

Exhibit 7

Anatomy of a Subway Hack

Russell Ryan

Zack Anderson

Alessandro Chiesa

For updated slides and code, see: <http://web.mit.edu/zacka/www/subway/>

what this talk is:

Pen-testing a subway system



what this talk is not:

evidence in court
(hopefully)

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You'll learn how to

- Generate stored-value fare cards
- Reverse engineer magstripes
- Hack RFID cards
- Use software radio to sniff
- Use FPGAs to brute force
- Tap into the fare vending network
- Social engineer
- WARCART!

AND THIS IS VERY ILLEGAL!

So the following material is for educational use only.

5



Boston T System Vulnerabilities



Legend

- network vulnerabilities
- social engineering weakness
- confidential information
- open locks

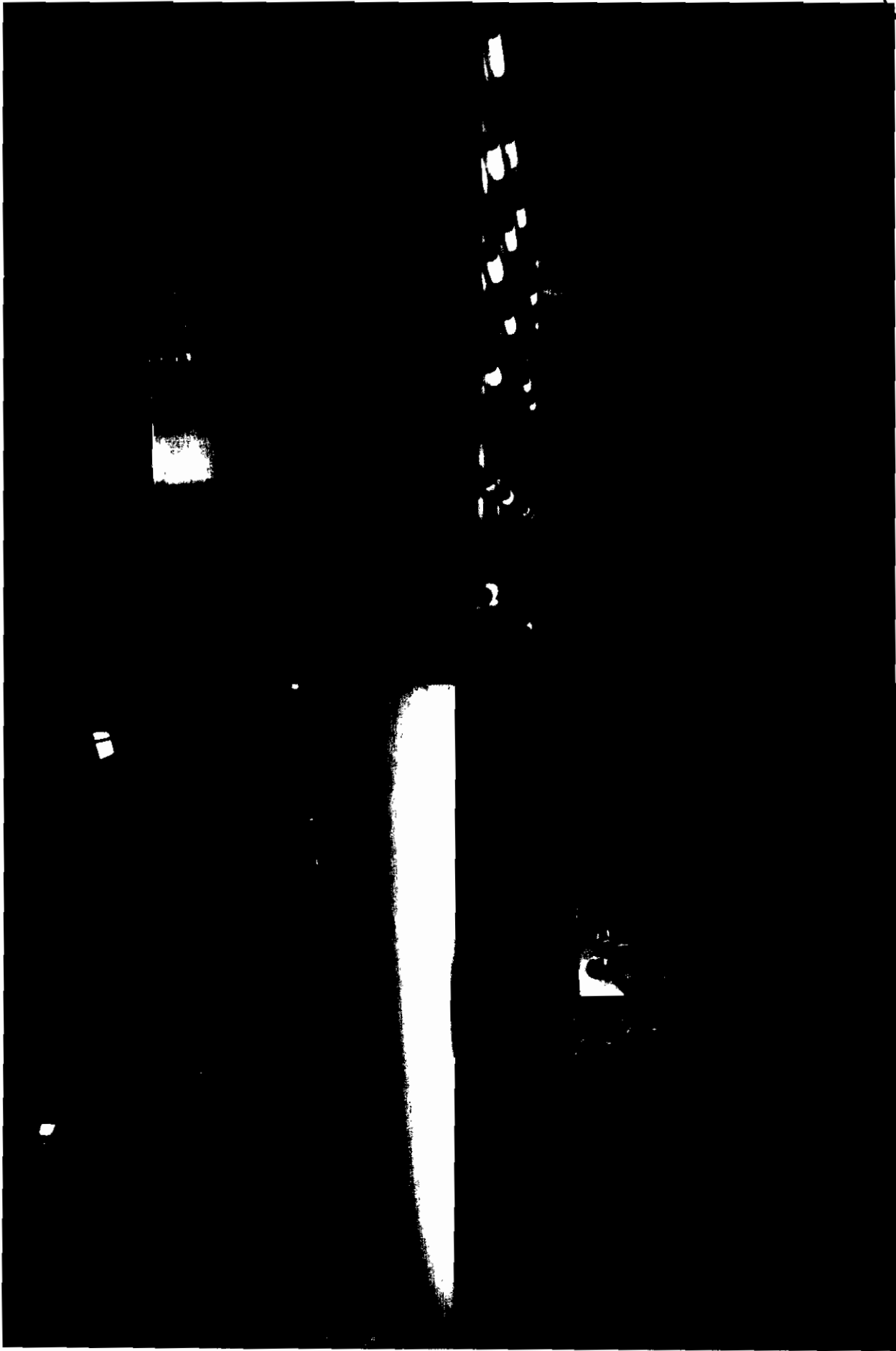


1

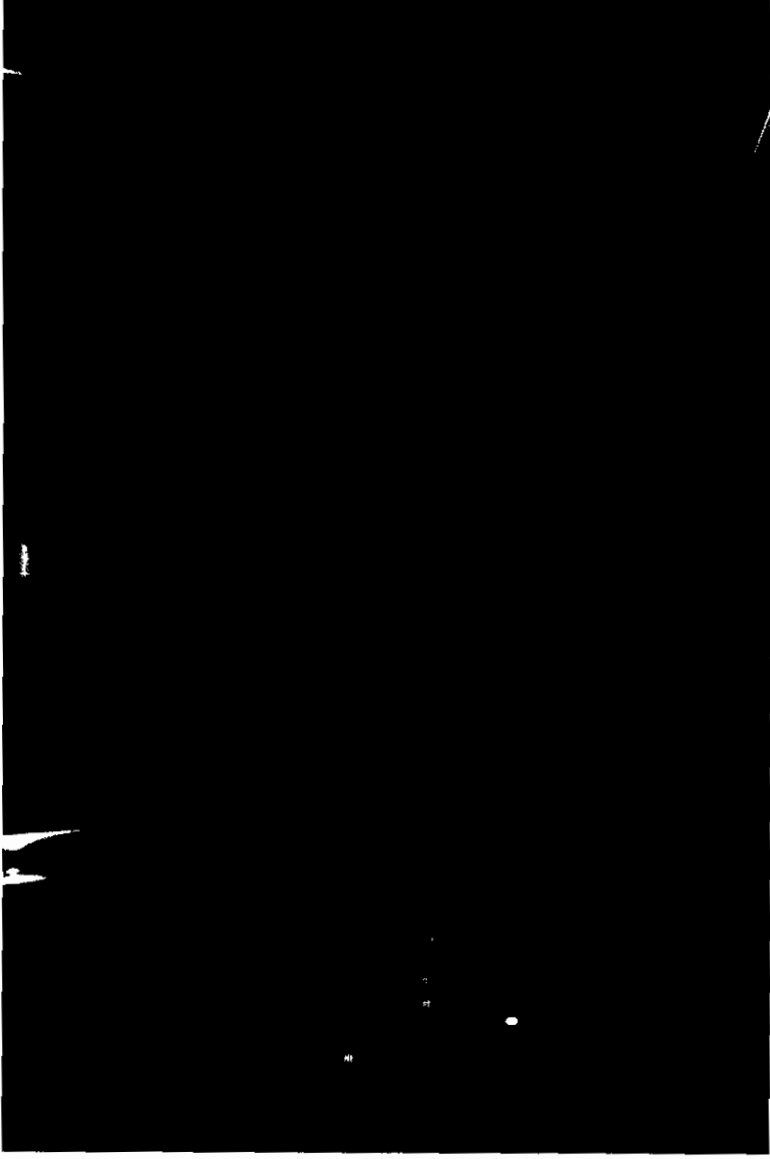


**ATTACK
PHYSICAL
SECURITY**

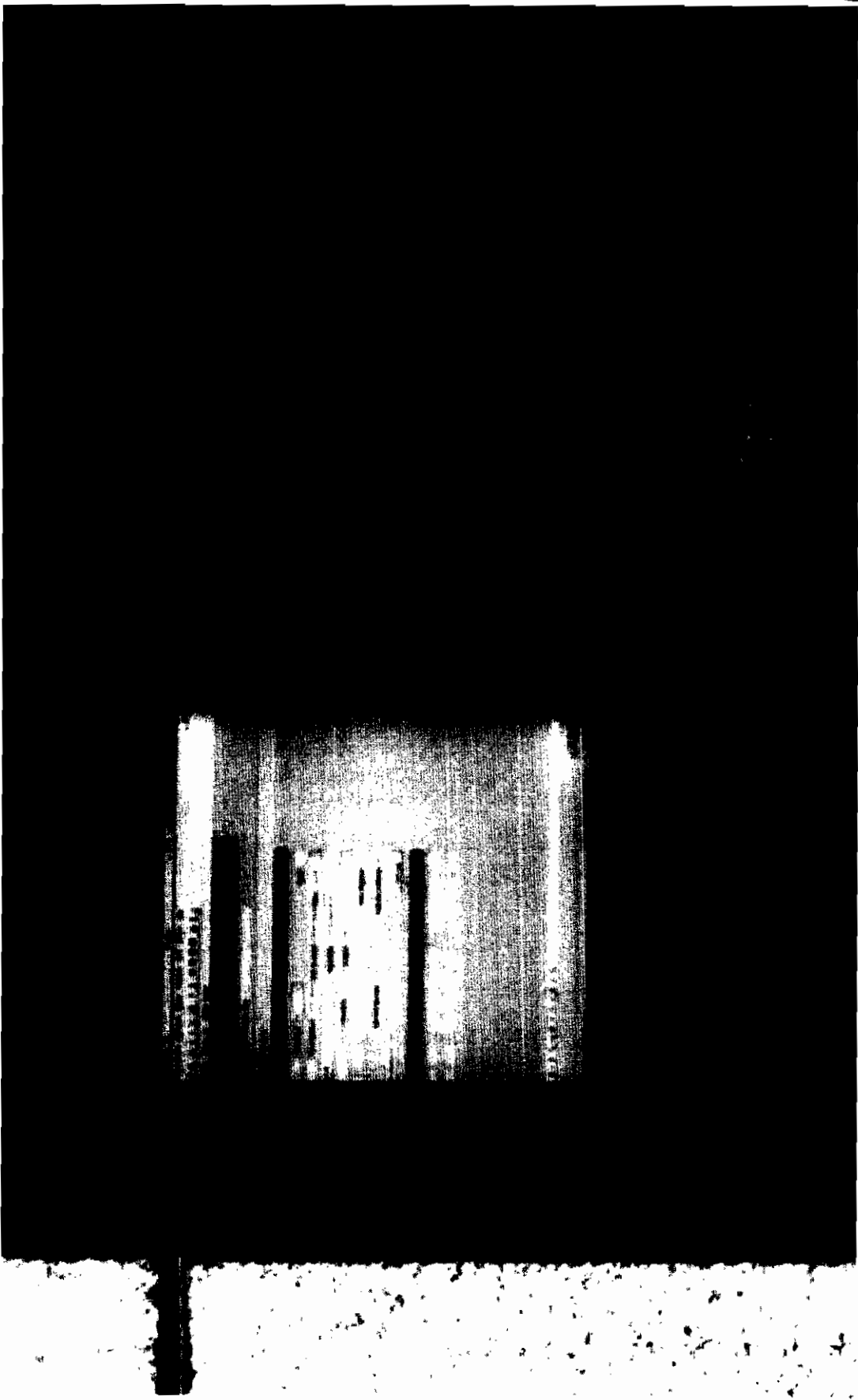
there is almost always a free way to get in



