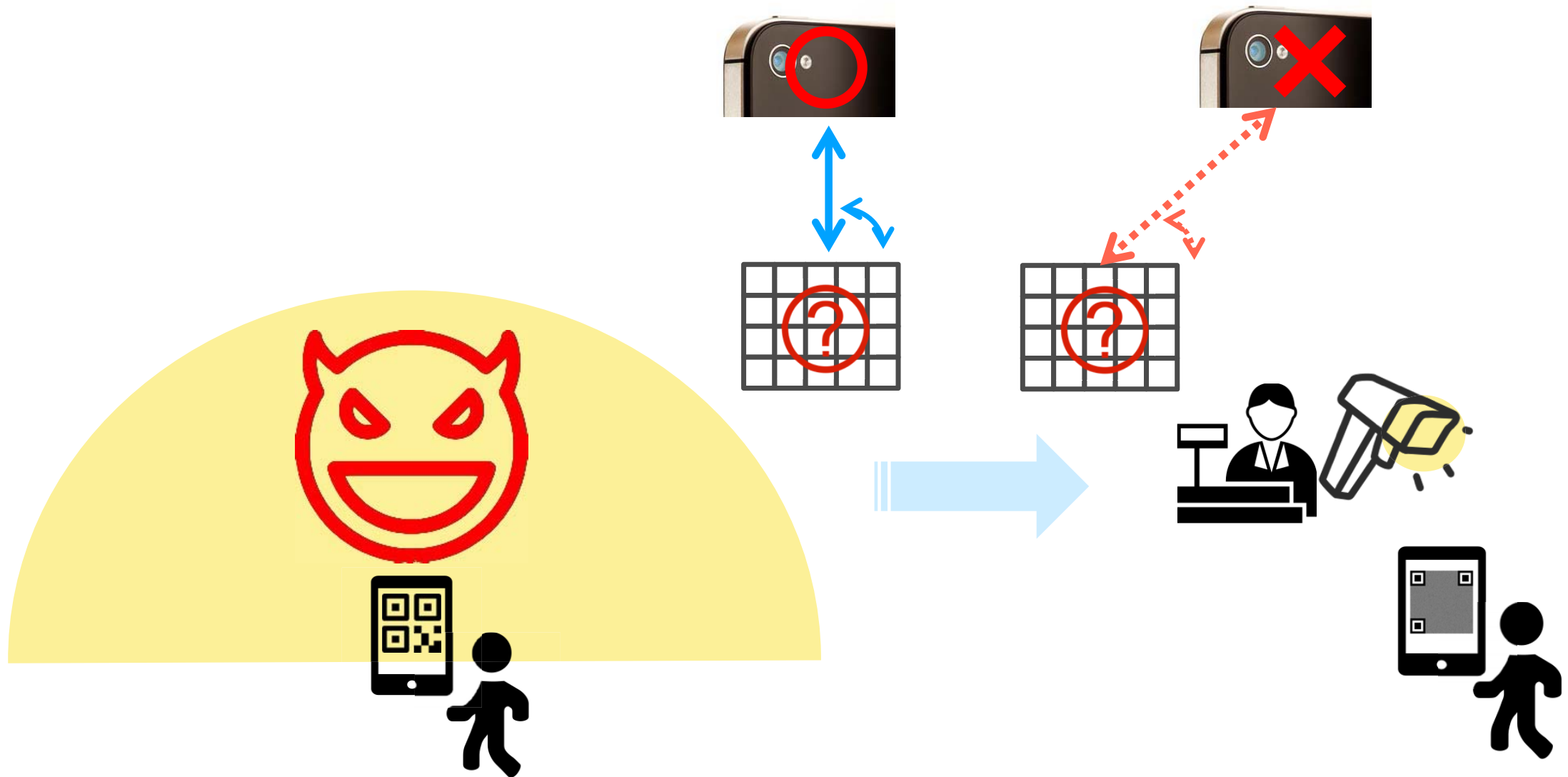


$$|f_1| \gg |f_2|$$

$f_1 - f_2$  is not evident



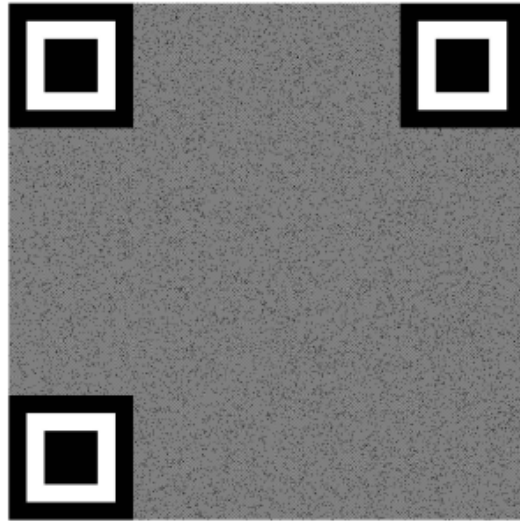
# Why Using Nonlinearity



# Example of mQR Code



QR Code



mQR Code



Photographs  
taken at the  
designated position



Photographs  
taken at other  
positions

# Outline

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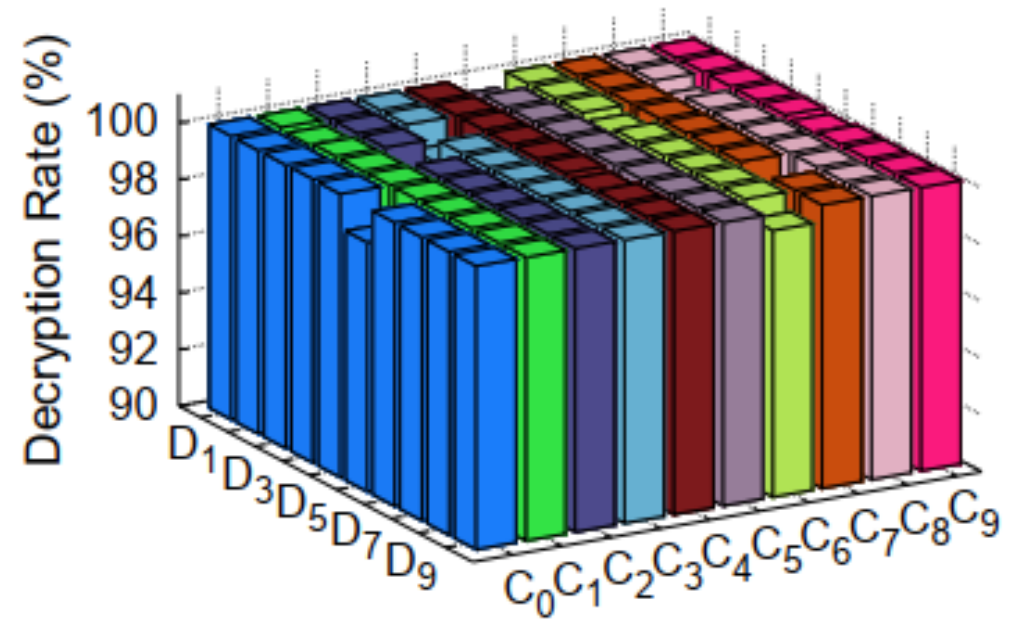
Against Attacks

