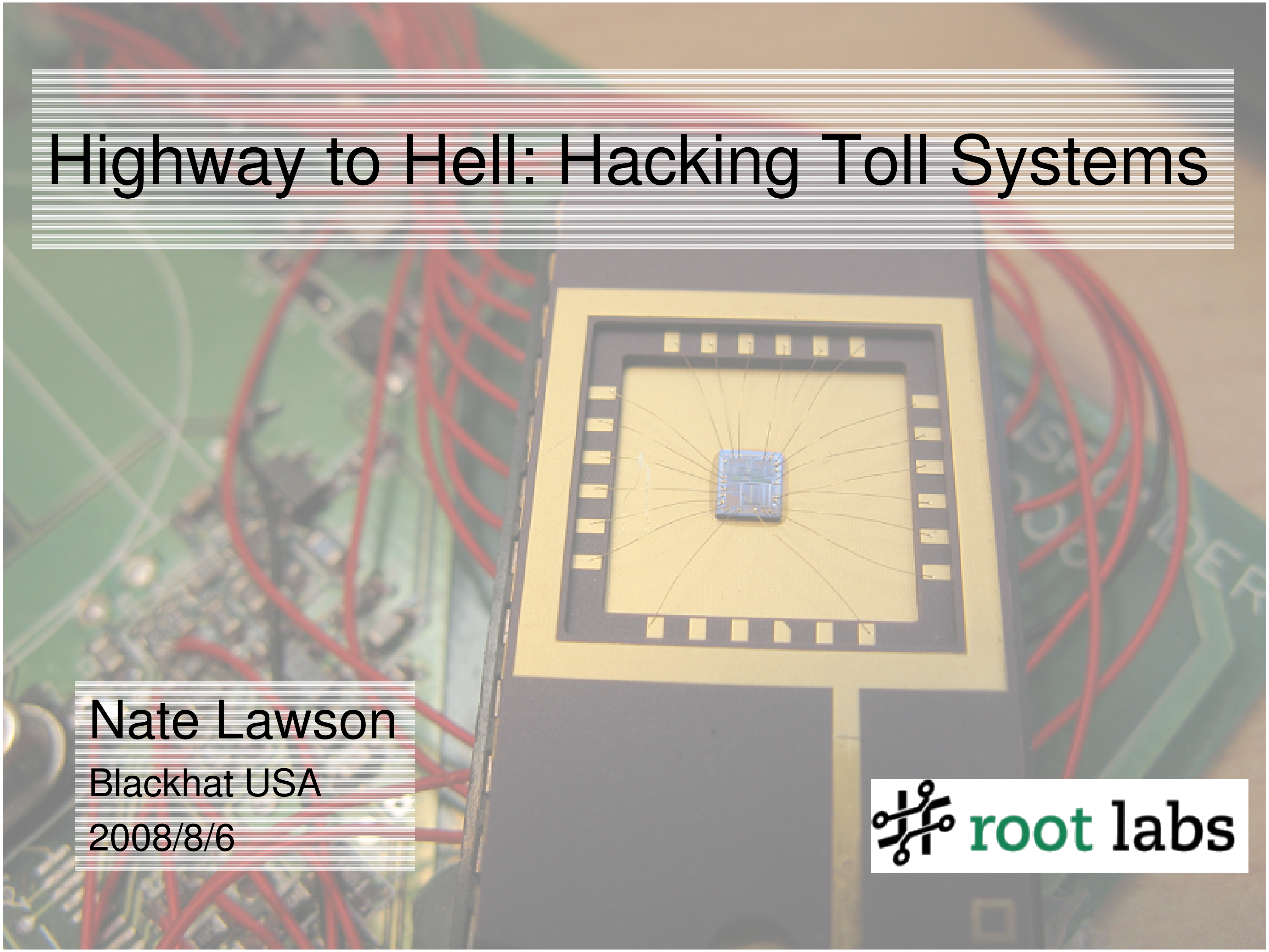

Highway to Hell: Hacking Toll Systems

Nate Lawson

Blackhat USA

2008/8/6

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My background

- Root Labs founder
  - Design and analyze security components
  - Focused on:
    - Embedded and kernel security
    - Software protection
    - Crypto
- IBM/ISS
  - Original developer of RealSecure IDS
- Cryptography Research
  - Co-designed Blu-ray disc content protection layer, aka BD+

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How I got interested in toll passes

- I have never used FasTrak
  - Privacy concerns
    - Bridge
    - Freeways
  - Pay cash or take public transit
- How does it work?
  - Almost no analysis available online
  - Title 21 (protocol) is a standard though
- What's really inside?
  - Buy transponder from Safeway without signing up ($26 cash)
- Perhaps privacy issues can be fixed?