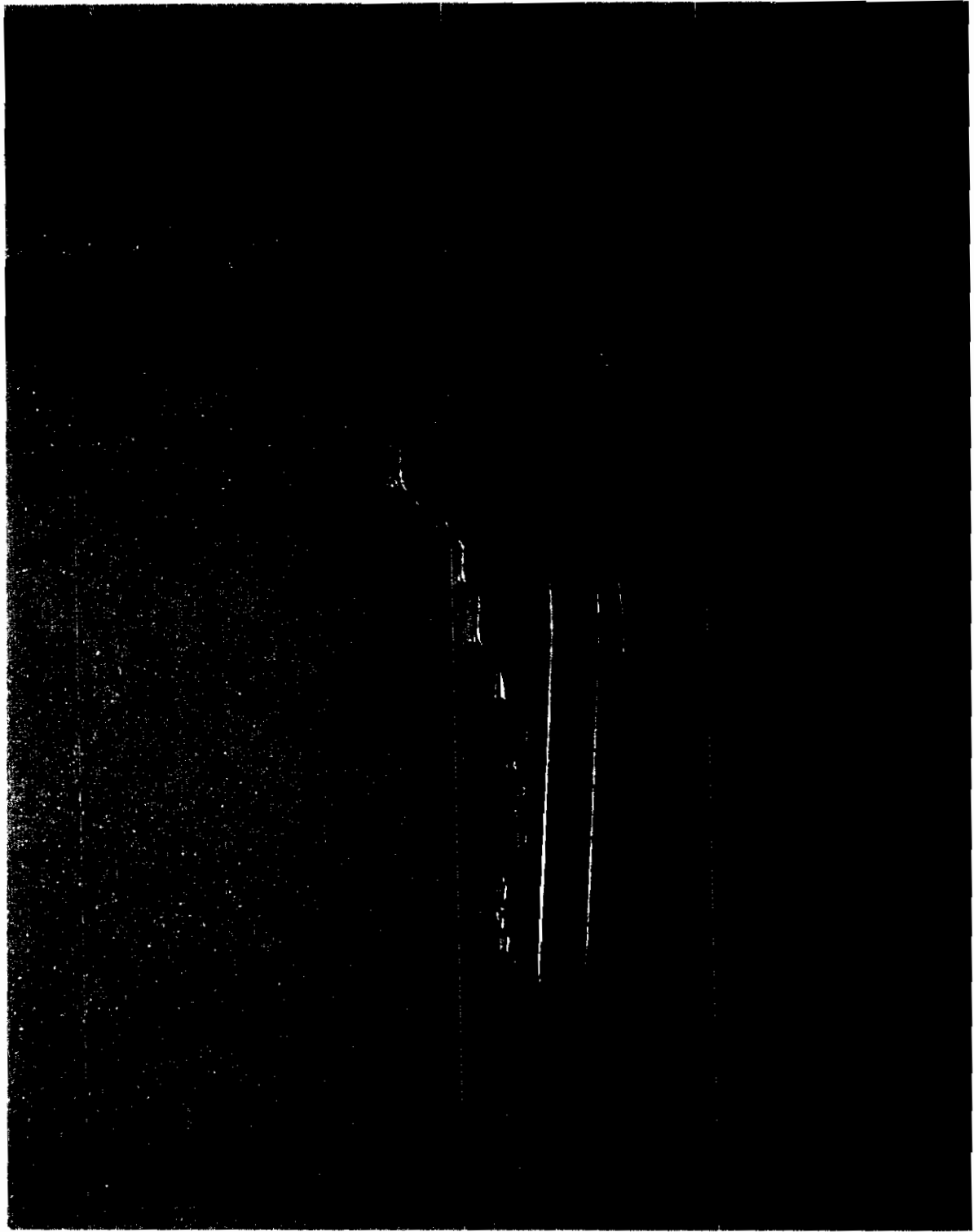
**turnstile control boxes open...
almost everywhere**



computer screens visible through windows

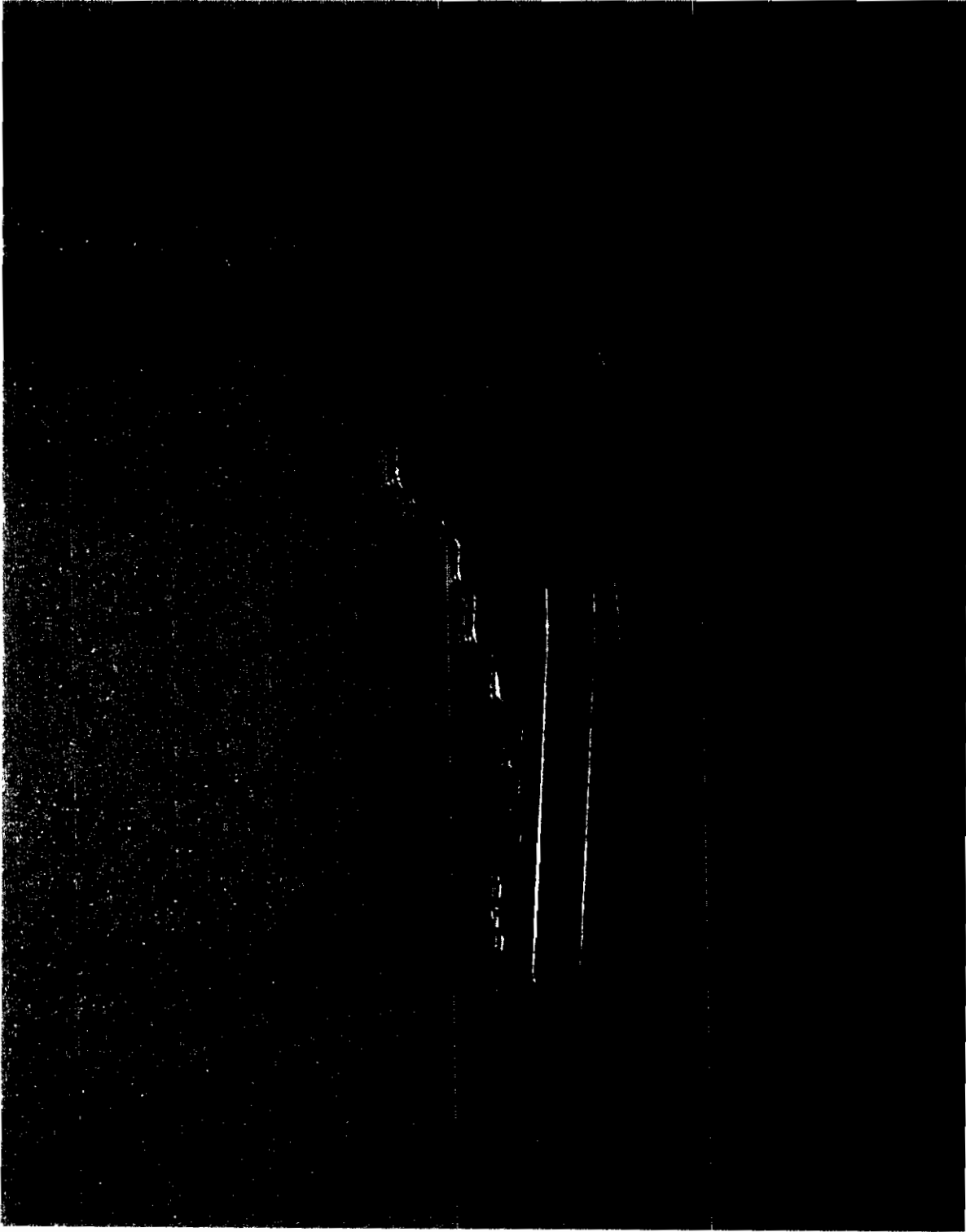


door keys left in open boxes



11

door keys left in open boxes

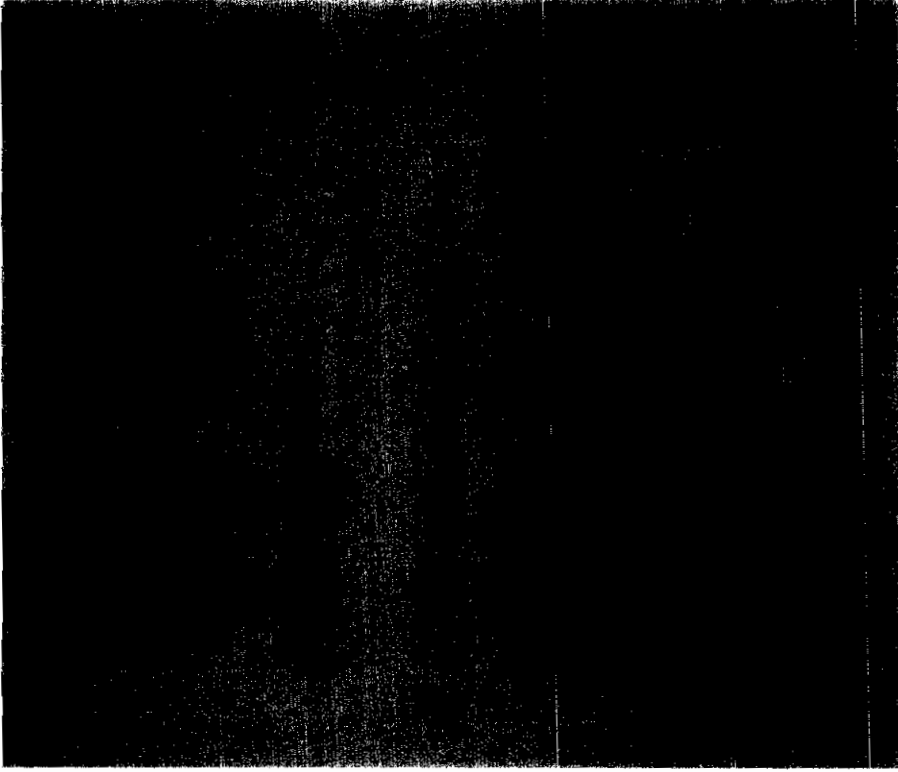


(12)

state-of-the-art surveillance... often unattended

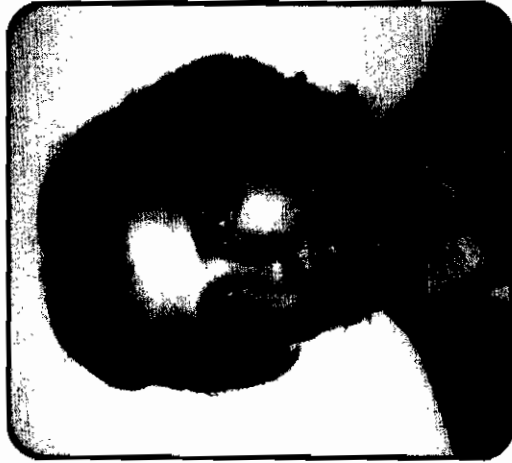


documents left in the open



Document Name	Path	Access	Permissions
Document 1	C:\Users\user\Documents\Doc1.docx	Full Control	Administrators, Full Control
Document 2	C:\Users\user\Documents\Doc2.pdf	Full Control	Administrators, Full Control
Document 3	C:\Users\user\Documents\Doc3.txt	Full Control	Administrators, Full Control

(1)



Employee

Zackary Anderson
Director of Operations,
Red Line
10 Park Plaza

Expires 04/27/2010
5 - 1979832024

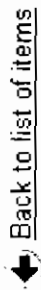
Emp. #
9358211

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Sign in

Categories ▾ Motors Express Stores



Listed in category: [Computers & Networking](#) > [Printers](#)

Fargo DTC515 Thermal Card Printer

Bidder or seller of this item? [Sign in](#) for your status

Current bid: **US \$79.99**



Your maximum bid:

US \$

[Place Bid >](#)

(Enter US \$80.99 or more)

End time:

Jun-29-08 19:43:35 PDT (2 days 1 hour)

Shipping costs:

US \$30.12
UPS Ground
Service to [02142, United States](#)

Ships to:

[United States](#)
[Minneapolis, Minnesota, United States](#)

Item location:

1 of 2

History:

[1 bid](#)

High bidder:

[1***o \(804 ★\)](#)

[View larger picture](#)

You can also:

[Watch This Item](#)

Get [SMS](#) or [IM alerts](#) | [Email to a friend](#)

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what we found on Ebay



(H)

**ATTACK
THE
MAGGARD**

pick the hardware

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\$5<

Homebrew reader

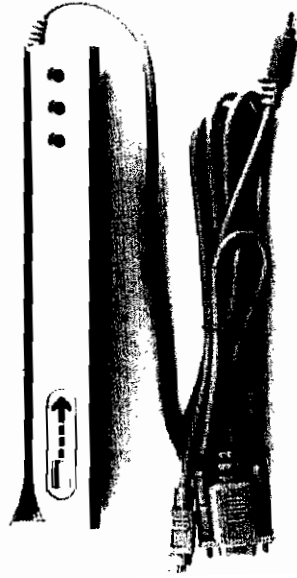
With inserts, can read 3-tracks
stripesnoop.sourceforge.net

\$139.95

Spark Fun Electronics

3-Track Lo-Co

Includes source code

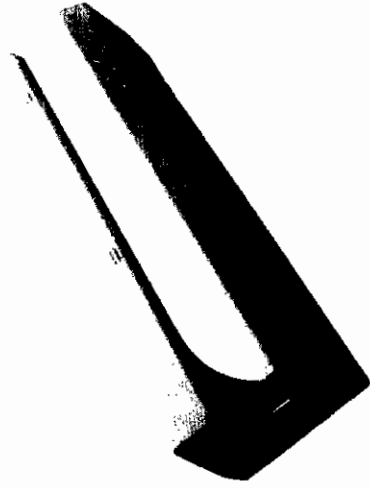


\$300

MSR206 or MAKStripe

3-Track Hi/Lo-Co

Works with our GPL'd software





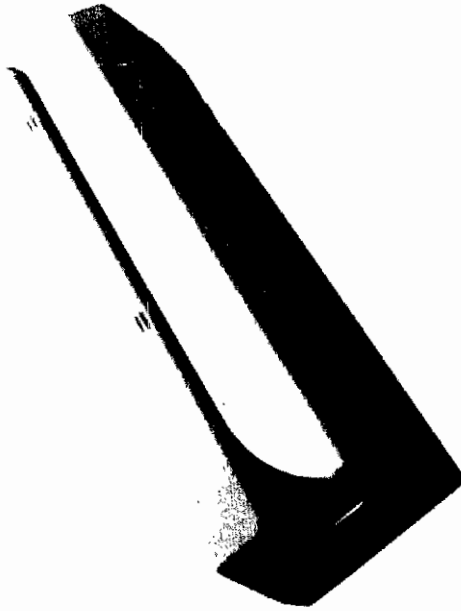
CharlieTicket



12



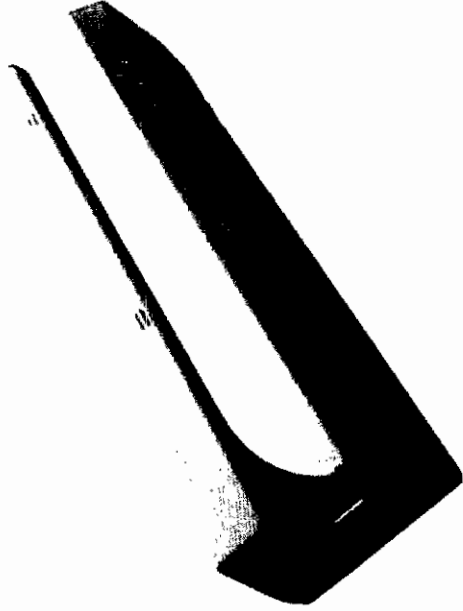
CharlieTicket



22

Ⓟ

CharlieTicket



EC9010402AC9D00000005B800C80150342248A
84EBD132BE1028000200000002025D0000FD60

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Is value stored on the card?

try a cloning attack

2

If yes, then

**you now have free subway
rides for life**

25

Oh,
but you want more than that,
eh?