**Evaluation**

Conclusion

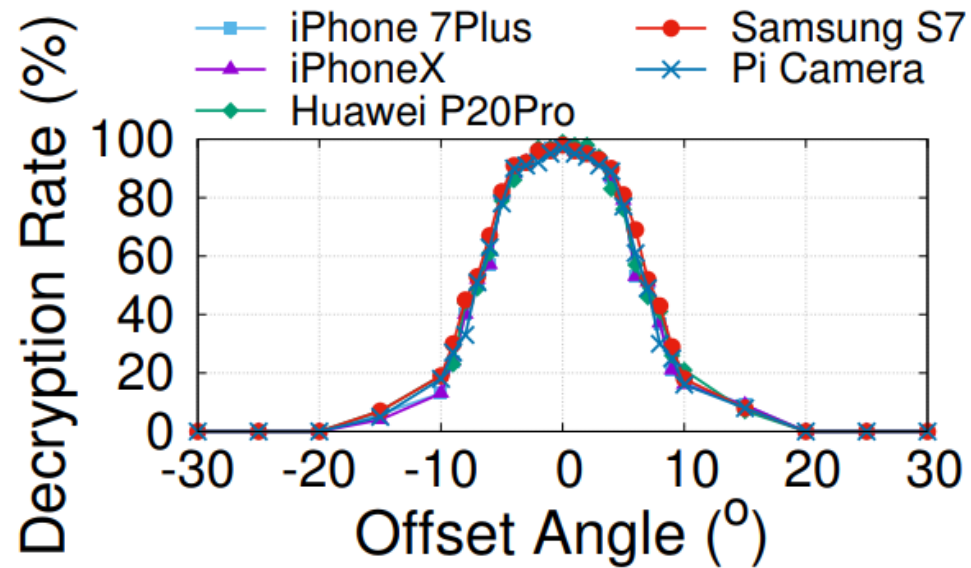
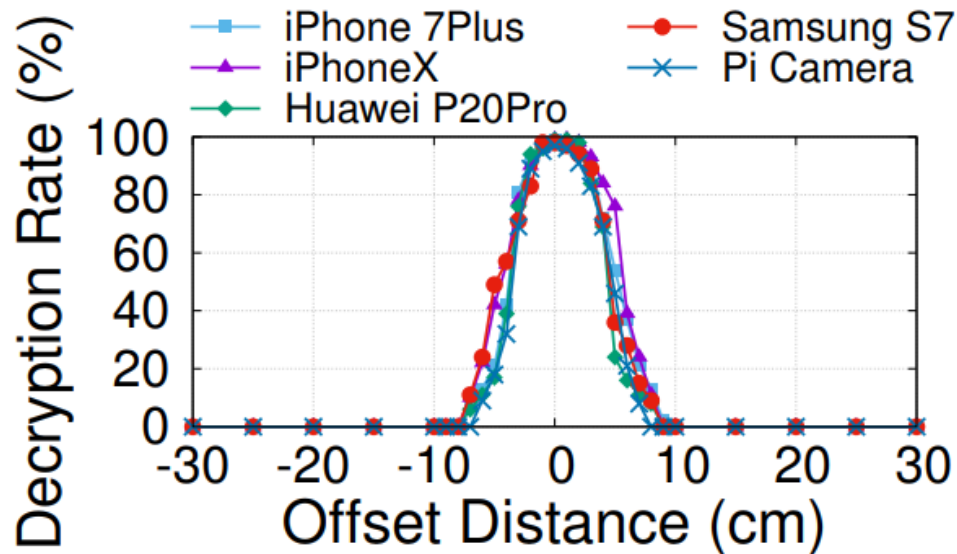
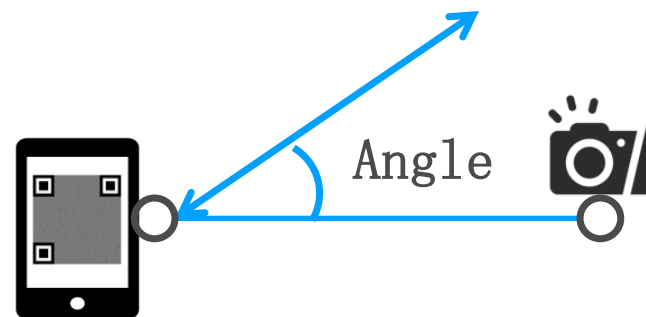
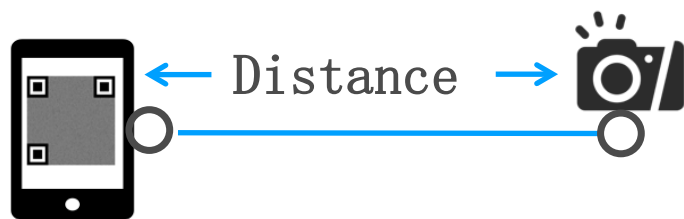
# Evaluation: Cameras and Displays

Displays	Cameras
D0: iPhone 6	C0: iPhone 6
D1: iPhone 7Plus	C1: iPhone 7Plus
D2: iPhone X	C2: iPhone X
D3: iPhone XS	C3: iPhone XS
D4: Huawei P20Pro	C4: Huawei P20Pro
D5: Samsung S7	C5: Samsung S7
D6: Nexus 6P	C6: Nexus 6P
D7: Google Pixel 2	C7: Google Pixel 2
D8: DELL S2340M	C8: Pi Camera (5MP)
D9: MacBookPro 2016	P9: Pi Camera (8MP)





# Evaluation: Multi-Frame Decryption



# Outline

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Against Attacks

Evaluation

**Conclusion**

# Conclusion

mQRCode enables secure QR Code applications:

Novel visual encryption method using nonlinear interaction between camera and display.

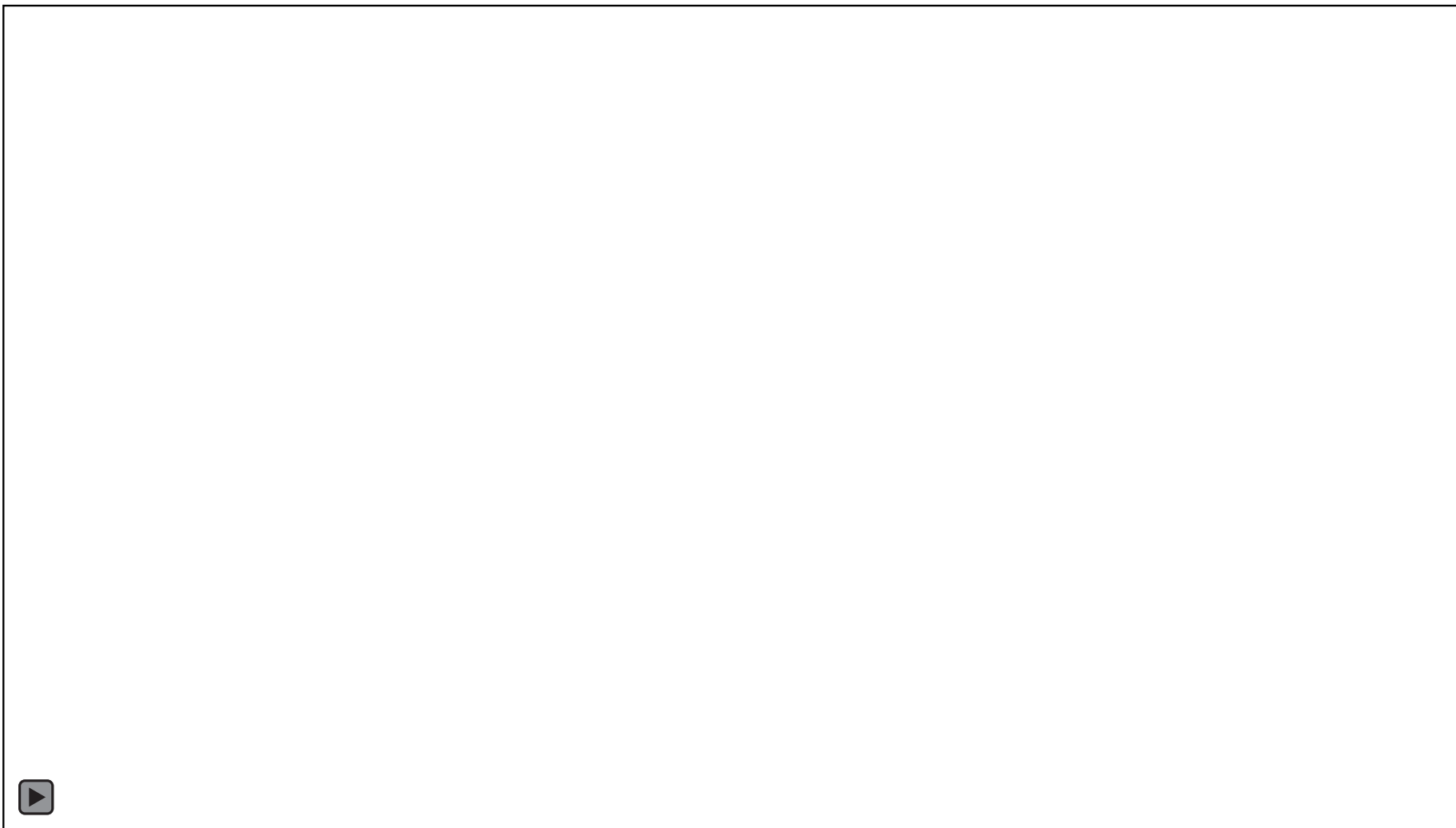
No additional hardware.

No additional communication channel.

The same using behavior.