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What is electronic toll collection?

- Automatic debit of an account for use of a bridge or toll road
- Many possible implementations
  - RFID transponder
  - Image recognition of license plate
- Current systems
  - E-ZPass (East Coast)
  - TollTag, Sunpass, etc.
  - FasTrak (Bay Area + Southern California)

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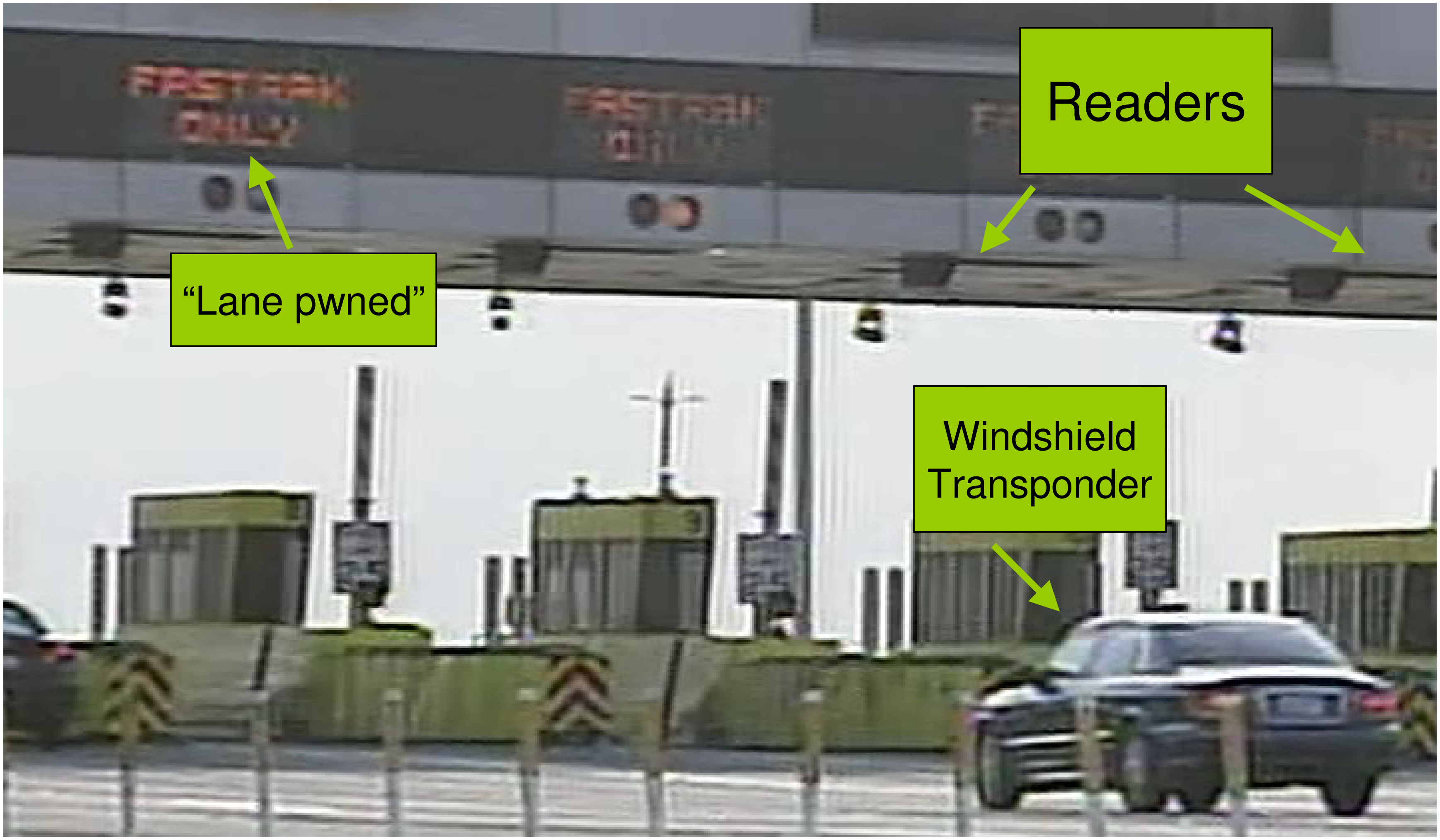
Electronic toll collection