25

reverse engineering

The Charlie Ticket

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reverse engineering

**Everybody talks about it,
But where do you start?**

- 1) Make a guess about what's in the data
- 2) Change a single variable; see what changes
- 3) Repeat many times with varying data
- 4) Compare similar and dissimilar data
- 5) Ignore constant regions
- 6) Build/use tools

2x

reverse engineering

Isolate Variables method

To locate a single variable:

- Group data by that variable
- Ignore global similarities (between different groups)
- Ignore differences within groups

Resulting locations are probably where the data is stored

28

EC901 0402AC9D 000000005B8 00C8

0150342 248 A84EBD 132 BE 1

028 0002 000000002025D0000 FD60

(29)

EC901 0402AC9D 000000005B8 00C8

const ticket # ticket type value
(ticket / pass) (in cents)

0150342 248 A84EBD 132 BE 1

time const time last last const
reader station (approx)
used used

028 0002 000000002025D000 FD60

last trans # of const checksum
(in nickels) uses (approx)

forging

The Charlie Ticket

15

EC901 0402AC9D 000000005B8 00C8

const ticket # ticket type value
(ticket / pass) (in cents)

0150342 248 A84EBD 132 BE 1

time const time last last const
reader station (approx)
used used

028 0002 000000002025D000 FD60

last trans # of const checksum
(in nickels) uses (approx)

32

EC901 0402AC9D 000000005B8 FE4C

const ticket # ticket type value
(ticket / pass) (in cents)

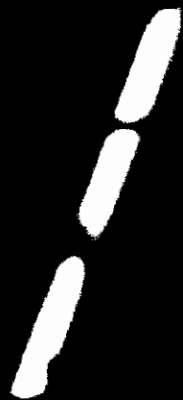
0150342 248 A84EBD 132 BE 1

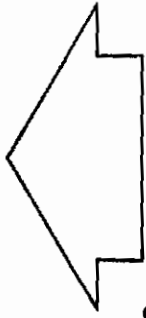
time const time last last const
reader station (approx)
used used

028 0002 000000002025D000 FC90

last trans # of const checksum
(in nickels) uses (approx)

33





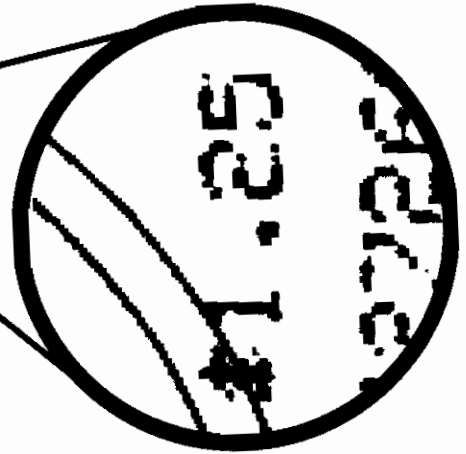
83

MASSACHUSETTS Bay Transportation Authority
ADULT
Stored Value
Expires 08/25/2008



Initial Value: \$1.25
Ticket No: 1-034278680
Cash
08/25/2006 01:27 PM

Subject to applicable tariff regulations and conditions of use. Ticket may be confiscated for misuse. Not replaceable if lost or stolen. Non-refundable.



Schedule & Fare Information: 617-222-3200 Website: www.mbta.com © MBTA

Device: 201144

Kendall/MIT

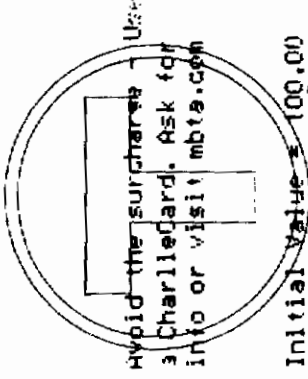
+



=

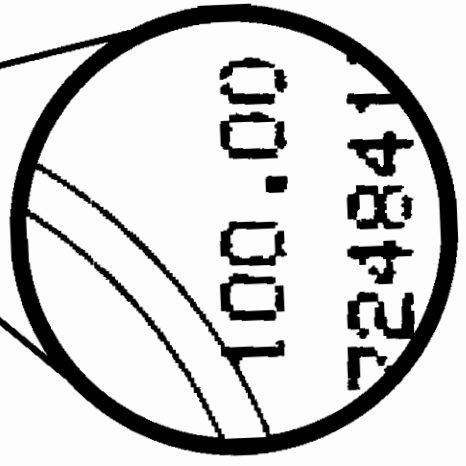
Massachusetts Bay Transportation Authority

Stored Value
CharlieTicket



Initial Value: 100.00
Ticket No: 1-072484133
Cash
06/29/2008 06:45 PM

Subject to applicable tariff regulations and conditions of use. Ticket may be confiscated for misuse. Not replaceable if lost or stolen. Non-refundable.



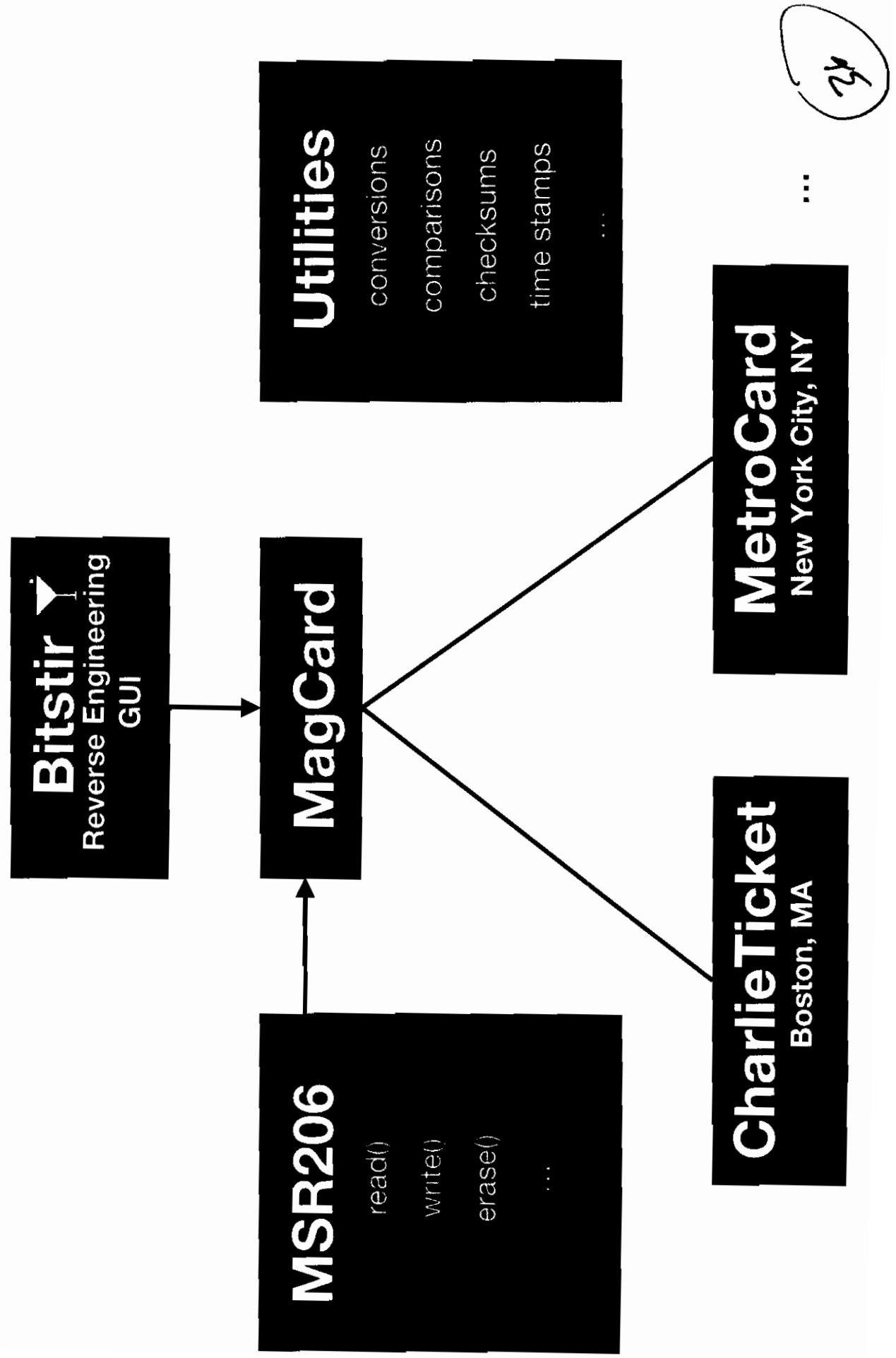
Schedule & Fare Information: 617-222-3200 Website: www.mbta.com © MBTA

Device: 201144

Kendall/MIT

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MagCard Reverse-Engineering Framework



Demo: MagCard and Reverse Engineering Toolkit

- ◆ wrote Python libraries for analyzing magcards
- ◆ integrated with the MSR206 reader/writer
- ◆ GUI helps visualize and organize data



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what about other subways?

- Most subway fare collection systems in US are made by two major integrators
- **Scheidt & Bachmann** made Boston T, San Francisco Bart, Long Island Railroad, Seattle Sound Transit, London Silverlink, etc. systems
- **Cubic Transportation** made NYC MTA, Washington DC WMATA, Chicago CTA, Shanghai Metro, etc. systems

Are they hackable? Yes!