# Demo of mQRCode



# Backup

Alipay System and STLS Attack

System Overview

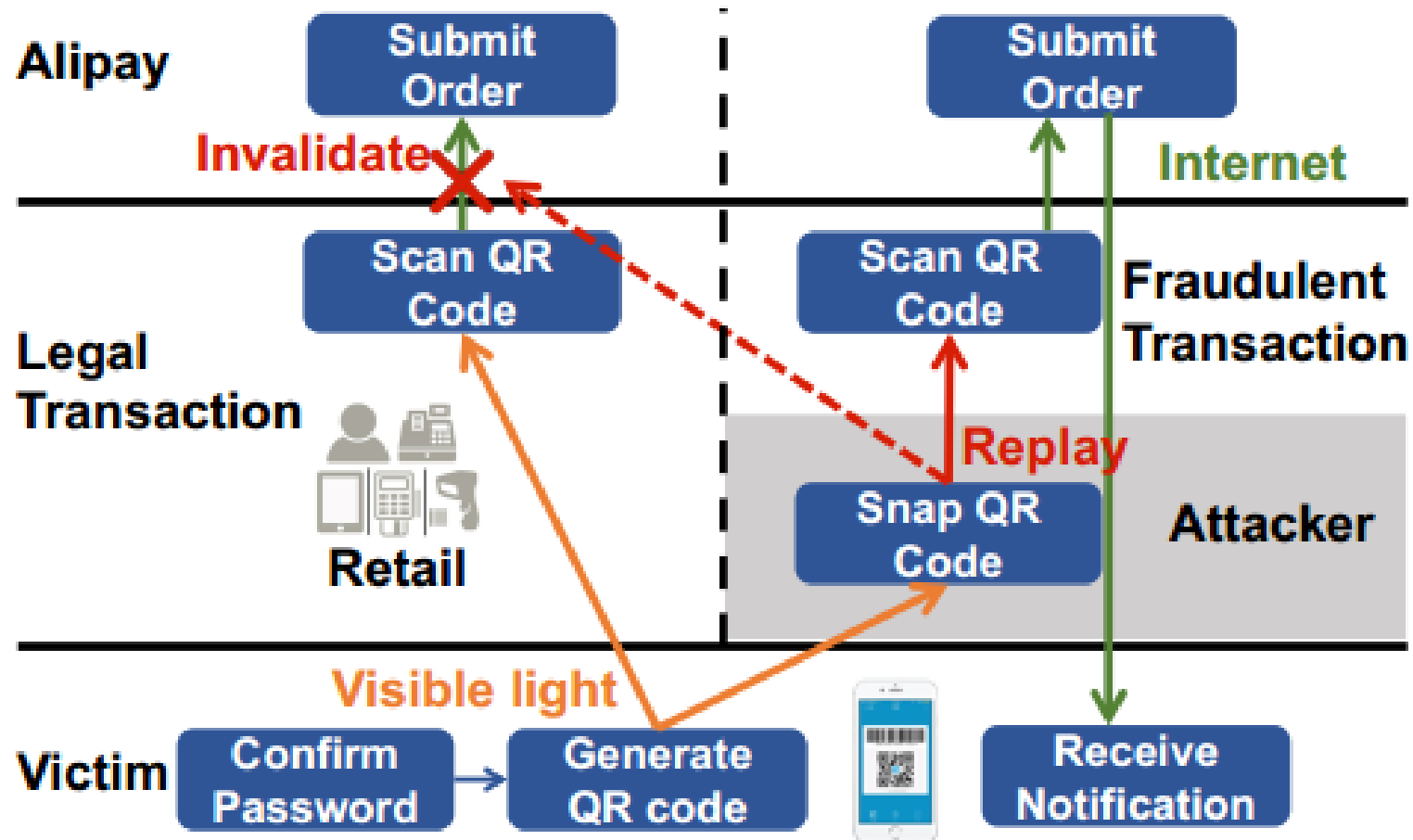
Pinhole Imaging Model

Decryption Scheme

Evaluation (Supplement)

Can mQRCode work with printed QR Code?

# Alipay System and STLS Attack



# Backup

Alipay System and STLS Attack

**System Overview**

Pinhole Imaging Model

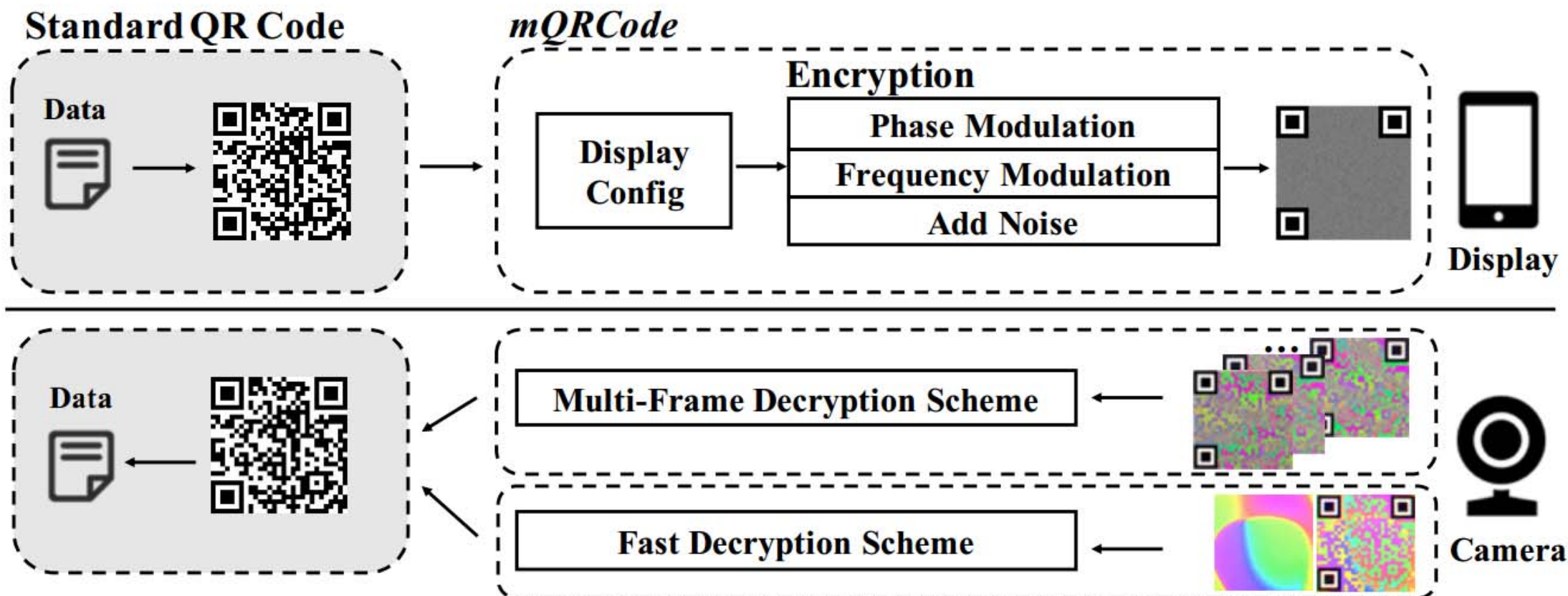
Decryption Scheme

Evaluation (Supplement)

Can mQRCode work with printed QR Code?



# System Overview



# Backup

Alipay System and STLS Attack

System Overview

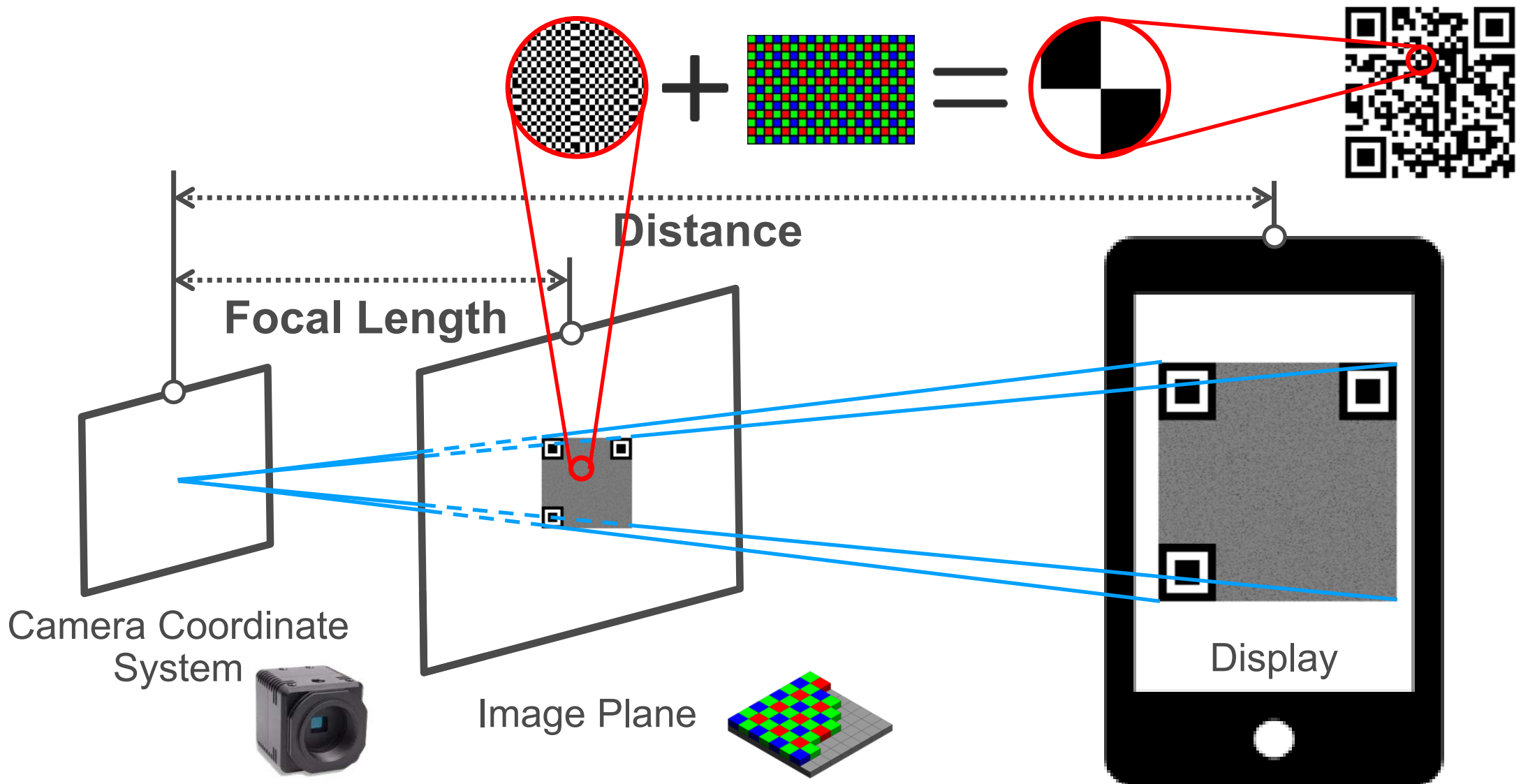
**Pinhole Imaging Model**

Decryption Scheme

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Can mQRCode work with printed QR Code?