Screen grab courtesy of KTVU News

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Tracking and privacy

- Few realize all freeway travel is also tracked
  - Transponders are queried by readers on signs to generate realtime traffic statistics (511.org)
  - Separate agency (and thus servers) from toll collection, but same transponder

Screen grab courtesy of KTVU News

Tracking and privacy

- Toll transactions are logged
  - Indefinitely? No info in privacy policy
- Freeway travel is separately logged by 511.org
  - The transponder ID is “anonymous” and “only stored for 24 hours” (KTVU news report)
  - “Users remain anonymous through … encryption software that scrambles each FasTrak toll tag ID” (privacy policy)
- Lawyers know this info is available
  - “FasTrak gets about one subpoena a month for toll records.” (KTVU news report)
  - Wouldn’t they stop bothering if this info wasn’t useful?

Adding anonymity afterwards difficult

- Conventional approach (adding anonymity)
  - ID → Hash(ID)
    - Not anonymous, just exchanges one ID for another
    - Subject to correlation attacks
    - Ignores meta-information (timing, length, date)
- AOL anonymized search term scandal (2006)
  - Real names and addresses could be recovered by correlating info across multiple searches

Robust anonymity has to be built-in

- Reduce collection
  - Query based on a random timer, not all cars
  - Only one 1 out of 100 cars necessary to get average speed
- Limit distribution
  - Calculate speed and throw away original IDs after two readings
  - Limit the number of systems that touch it along the way
- Expire aggressively
  - Only statistic needed is sign-to-sign interval
  - Discard IDs after a few minutes
- Cryptography
  - “Untraceable RFID Tags via Insubvertible Encryption” (Ateniese, Camenisch, and de Medeiros)
  - "A Scalable, Delegatable Pseudonym Protocol Enabling Ownership Transfer of RFID Tags" (Molnar, Soppera, and Wagner)

Title 21 system history

- California legislature passed a technical law
  - Title 21, Chapter 16 (1992)
  - Developed mostly by Texas Instruments
- FasTrak
  - All Bay Area bridges (BATA)
  - Orange County toll highways
  - Airport parking lots
- Over one million transponders purchased

Title 21 standard

- Layer 1: modulation and frequency
  - Reader downlink
  - Transponder uplink
- Layer 2: packet framing
  - Start sequence, checksum
- Layer 3: packet types
  - Poll messages
  - Responses
- Layer 7: allocation of IDs among agencies

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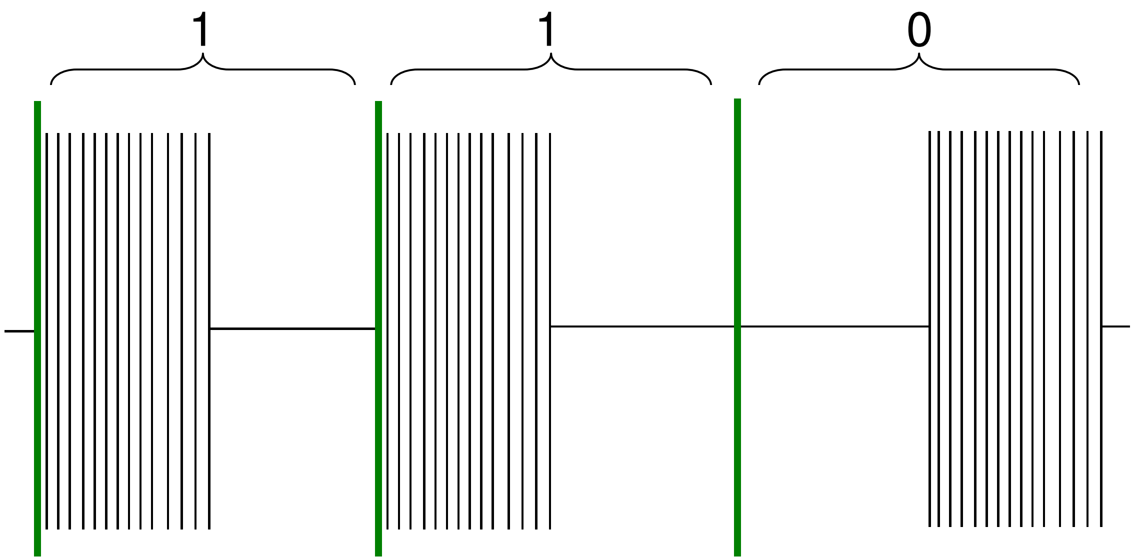
Layer 1: modulation and frequency