250

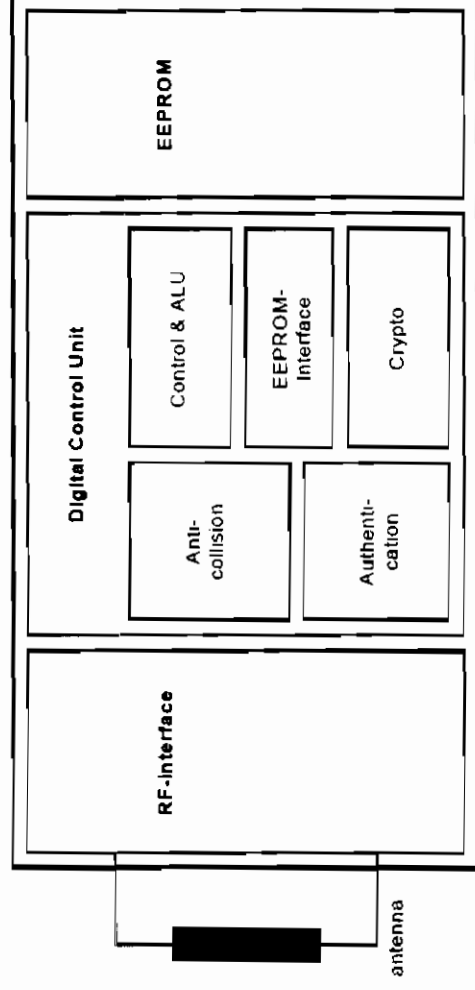
ATTACK THE RFID

learn about your RFID card

40

MIFARE Classic

- 13.56MHz RFID smartcard
- End-to-end proprietary “crypto” (Crypto-1)
- 1K memory & unique identifier on card
- Over 500 million tags in use

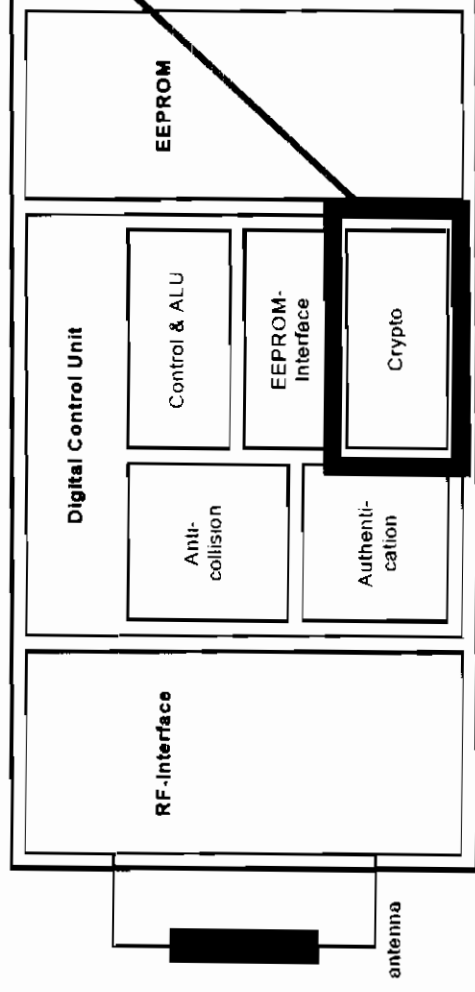


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Crypto-1 Cryptanalysis

Crypto-1 reverse engineered by Karsten Nohl, University of Virginia, 2007:

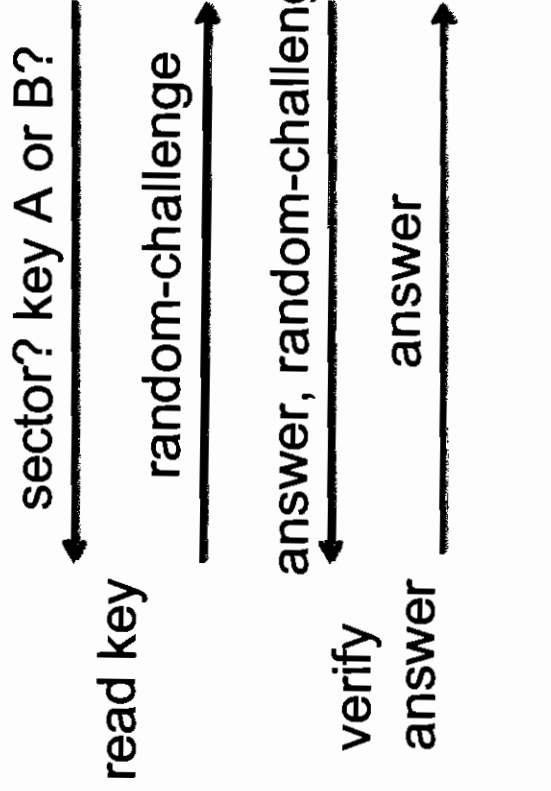
- Etched and inspected silicon wafer using high-powered imagery.
- Found and reconstructed crypto portions from over 10k gates.
- Found vulnerabilities in the cipher and implementation



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security of the MIFARE card

Mutual 3-pass authentication



Each sector two keys

Non-linear filter
functions

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security of the MIFARE card

Mutual 3-pass authentication



sector? key A or B?



read key

random-challenge



answer, random-challenge



verify

answer



verify

answer



Non-linear filter
functions

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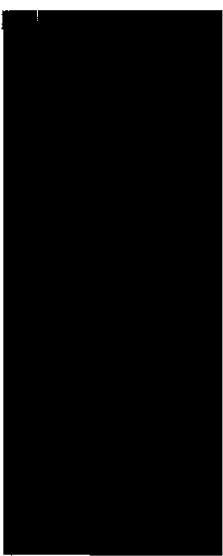
security of the MIFARE card



Non-linear filter
functions

15

security of the MIFARE card



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to execute these attacks we need to interact with the card

choose your hardware



\$50

MiFare RFID Reader/Writer

Comes with source code

Hard to hack, but doable



\$220

OpenPCD + OpenPICC

Open design 13.56MHz RFID reader + emulator

Free schematics (www.openpcd.org)

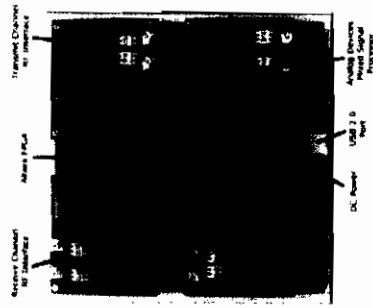


\$700

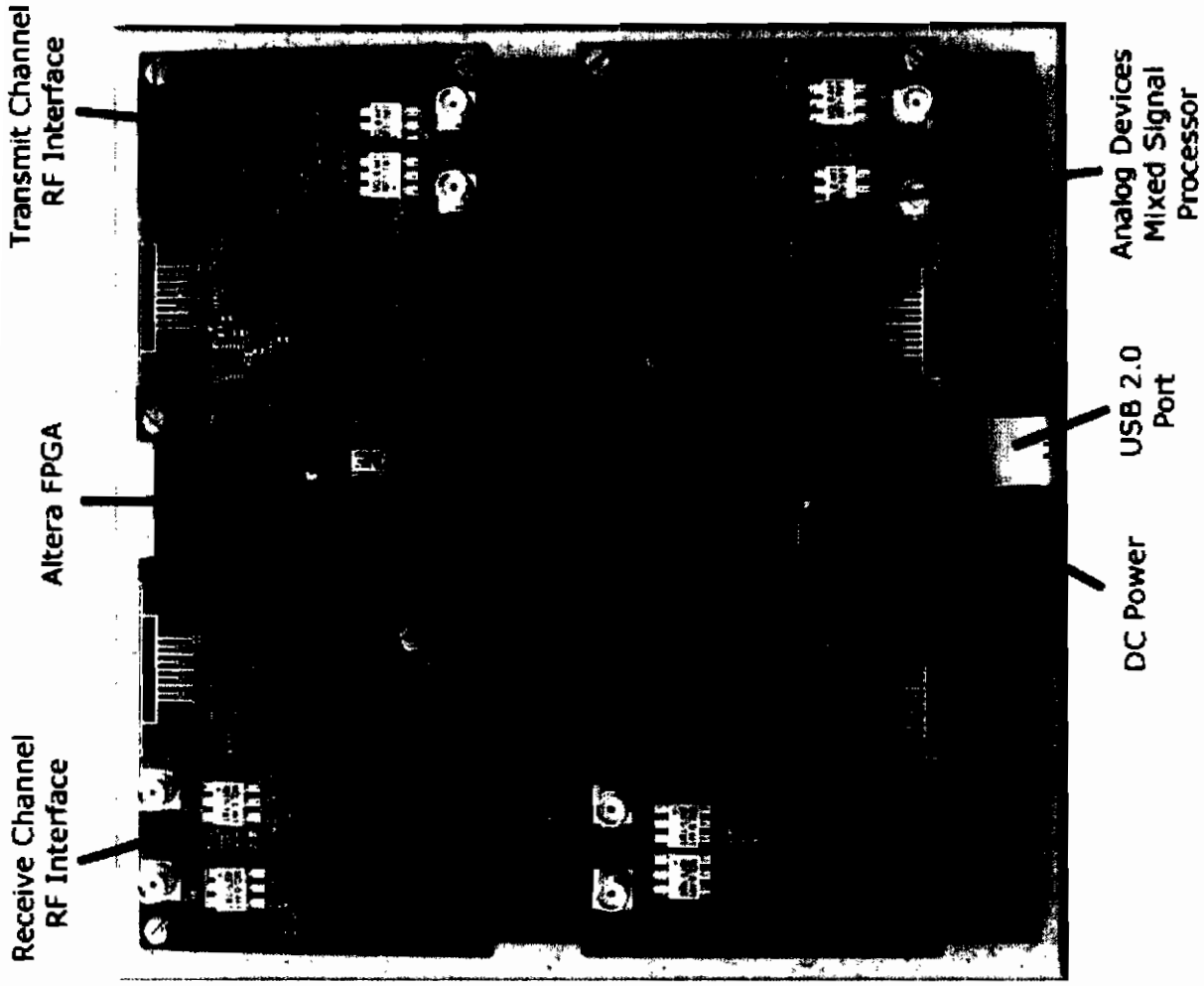
USRP

Full control over signal input/output

Works with GNU Radio + our plugin



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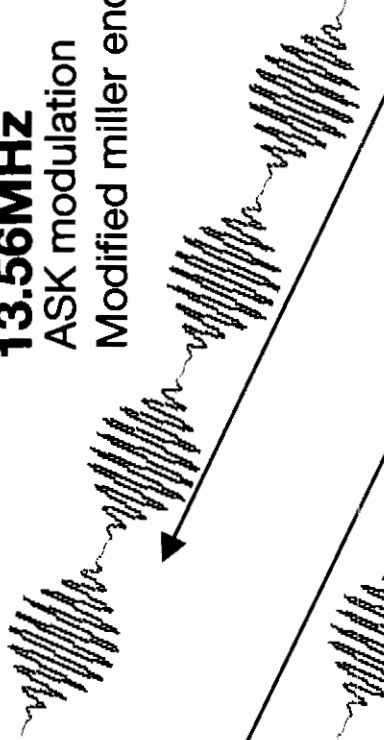
49

USRP

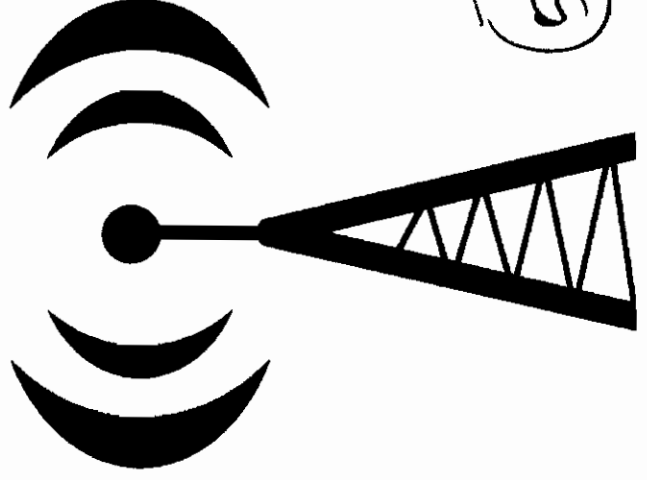
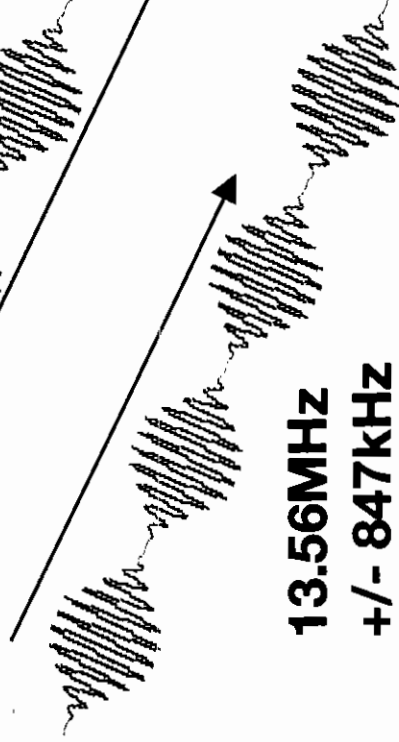
card/reader communication