# Pinhole Imaging Model



# Backup

Alipay System and STLS Attack

System Overview

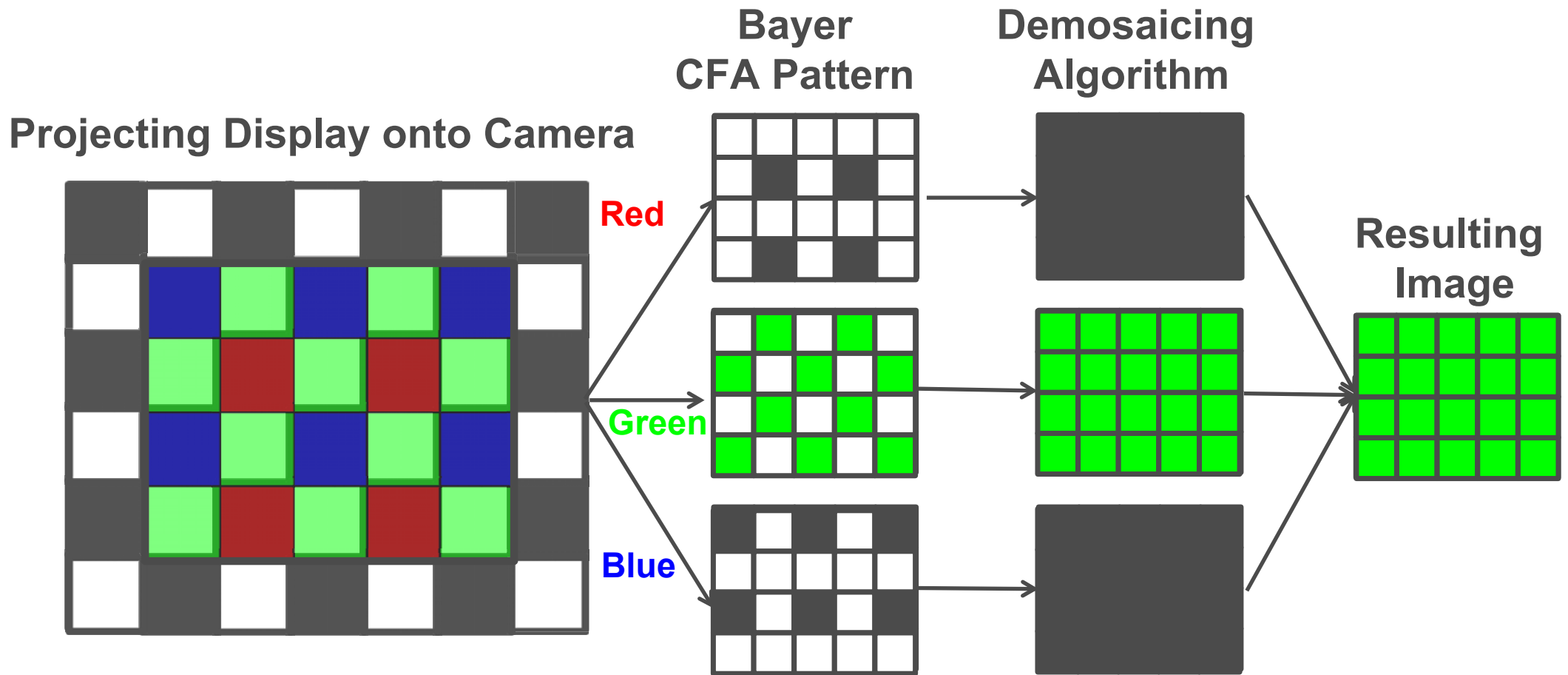
Pinhole Imaging Model

**Decryption Scheme**

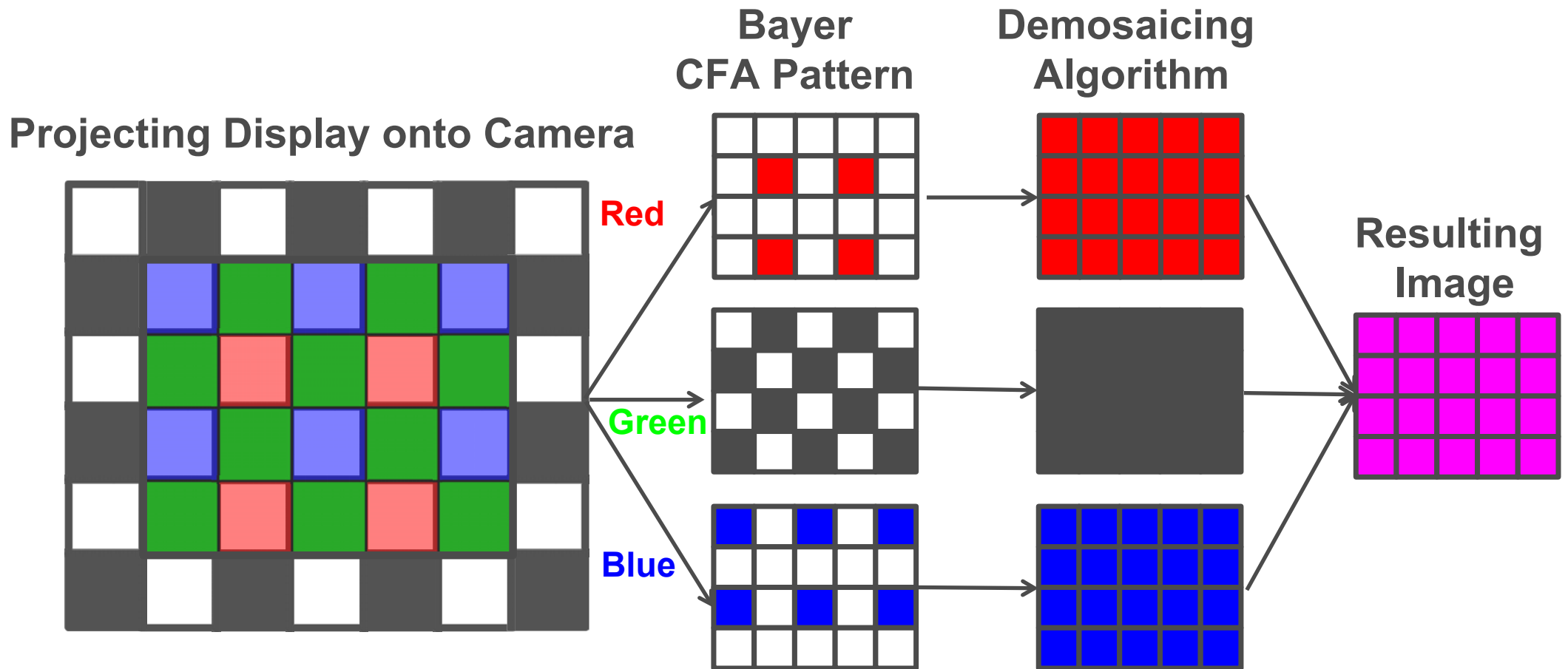
Evaluation (Supplement)

Can mQRCode work with printed QR Code?

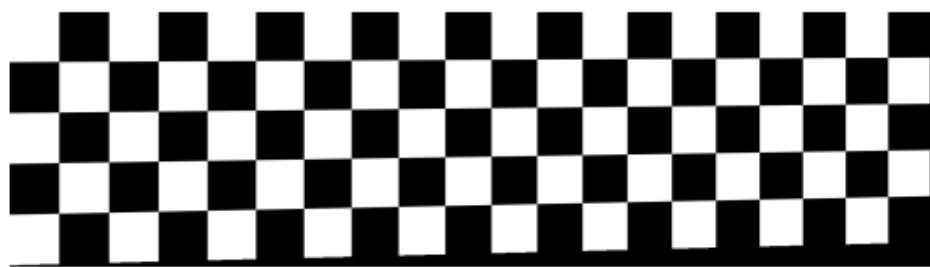
# Decryption: Why not Black and White?



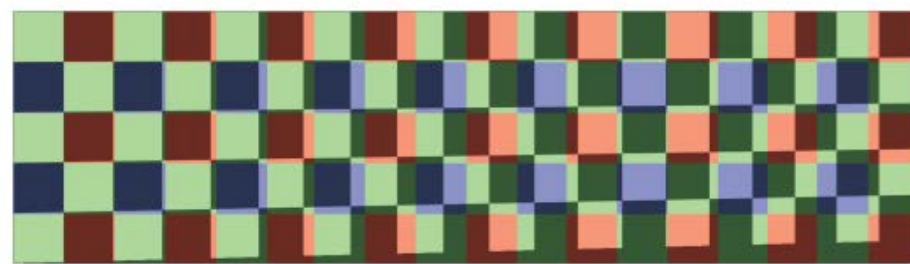
# Decryption: Why not Black and White?