- Downlink from reader
  - ~900 MHz carrier frequency
  - Square-wave AM
    - Unipolar ASK of the carrier using Manchester encoding
    - “1”: signal during first half, “0”: signal during second
- Uplink from transponder
  - Backscatter of carrier via antenna polarization
  - Dual-frequency AM
    - FSK of 1200 KHz/600 KHz (“1” and “0”, respectively)
- 300 Kbps data rate (both directions)

Layer 1: reader modulation

- Downlink from reader



- 300 Kbps data rate
- 600 KHz square wave (ASK)
  - "1" = high in first half of period
  - "0" = high in second half of period

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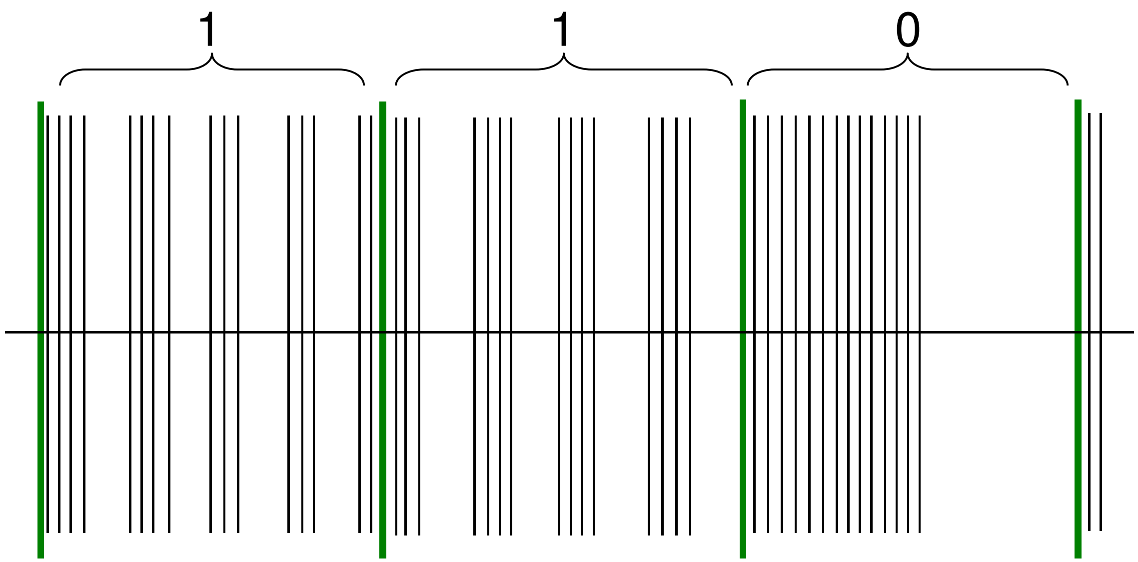
Layer 1: transponder modulation

- Uplink from transponder



- 300 Kbps data rate
- 1200/600 KHz square wave (FSK)
  - “1” = higher frequency
  - “0” = lower frequency

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Layer 2: packet framing

- Wakeup signal before message
  - 33 μs burst of 1-bits
  - 100 μs no signal
- Packet start: 0xAAC
- Ends with 16-bit CRC
  - Standard says "CRC-CCITT"
  - Spec bug: initial value is 0, not 0xFFFF like CCITT says
    - If you actually implemented the Title 21 spec, you'd be incompatible

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Layer 3: standard messages

Reader → **Transponder**

Polling Message Type 1 (8000)
- Requests the transponder to send its ID
- Agency code, 16-bit

Data Message Type 1 (0001)
- Transponder ID, 32-bit

Acknowledge Message Type 2 (C000)
- Confirms reception of the transponder ID
- Transponder ID, 32-bit
- Reader ID, 32-bit
- Status, 16-bit