13.56MHz
ASK modulation
Modified miller encoding



13.56MHz
+/- 847kHz
OOK modulation
Manchester encoding

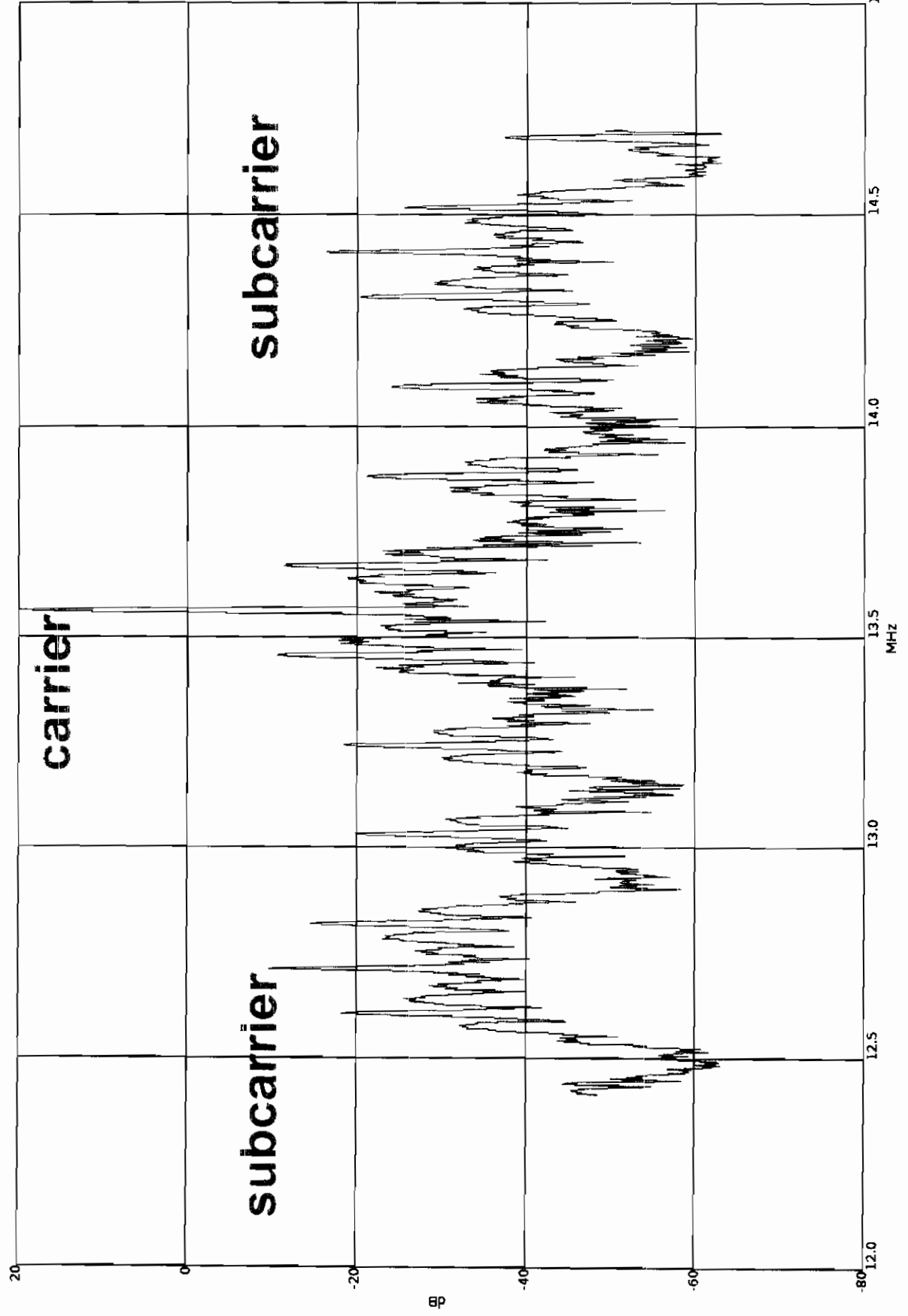


GNU radio RFID toolchain

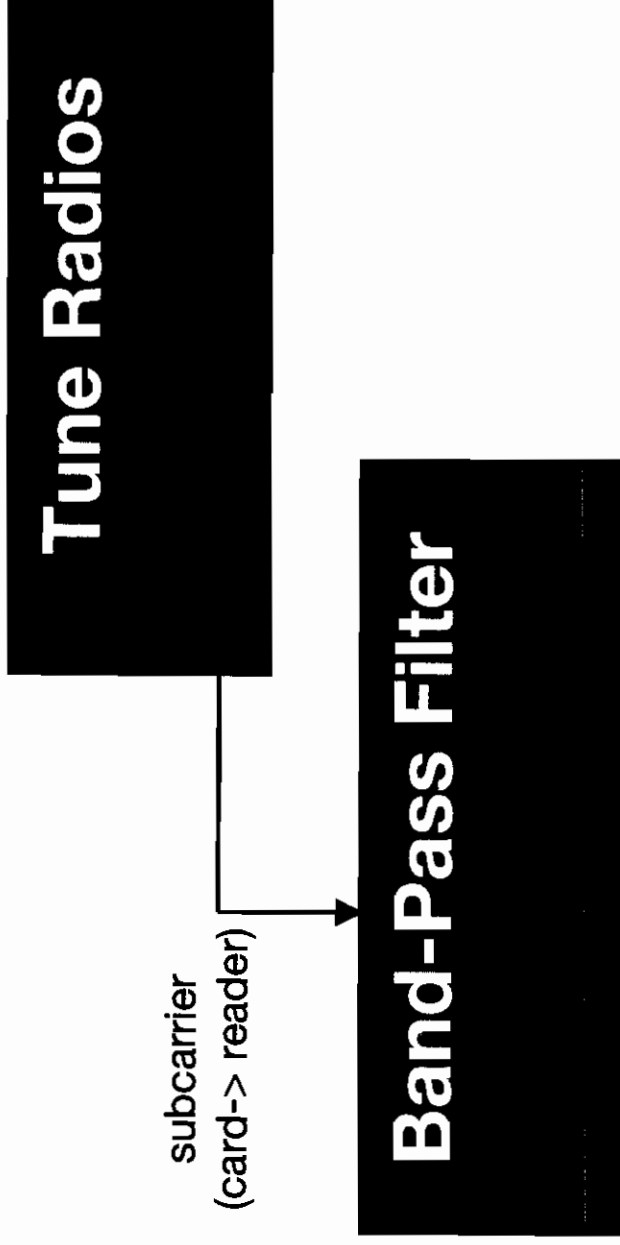
Tune Radios

5

charlie card + reader FFT

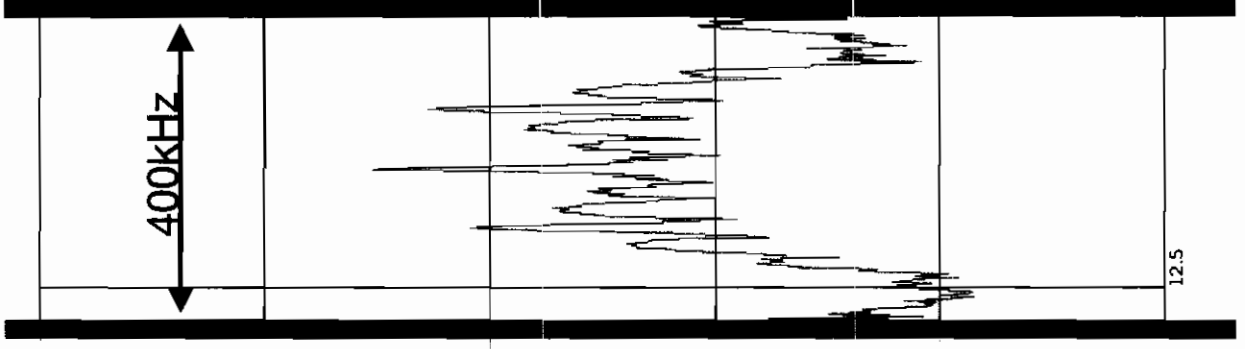


GNU radio RFID toolchain



53

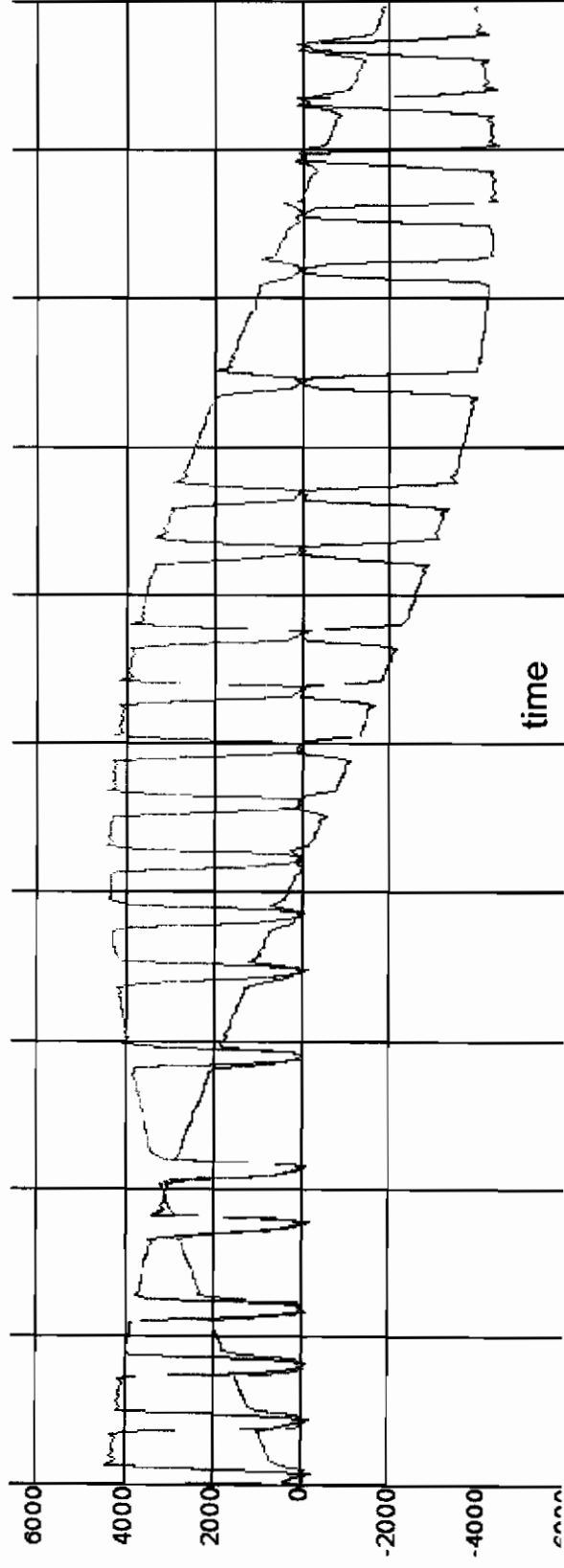
charlie card + reader FFT



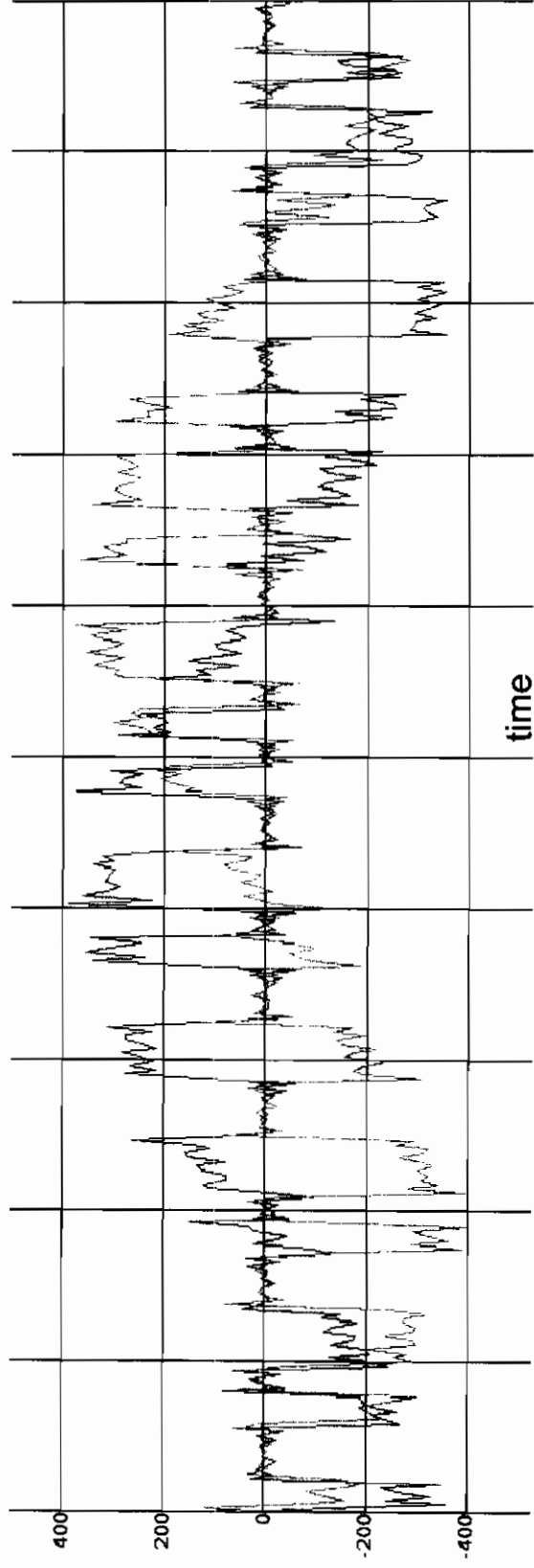
Band Pass Filter

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13.56MHz reader -> card transmission