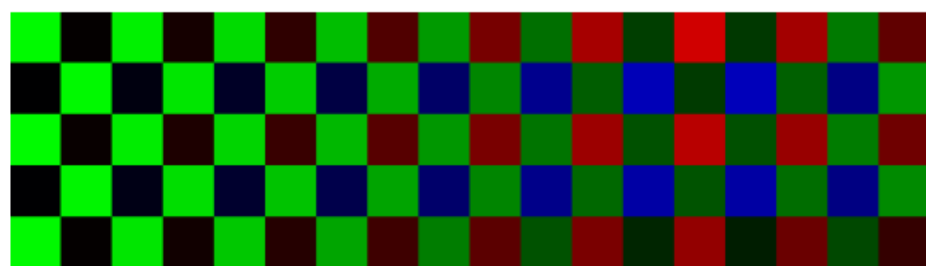
# Decryption: Simulation-based Analysis



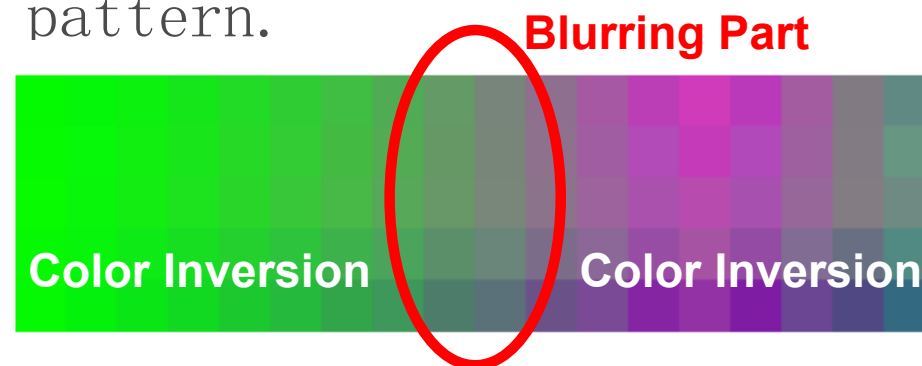
1. Projecting display onto camera with distortion.



2. Distorted image overlap with Bayer CFA pattern.

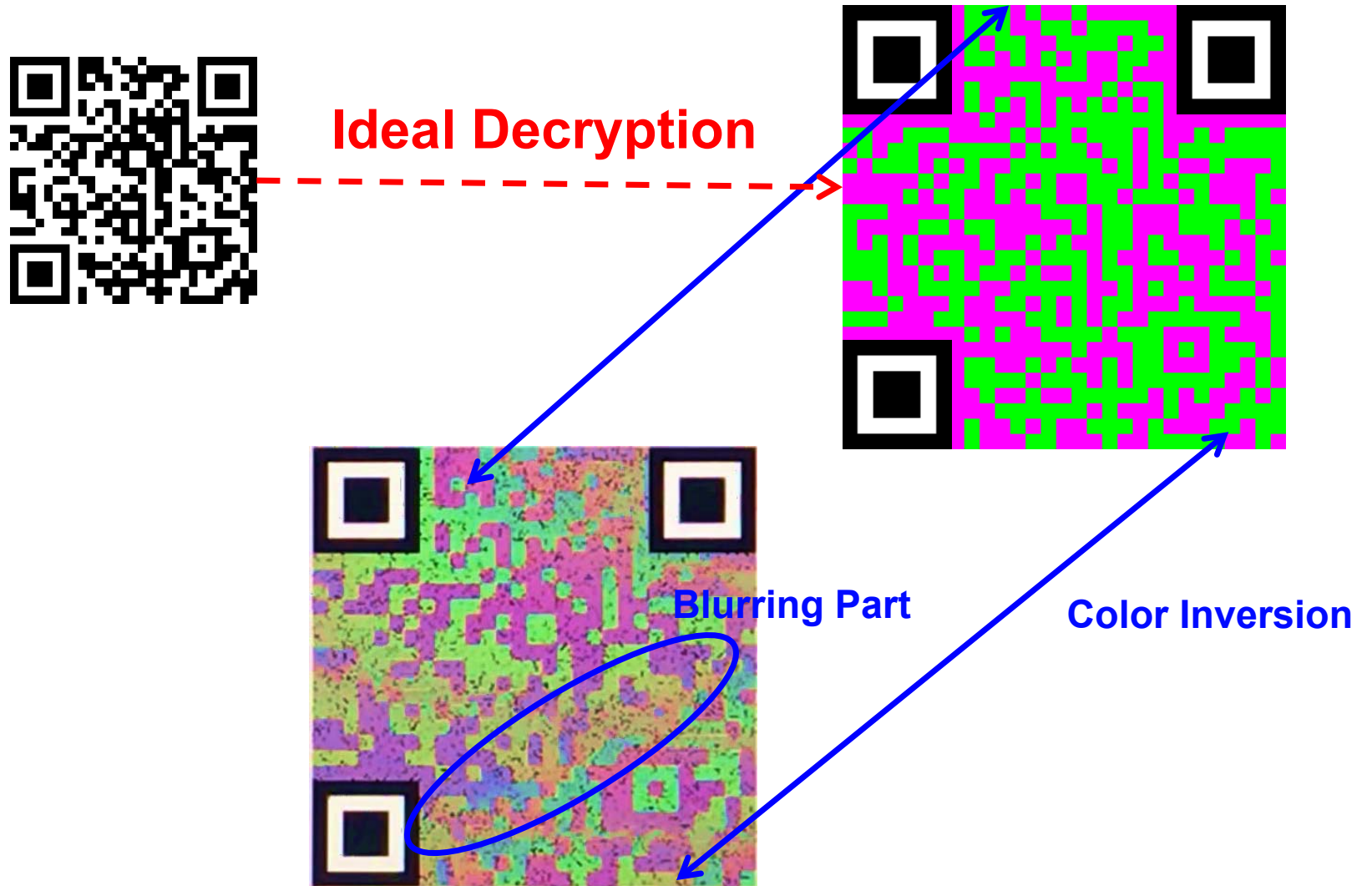


3. Image sensor values with Bayer CFA.



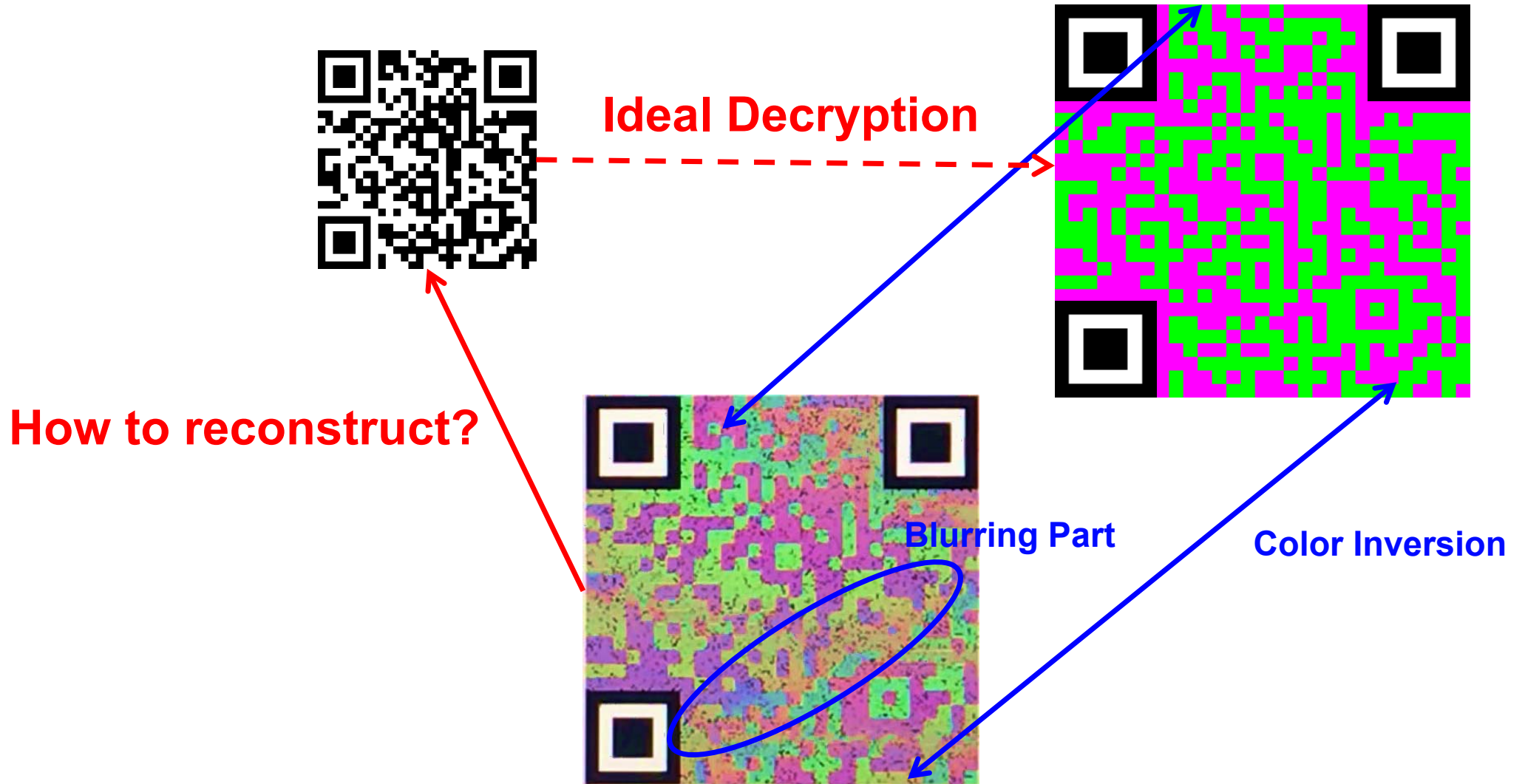
4. After Interpolation.