Enrollment process

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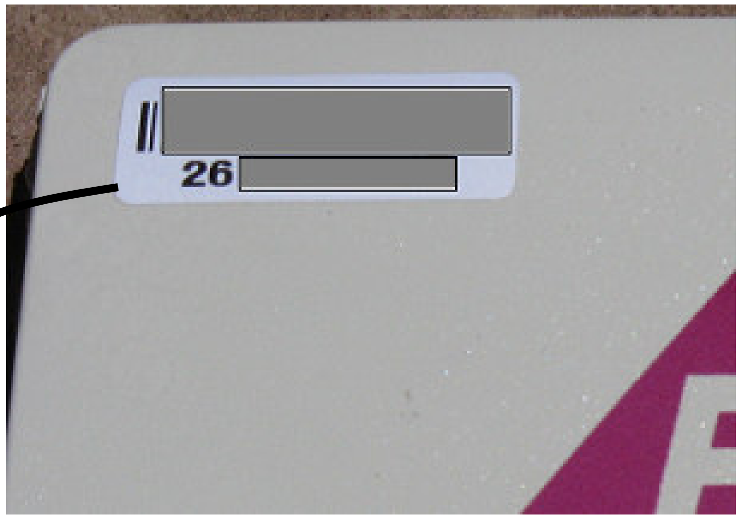
Enrollment process

- Validation code is just toll tag serial number in hex
- Used as a checksum for typos



Toll Tag Number*: (This is the 10-digit number located in the upper left corner of your toll tag.)

Validation Code*: (This is the 8-digit alpha-numeric code located on the velcro strip.)

Diving into the transponder

"If a Toll Tag fails to operate for reasons other than abuse… we will replace it…"

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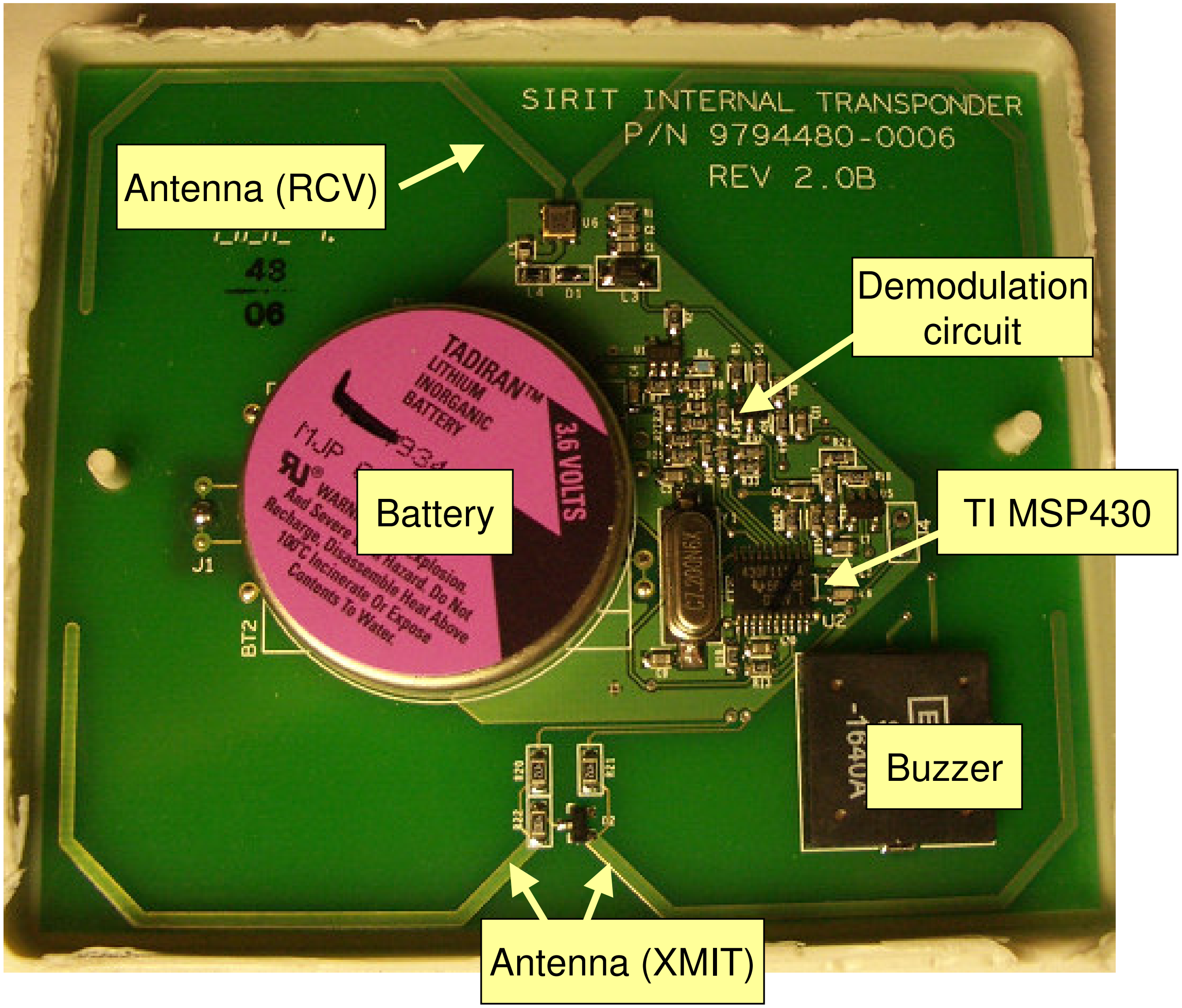
Diving into the transponder