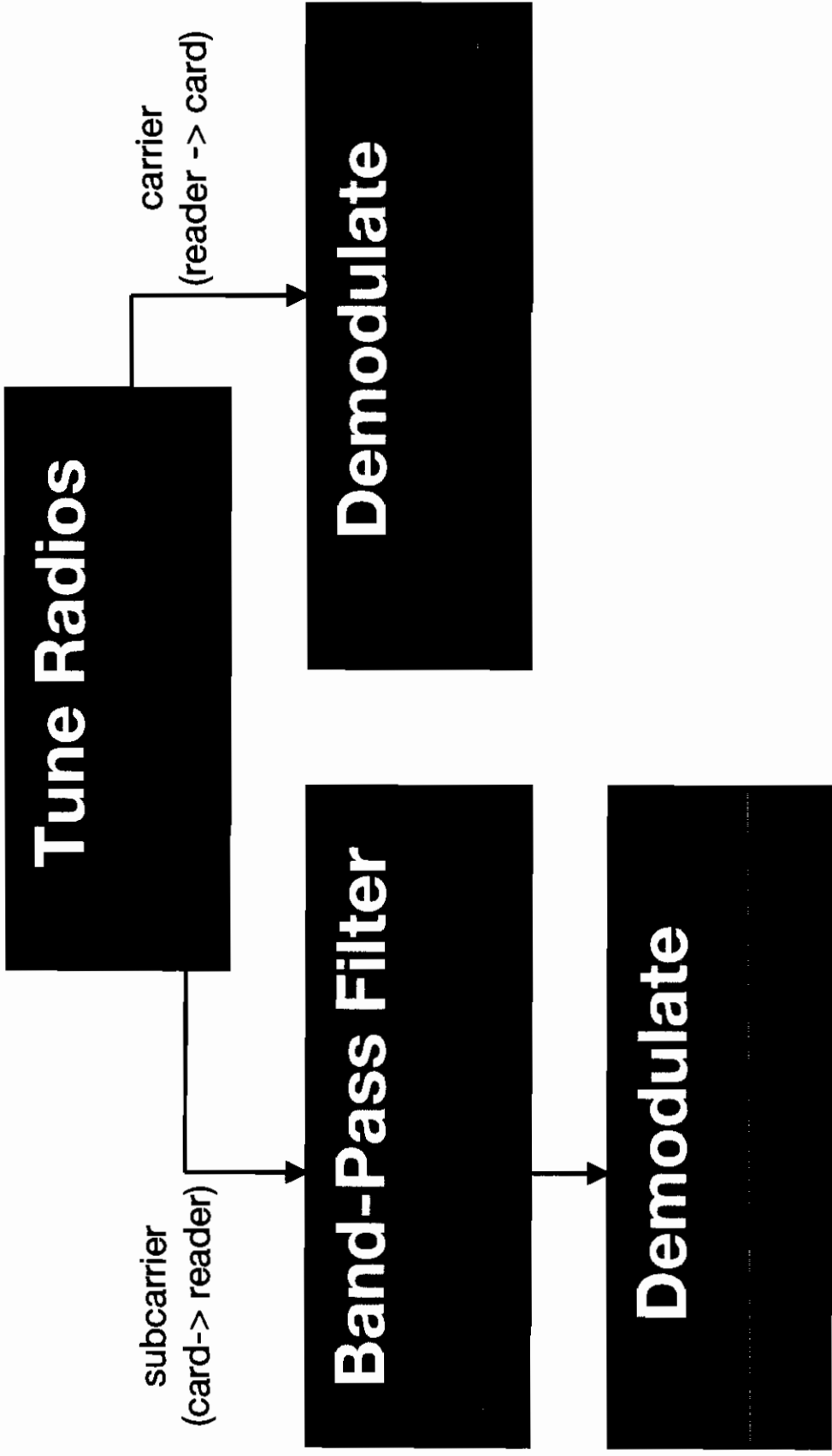


12.71MHz card -> reader transmission

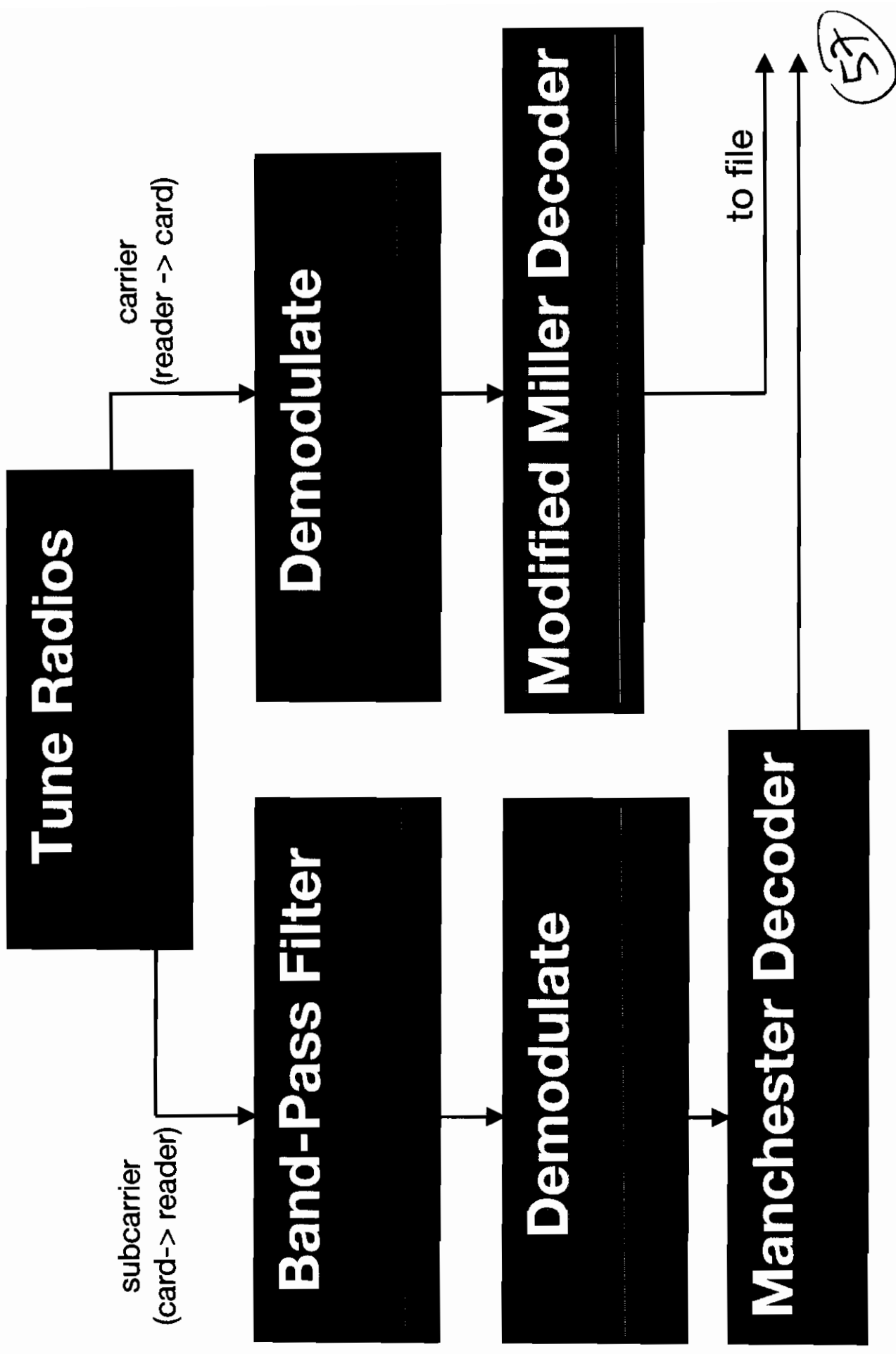


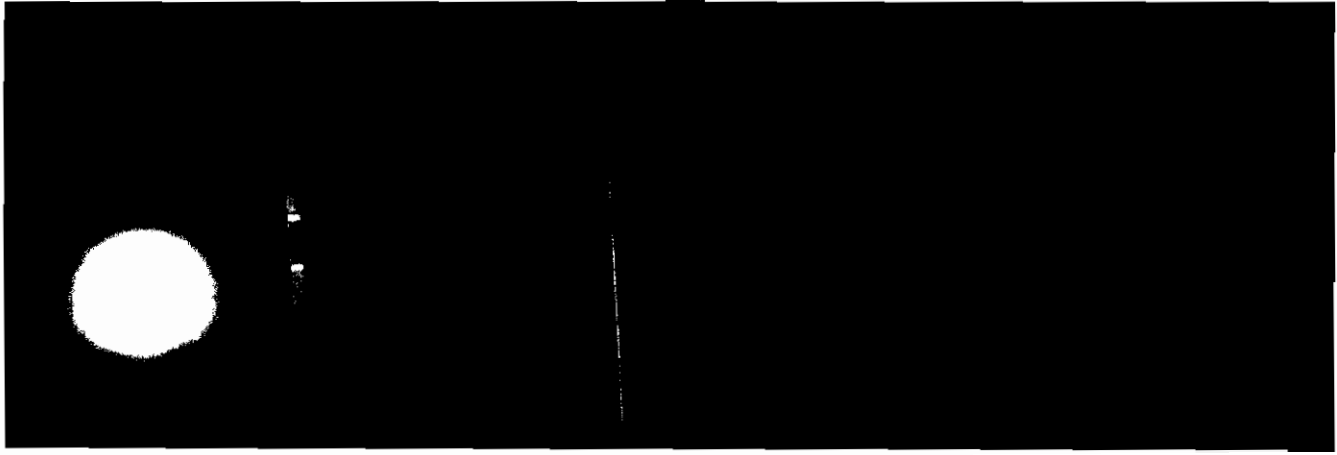
55

GNU radio RFID toolchain

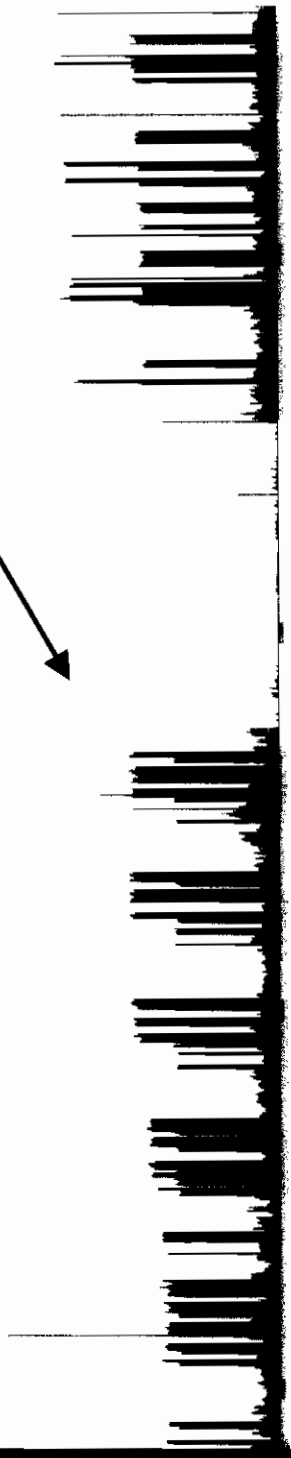


GNU radio RFID toolchain





challenge/response pairs



sniffing the turnstile

85

attacks on the MIFARE card

Goal: get secret key (can clone card with it)

Brute Force

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attacks on the MIFARE card

Goal: get secret key (can clone card with it)

Brute Force

Manipulate PRG Timing

attacks on the MIFARE card

Goal: get secret key (can clone card with it)

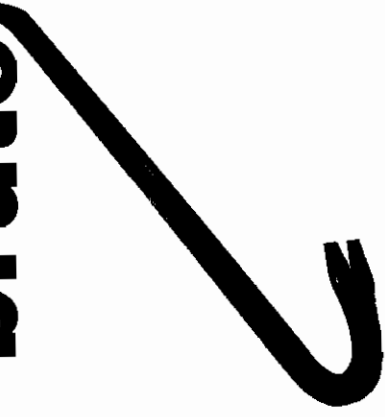
Brute Force

Manipulate PRG Timing

Algebraic Attacks

when all else fails

brute force it

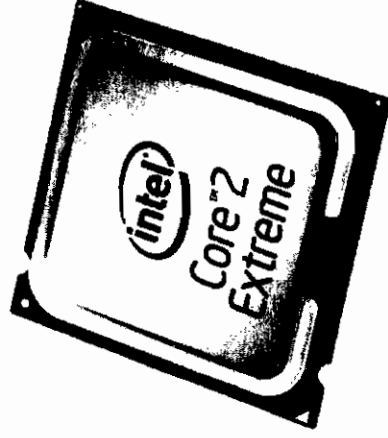


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Why Brute Force with an FPGA?