# Decryption: Challenges

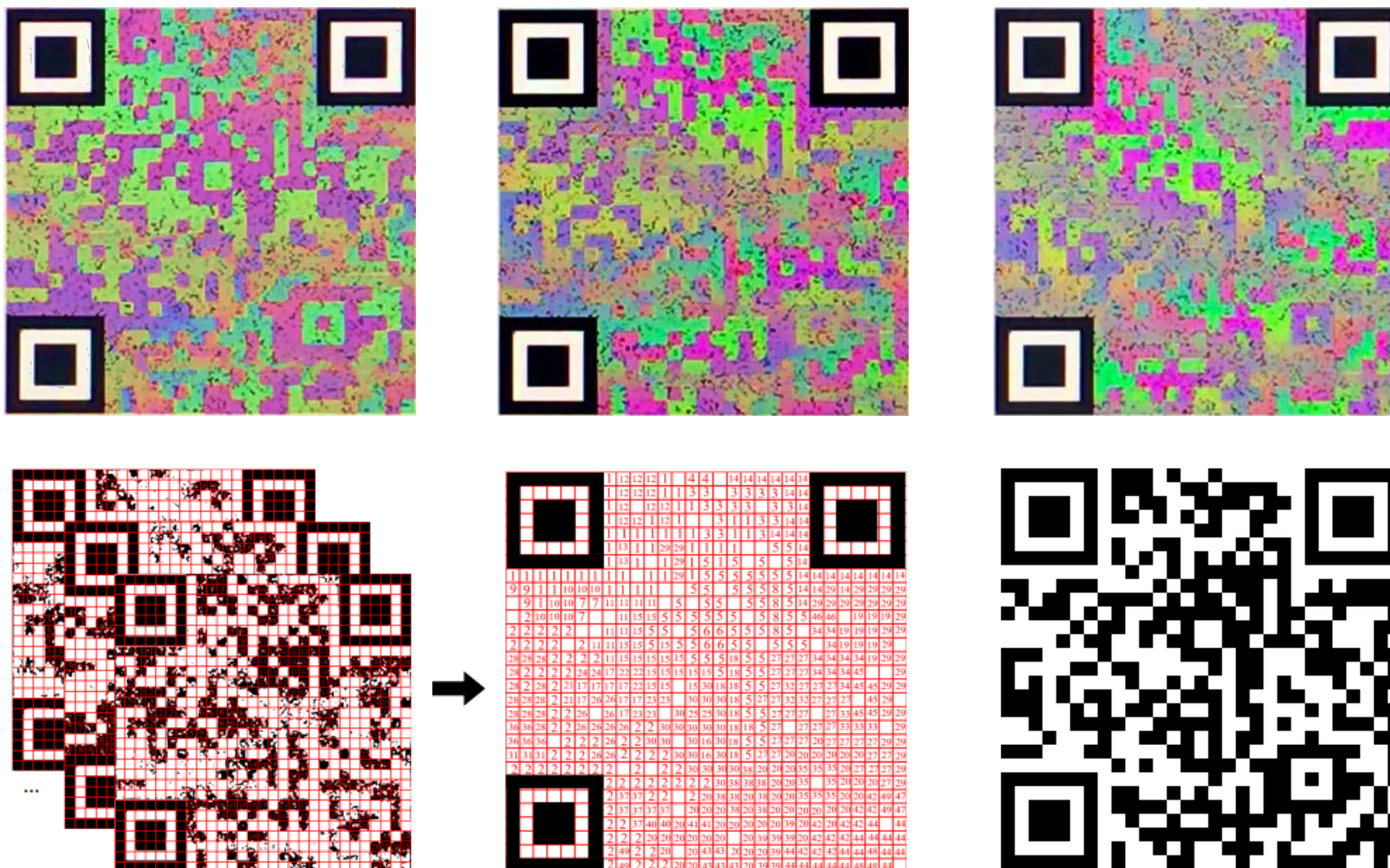




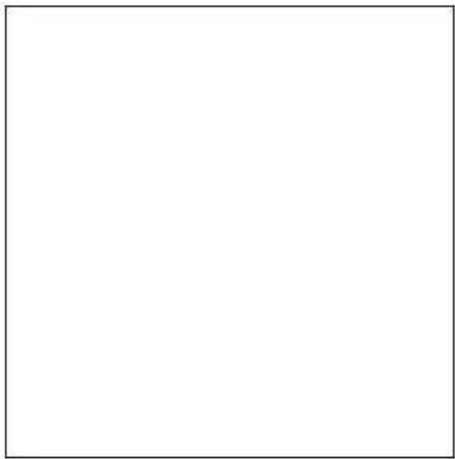
# Decryption: Challenges



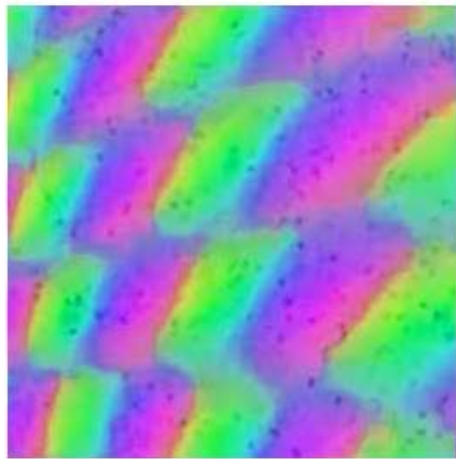
# Decryption: Multi-Frame Decryption Scheme