Because it's fast!

microprocessor



- General purpose device
- Finite instruction set
(Uh, oh. Sounds RISCy)
- 1-8 parallelizations

FPGA

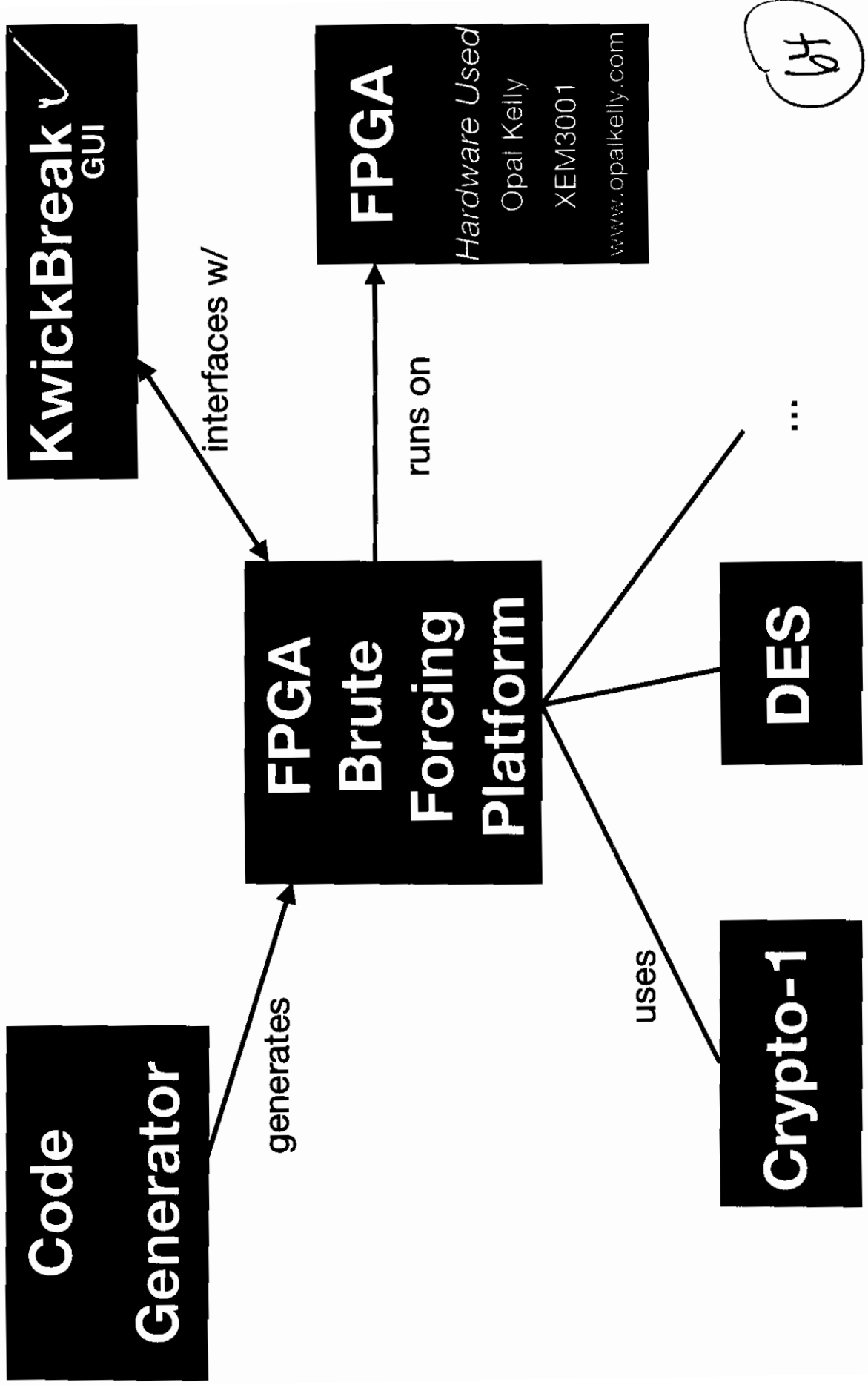


- Dedicated logic
- Hardware description language defines hardware
- Hundreds of parallelizations

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KwickBreak FPGA Brute-Forcer

Executes known plaintext attack to recover key



KwickBreak



Plaintext

DEAD

BEEF

FOOF

Ciphertext

7407

1444

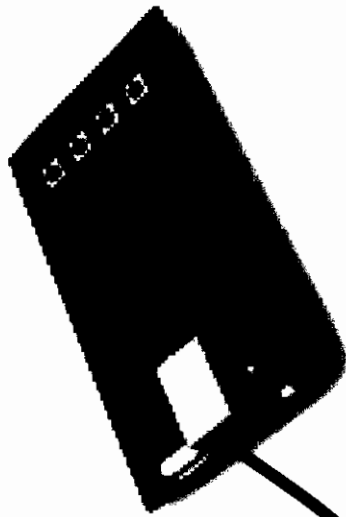
E338

Key - Result

AAAA

AAAB

1337



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writing a (trivial) XOR module

```
module xorPlugin(  
    input wire clk,  
    input wire [47:0] key,  
    input wire [47:0] plaintext,  
    output reg [47:0] encrypted,  
    output reg ready);  
  
    always @(posedge clk) begin  
        ready <= 1;  
        encrypted <= key ^ plaintext;  
    end  
endmodule
```

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writing a (trivial) XOR module (cont)

```
./kwickbreakGenerator.py  
>>>  
Please enter your plugin module name, as written.  
xorPlugin  
Output filename (and path)  
xorBruteForceUtil.v  
How many cores would you like on the chip?  
50  
If you have a pipelined design, how many clock delays for valid data?  
0  
xorBruteForceUtil.v successfully written!
```

Now just create a new project in Xilinx ISE,
load the files, and synthesize

Done!



Subways using MiFare Classic

- Boston (CharlieCard)
- London (Oyster Card)
- Netherlands (OV-Chipkaart)
- Minneapolis
- South Korea (Upass)
- Hong Kong
- Beijing
- Madrid (Sube-T)
- Rio de Janeiro (RioCard)
- New Delhi
- Bangkok

and more

9



**ATTACK
THE
NETWORK**

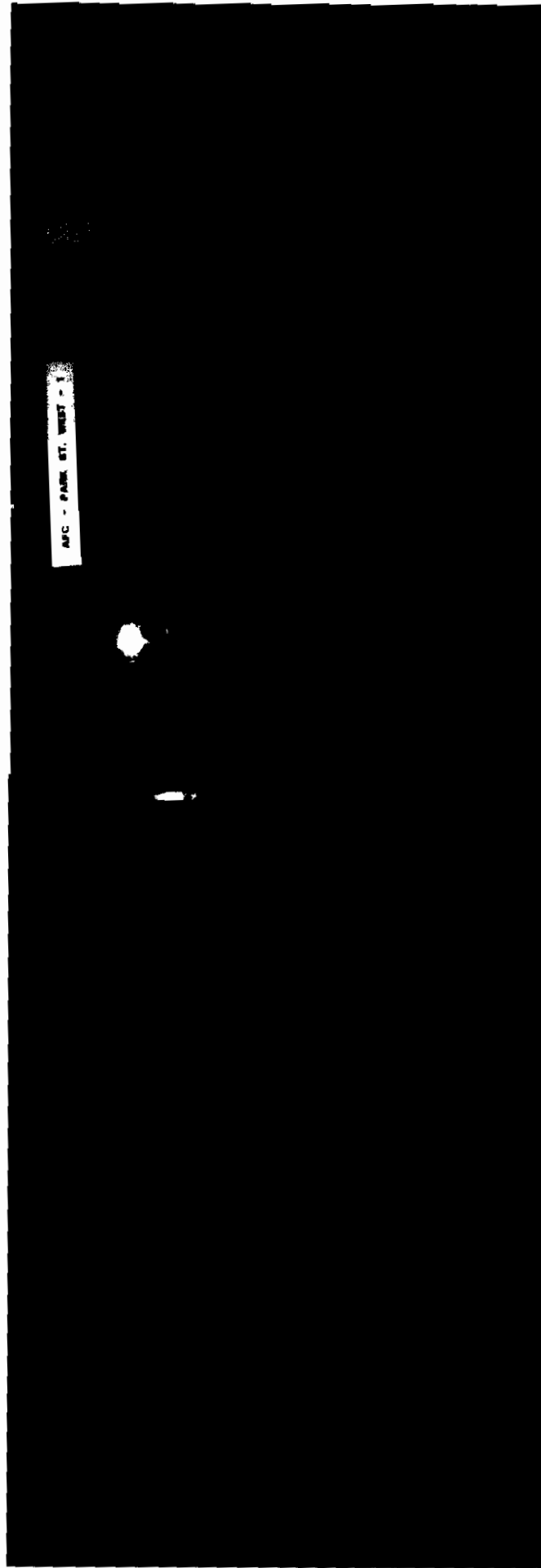
network security

- Performed site surveys of T stations and offices (no WiFi found)
- Performed wireless device audit
- Found unguarded network switches

OK

fiber switches in unlocked room

connect fare vending machines to the internal network

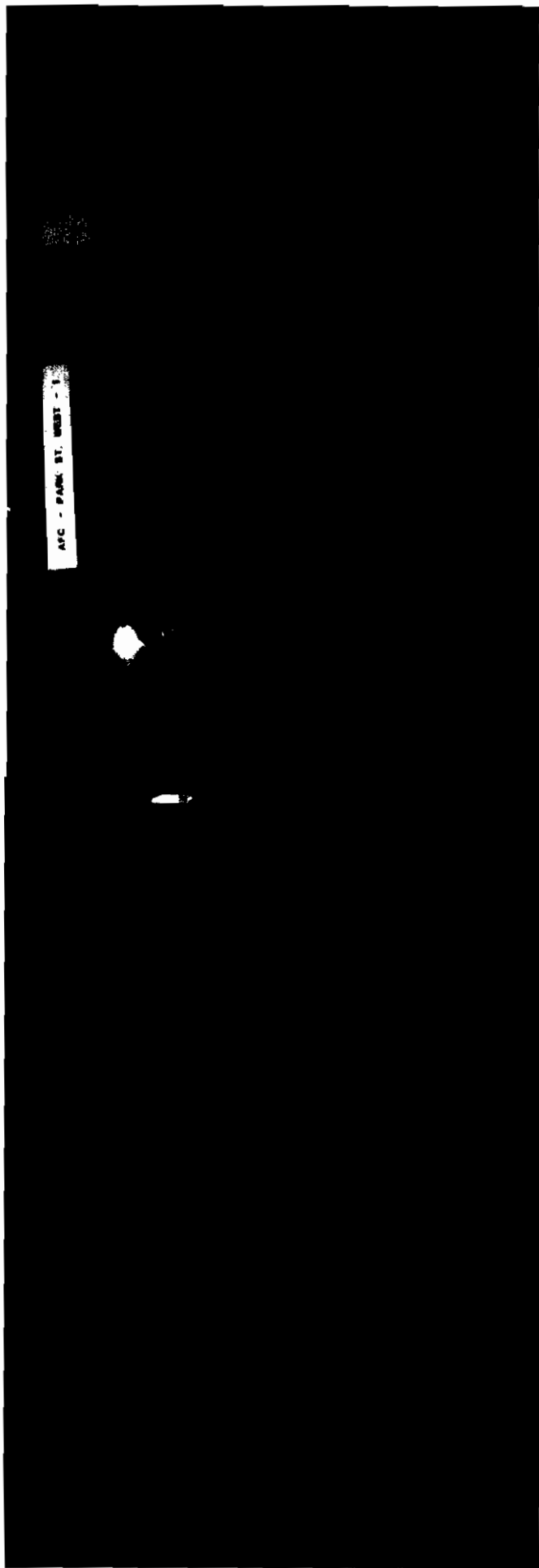


AFC - PARK ST. WEST - 1

17

fiber switches in unlocked room

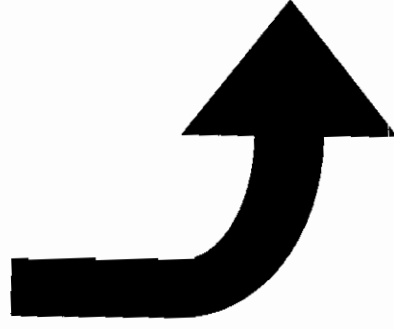
connect fare vending machines to the internal network



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Social Engineering

Executed the “PHANTOM MEETING” attack



Gained access to internal
network drops and computers

Nobody suspected a thing as we walked into
offices and conference rooms...

So we took it up a notch.

73

first there was wardialing

c.1983 - 2000 - 2001 - 2002 - 2006 - 2007 - 2008

HY

then there was **wardriving**

c.1983 - **2000** - 2001 - 2002 - 2006 - 2007 - 2008

57

then there was warwalking

c.1983 - 2000 - **2001** - 2002 - 2006 - 2007 - 2008

96

then there was **warflying**
and **warboating**

c.1983 - 2000 - 2001 - **2002** - 2006 - 2007 - 2008

9x

then there was war-rocketing

c.1983 - 2000 - 2001 - 2002 - **2006** - 2007 - 2008

78

then there was warballooning

c.1983 - 2000 - 2001 - 2002 - 2006 - **2007** - 2008

675

and now... **warcarting**

c.1983 - 2000 - 2001 - 2002 - 2006 - 2007 - 2008

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WatCart

Pan/Tilt Mechanism

attachments include antennas or a smoke grenade launcher

19dBi WiFi Antenna

directional

Two Laptops

for control and data logging

12dBi WiFi Antenna

omnidirectional

Scanner

to pick up various communications

25-1300 MHz Antenna

general coverage, great for picking up the police

Control Box

w/ key switch for activation

Antenna Switch Box

To toggle between antennas and radios

CCD Camera

trip documentation

Flash Drive Dropper

for U3 hacksaws

Lights

2M candlepower for night operations

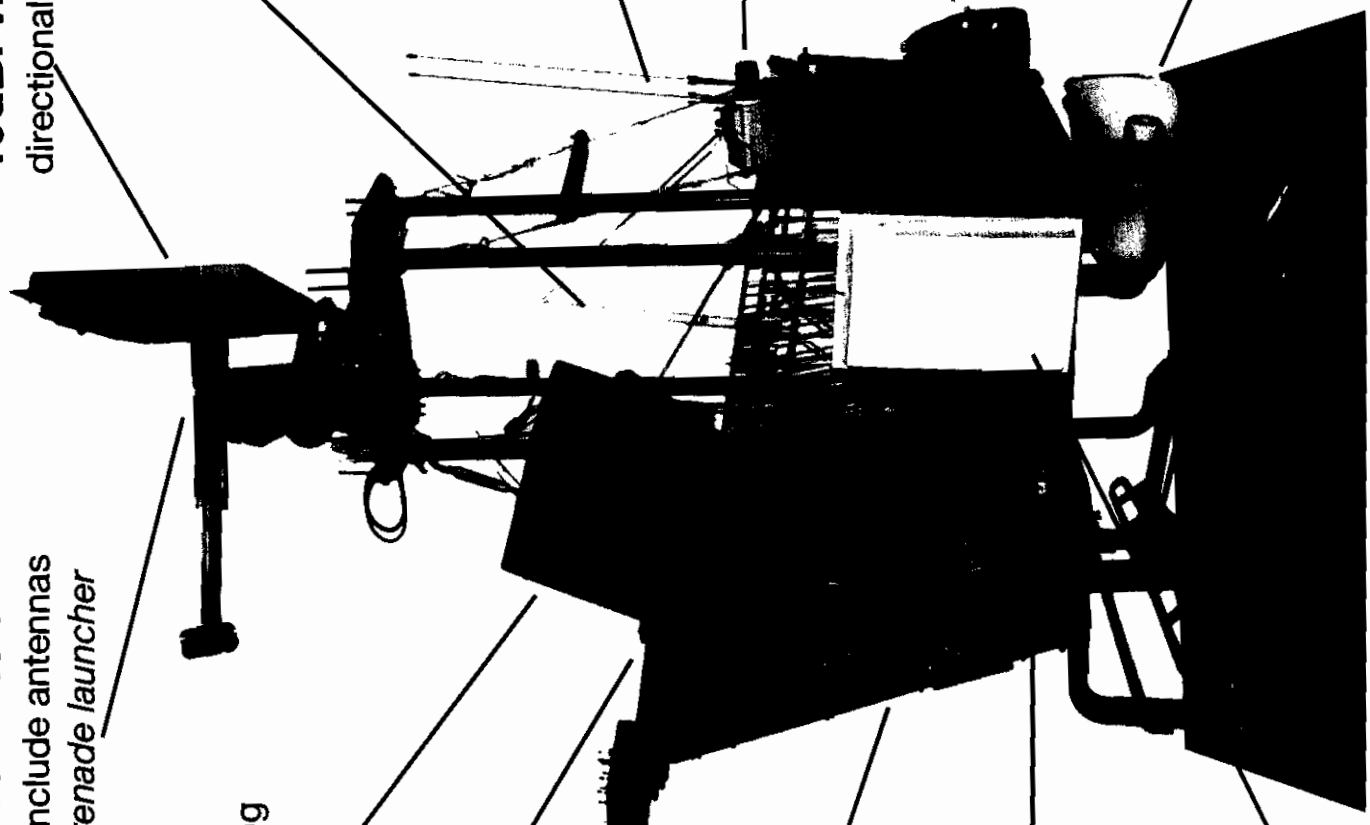
900 MHz Antenna

directional, great for cordless phones

PA Speaker

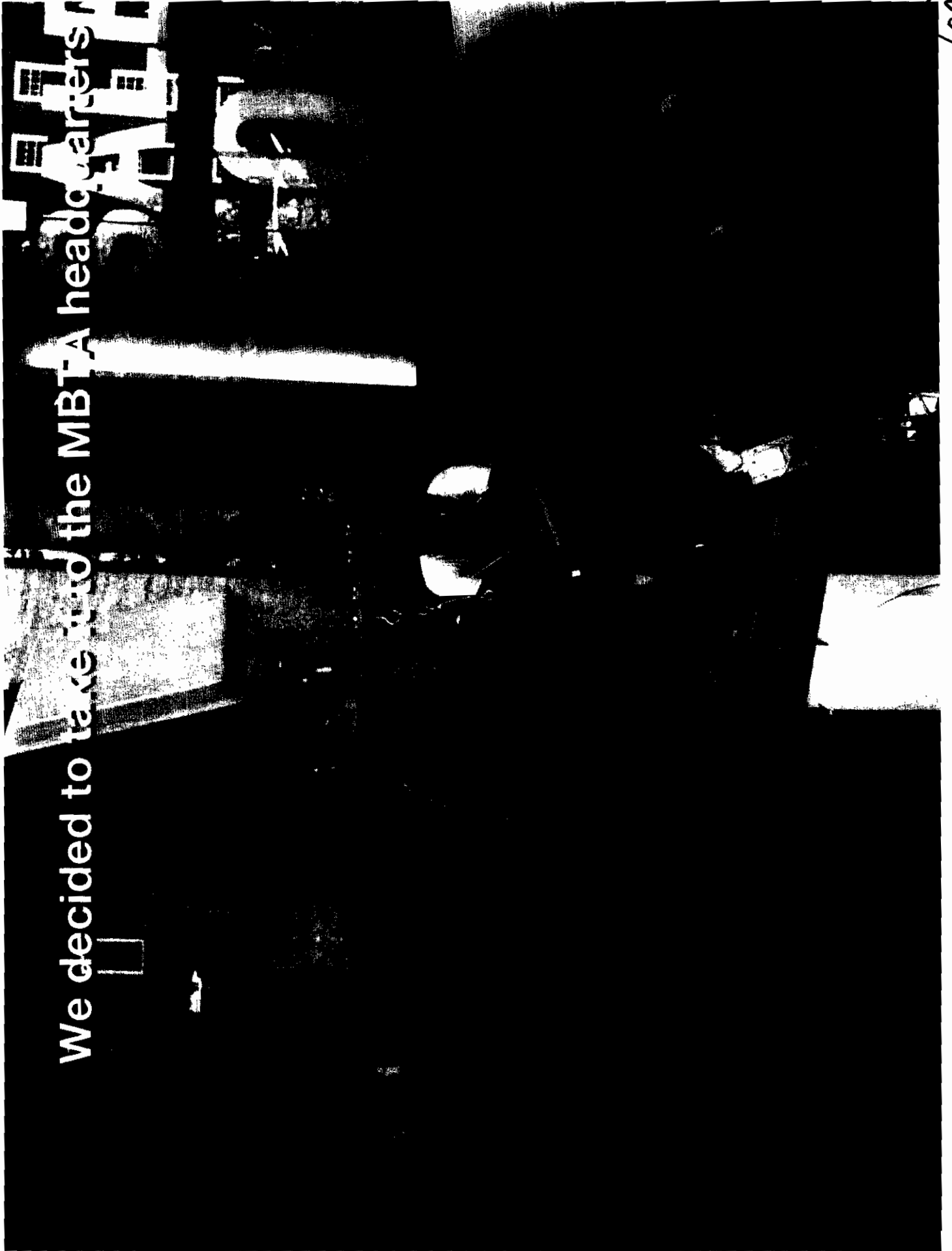
For announcements and intimidating music

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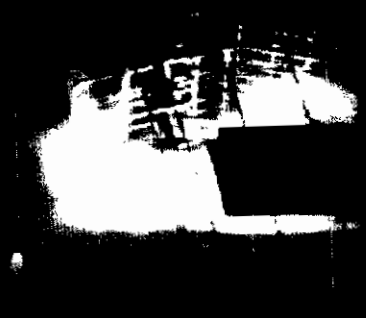


We decided to take into the MBTA headquarters

MA



And then we ran into some problems with the police



That's one of the WarCart's
smoke grenades, by the way

So to avoid ending up like this



We turned back

84

contributions

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contributions

- 1) **Exploited** physical security holes
- 2) **Reverse engineered** the CharlieTicket
- 3) Wrote code to analyze & generate magcards
- 4) Wrote a **toolchain** for analyzing 13.56MHz RFID transactions using the USRP+GNUradio
- 5) **Attacked** problems with the MIFARE Classic cards
- 6) Wrote **brute forcer-generator** to crack keys on an FPGA
- 7) Developed software to **reduce MQ to SAT**, allowing key recovery
- 8) Wrote code to **read and clone** MIFARE cards (given the key)

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Exhibit 8

Mahony, leuan (BOS - X75835)

From: Marcia Hofmann [marcia@eff.org]
Sent: Saturday, August 09, 2008 4:38 AM
To: Mahony, leuan (BOS - X75835)
Cc: kurt@eff.org; jennifer@eff.org; jaren@mit.edu
Subject: Re: MBTA v Anderson et al

Attachments: defcon-16-anderson-ryan-cheisa.pdf



defcon-16-anderson-ryan-cheisa..

Dear Ieuan:

Attached please find the presentation slides that our clients submitted to DEFCON.

As we discussed on the phone earlier today, the tone of this presentation is geared toward the DEFCON audience. To be clear, our clients do not intend to disclose information that would enable the audience to duplicate the research, and the presentation will omit key details to ensure responsible disclosure.

While we remain open to discussing the content of the presentation, please note that these slides have been included in a CD distributed to DEFCON attendees.

We will try to give you a call as early as possible tomorrow in light of the time difference. We will aim for 9:00 ET/6:00 PT.

Best regards,

Marcia

--

Marcia Hofmann, Staff Attorney
Electronic Frontier Foundation
454 Shotwell Street
San Francisco, CA 94110

tel: (415) 436-9333 x. 116 | fax: (415) 436-9993 marcia@eff.org | <http://www.eff.org>

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ieuan.mahony@hklaw.com wrote:

> Kurt, Marcia, and Jennifer:
> Per our 11:30 call, I will be available for another hour or so
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> Ieuan

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> *Holland + Knight*
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> *Ieuan G. Mahony*
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>
>

Exhibit 9

Mahony, Ieuan (BOS - X75835)

From: Mahony, Ieuan (BOS - X75835)
Sent: Saturday, August 09, 2008 5:15 AM
To: 'Marcia Hofmann'
Cc: kurt@eff.org; jennifer@eff.org; jaren@mit.edu; 'Swope, Jeffrey'; William Mitchell; Scott Darling; Mahony, Ieuan (BOS - X75835)
Subject: RE: MBTA v Anderson et al

Marcia:

I am circulating this now. Given the time, and Scott's flight, I am not sure how close a review of the substance we will have by the hearing.

I have the following two requests, and would appreciate a response as far in advance of the hearing as you are able:

(1) Please let me know the time at which the slide deck was first distributed to DEFCON attendees.

(2) Please let me know the relationship, if any, between (a) the point in time the MIT Undergrads understood the MBTA wanted an opportunity to view these materials; and (b) the point in time when the materials were distributed at DEFCON.

I will wait for your call, and would appreciate a response to the above two questions.

Ieuan

-----Original Message-----

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To: Mahony, Ieuan (BOS - X75835)
Cc: kurt@eff.org; jennifer@eff.org; jaren@mit.edu
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Dear Ieuan:

Attached please find the presentation slides that our clients submitted to DEFCON.

As we discussed on the phone earlier today, the tone of this presentation is geared toward the DEFCON audience. To be clear, our clients do not intend to disclose information that would enable the audience to duplicate the research, and the presentation will omit key details to ensure responsible disclosure.

While we remain open to discussing the content of the presentation, please note that these slides have been included in a CD distributed to DEFCON attendees.

We will try to give you a call as early as possible tomorrow in light of the time difference. We will aim for 9:00 ET/6:00 PT.

Best regards,

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Sent: Saturday, August 09, 2008 5:26 AM
To: 'Swope, Jeffrey'
Cc: 'Marcia Hofmann'; kurt@eff.org; jennifer@eff.org; jaren@mit.edu; William Mitchell; Scott Darling; Mahony, Ieuan (BOS - X75835)
Subject: RE: MBTA v Anderson et al

Jeffrey:

I make the following request of you, again, as far in advance of the hearing as you are able:

- (1) Please state when MIT first become aware of this slide deck?
- (2) Please state whether MIT at any point had access to a copy of this slide deck? If so, when?

Thank you

Ieuan

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