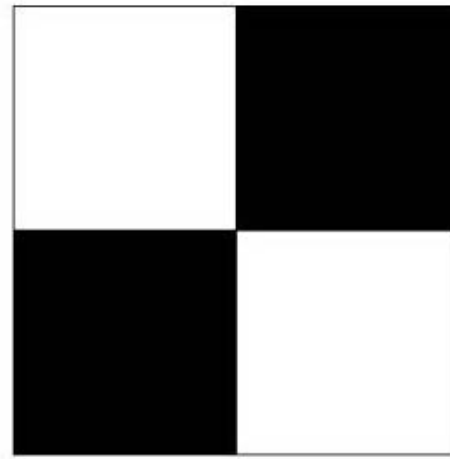
# Fast Decryption: Idea



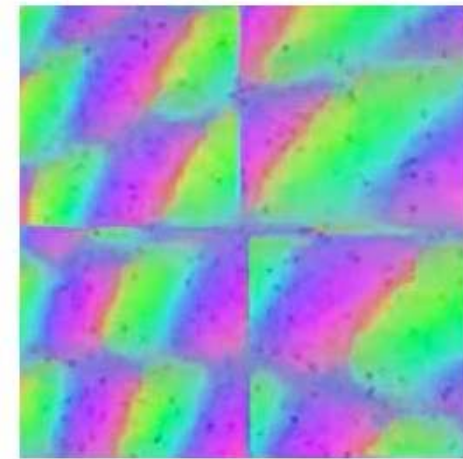
Original  
White Image



Nonlinearity  
between camera and  
display

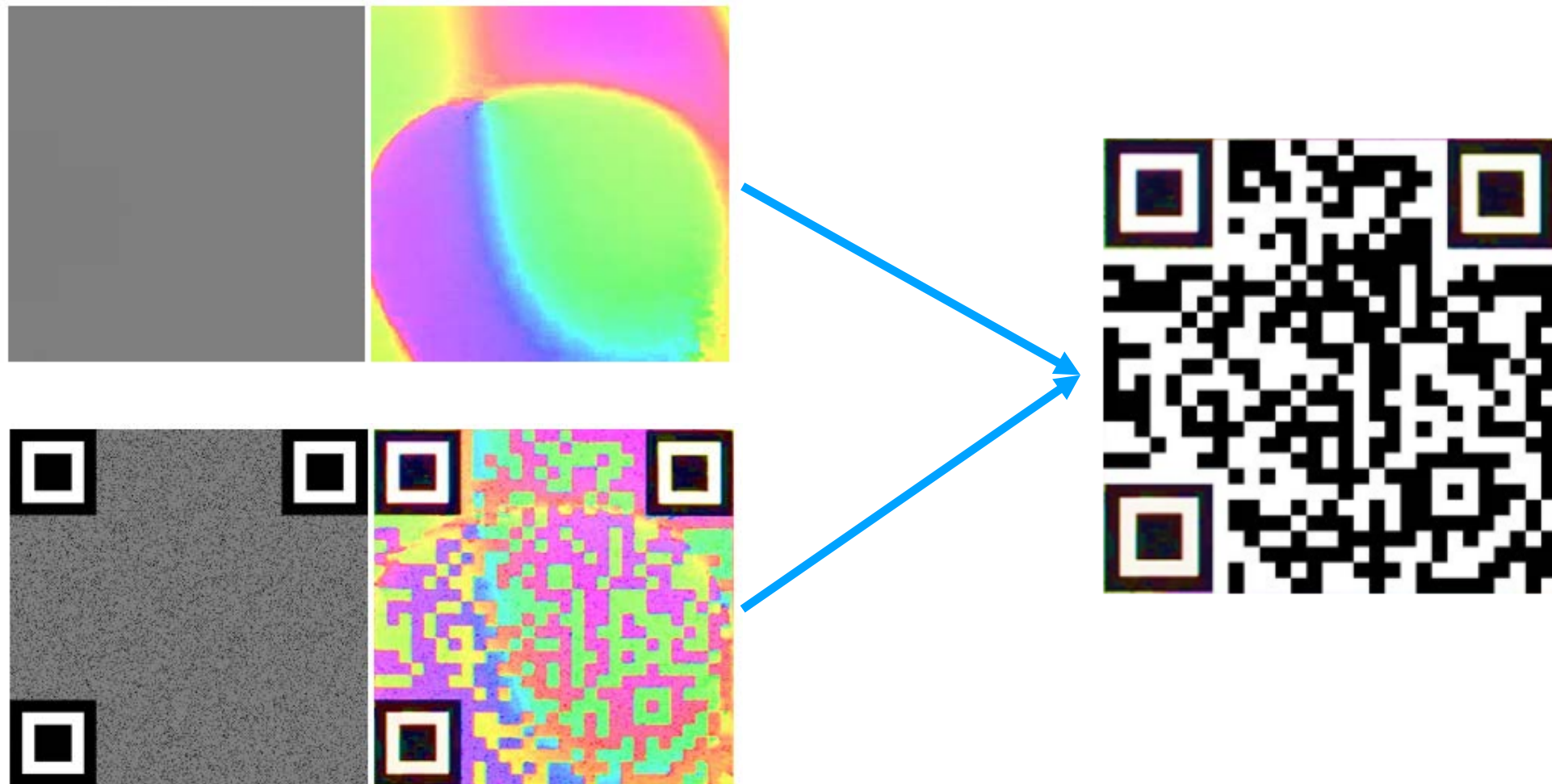


Original  
White/Black  
Image



Nonlinearity  
between camera and  
display

# Fast Decryption: Method



# Backup

Alipay System and STLS Attack

System Overview

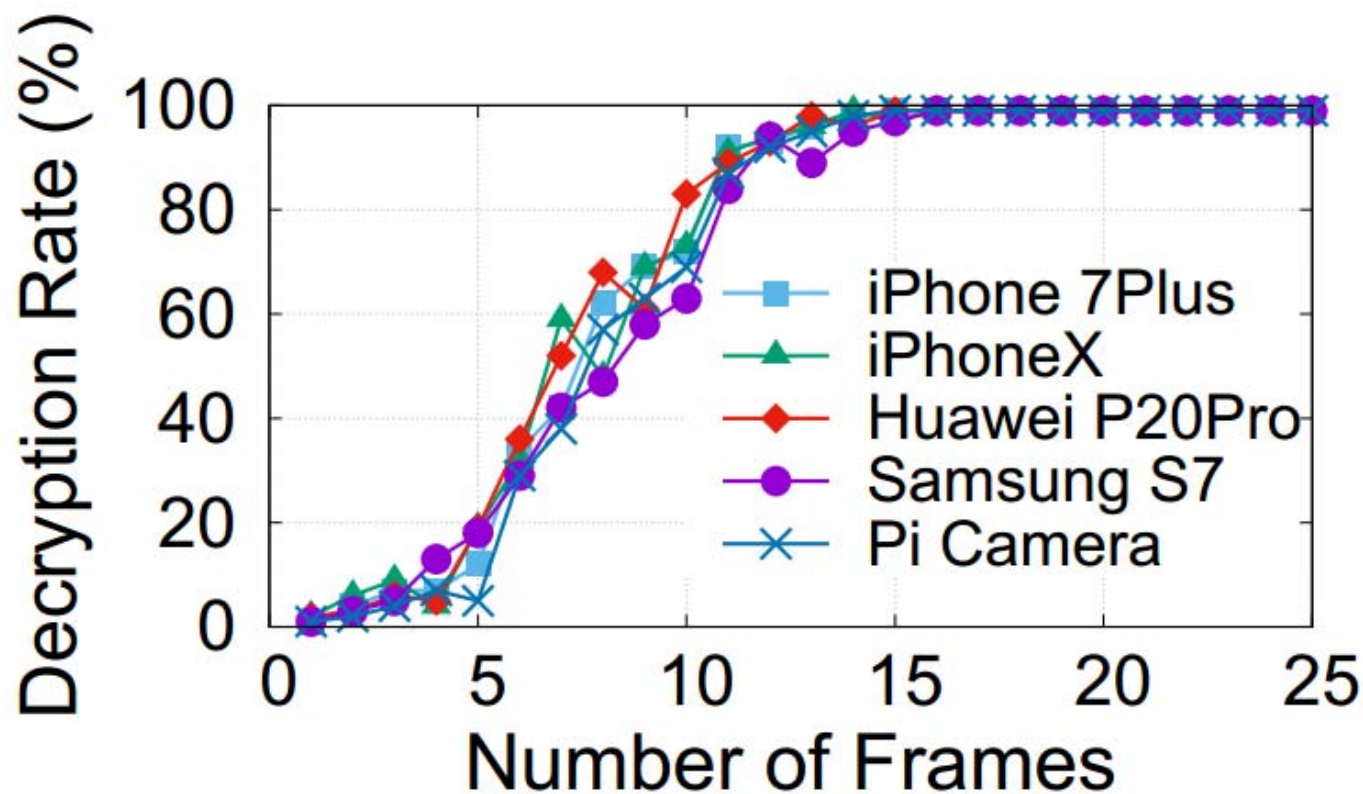
Pinhole Imaging Model

Decryption Scheme

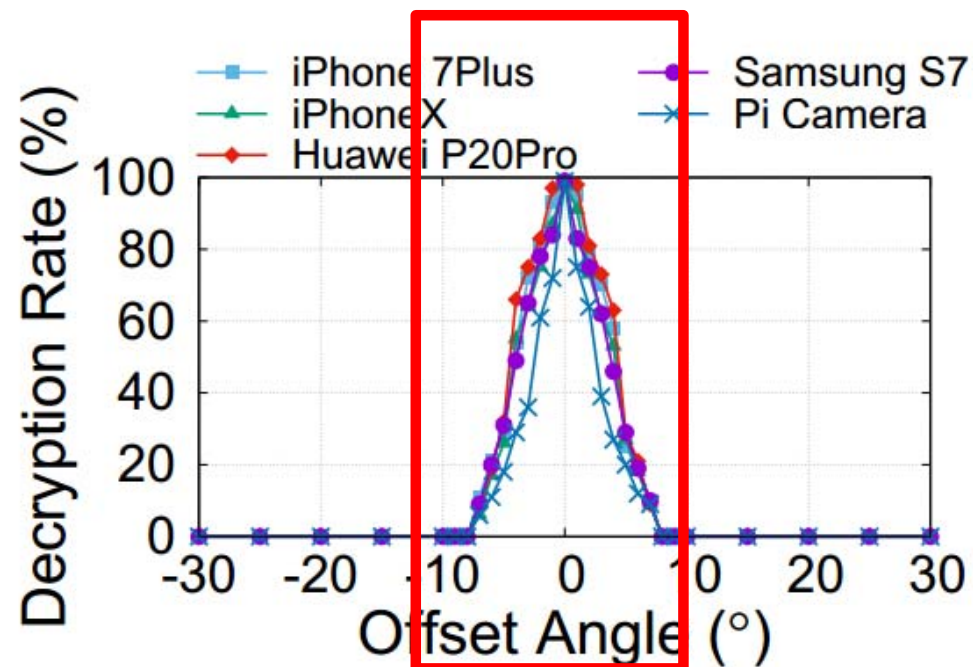
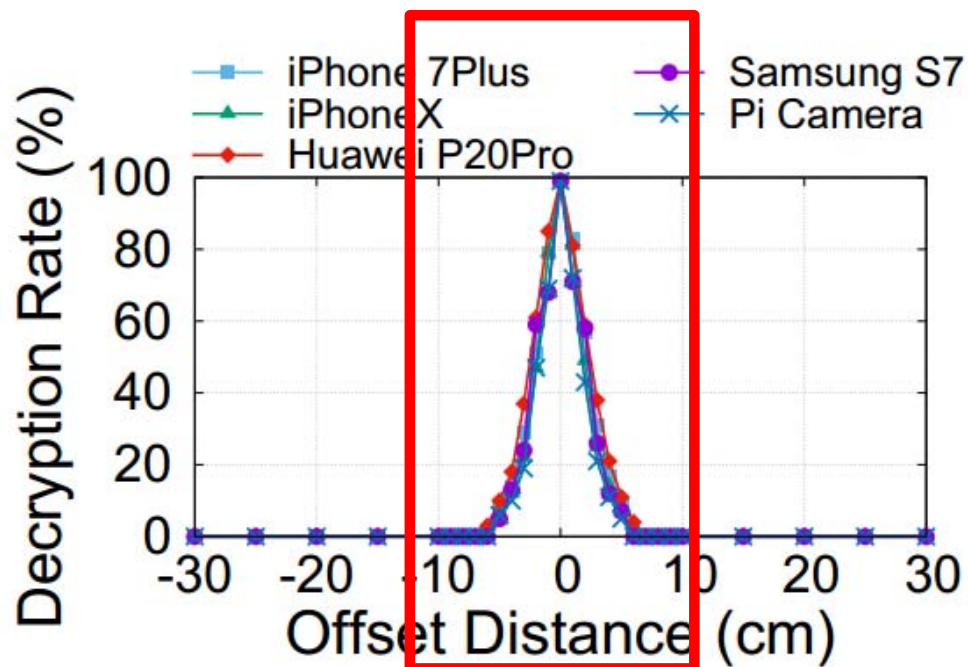
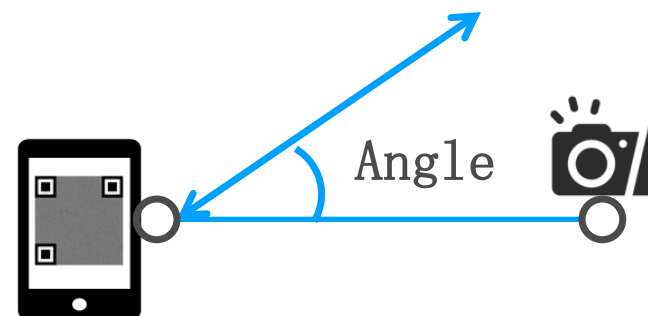
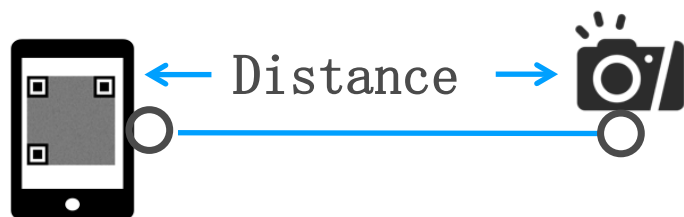
**Evaluation (Supplement)**

Can mQRCode work with printed QR Code?

# Evaluation: Number of Frames for Decryption



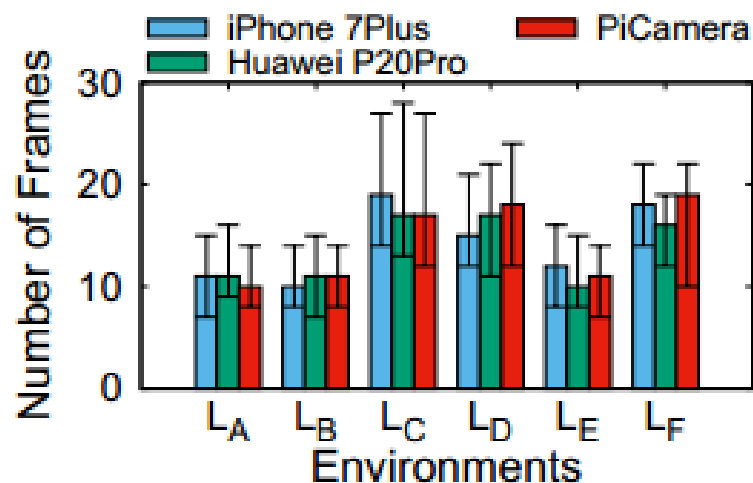
# Evaluation: Fast Decryption



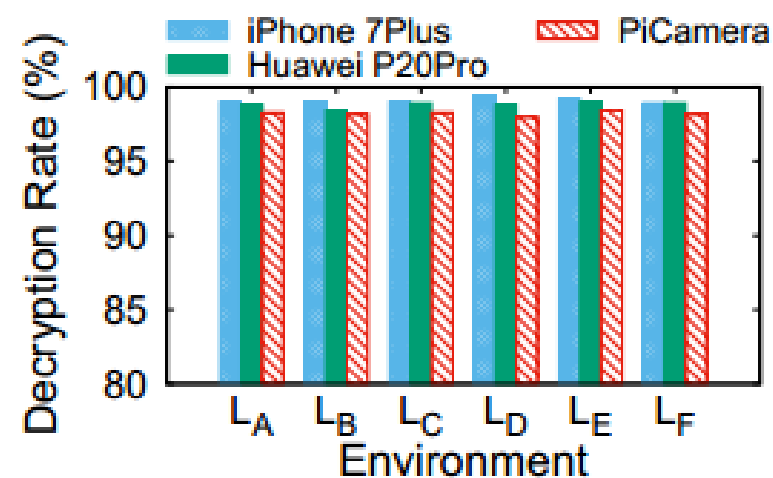
# Evaluation: Lighting Conditions

## Environments

LA: Outdoor at 8 A.M.  
LB: Outdoor at 12 P.M.  
LC: Outdoor at 11 P.M.  
LD: Outdoor in a cloudy day  
LE: Office  
LF: Office with all light off



(a) Multi-frame decryption.

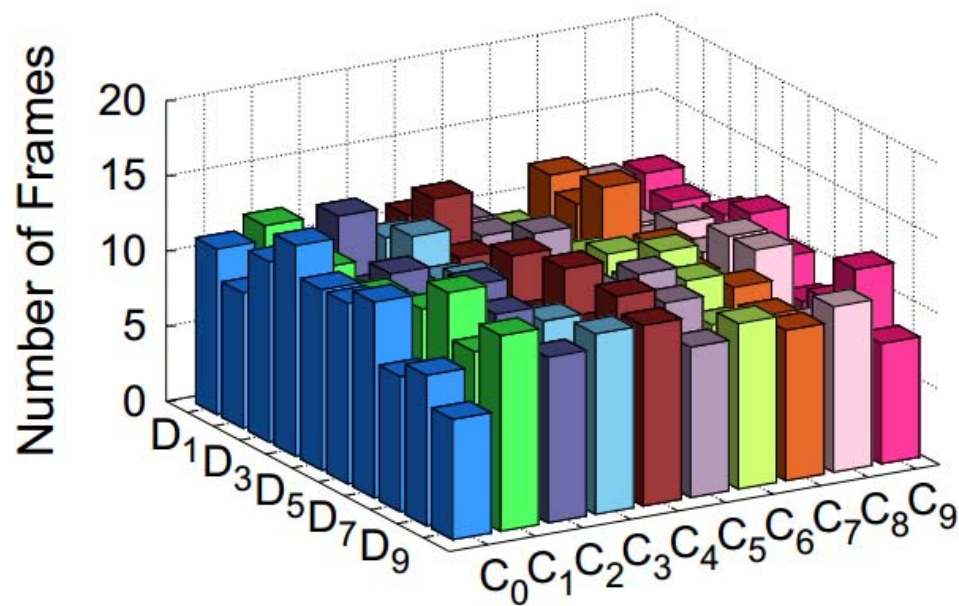


(b) Fast decryption.



# Evaluation: Cameras and Displays

Displays	Cameras
D0: iPhone 6	C0: iPhone 6
D1: iPhone 7Plus	C1: iPhone 7Plus
D2: iPhone X	C2: iPhone X
D3: iPhone XS	C3: iPhone XS
D4: Huawei P20Pro	C4: Huawei P20Pro
D5: Samsung S7	C5: Samsung S7
D6: Nexus 6P	C6: Nexus 6P
D7: Google Pixel 2	C7: Google Pixel 2
D8: DELL S2340M	C8: Pi Camera (5MP)
D9: MacBookPro 2016	P9: Pi Camera (8MP)



Multiframedirection

# Backup

Alipay System and STLS Attack

System Overview

Pinhole Imaging Model

Decryption Scheme

Evaluation (Supplement)

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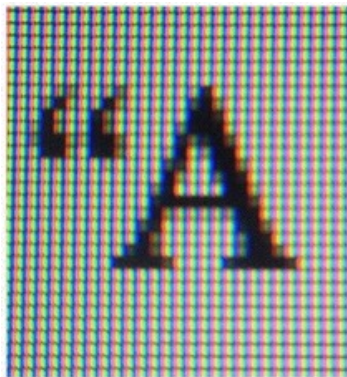
# Can mQRCode work on printed QR Code?



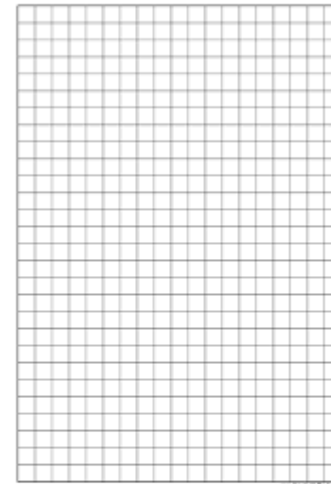
Display



Printer



Pixel Array



Point Array