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Transponder operation

- Receive side
  - Signal is received and amplified (analog)
  - Demodulated and presented to pin 2.5 as a square wave
- Transmit side
  - Carrier reflected back by swapping pins 1.6 and 1.7 quickly
- Buzzer
  - Timer interrupt + XOR (pins 2.0 and 2.1)

Thanks go to Adam O’Donnell for the RF help

MSP430 basics

- Low-power 16-bit microcontroller
  - 2, 4, and 6-byte instructions
    - Kinda strange: MOV @R14+, R15
  - Von Neumann address space (shared code/data)
    - Helpful for stack/integer overflows (Travis Goodspeed)
  - Self-programmable flash memory
    - Persist that exploit
- MSP430F1111A
  - Peripherals: timer, comparator, ports (address 0)
  - 128 bytes RAM (0x200)
  - 256 bytes data flash (0x1000)
  - 2 KB code flash (0xF800)

FasTrak MSP430 memory map

Interrupt vectors (FFE0 - FFFF)
Code flash (F800 - FFFF)
Data flash (1000 - 10FF)
Boot ROM (0C00 - 0FFF)
RAM (0200 - 027F)
Peripherals (0000 - 01FF)

Dumping the firmware

- Internal firmware is protected by JTAG fuse
  - Normal programming method is via JTAG
- Bootstrap loader (BSL)
  - 256-bit password allows access to flash
    - Probably checked with `memcmp()`
    - Go see Travis Goodspeed's talk on timing attacks in the BSL
- Rule 1: always try the front door

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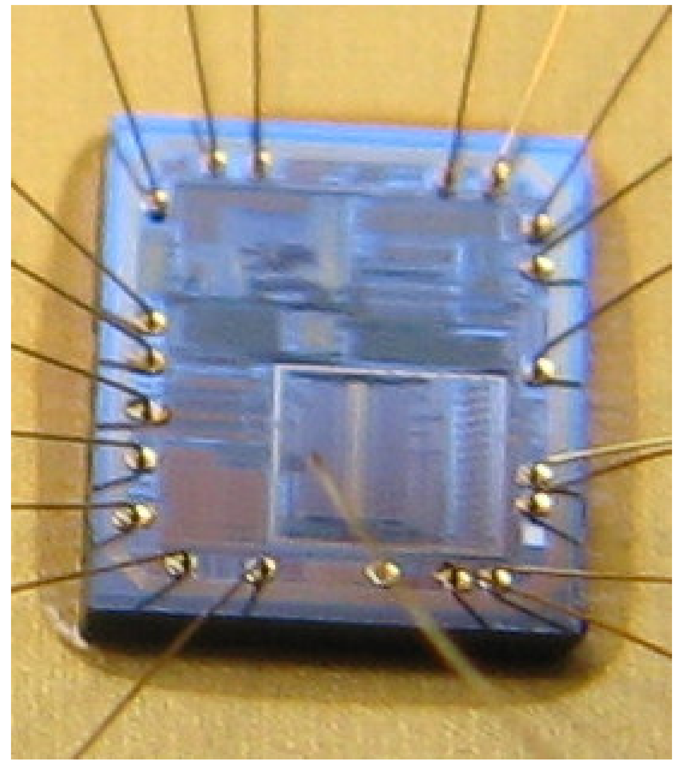
Old transponders are not locked

- JTAG fuse is not set
  - Plug in microcontroller and read flash memory
  - Verified on a transponder from Southern California
- Newer transponders *are* locked
  - Need more magic to verify their contents

Bypassing the JTAG fuse

- Silicon magic courtesy of Chris Tarnovsky
  - Depackage chip
  - [Fuse magic happens here]
  - Rebond to DIP package
  - Read out flash
- Code was identical to unlocked transponder



If you make silicon, Fly Logic does amazing analysis work.

http://flylogic.net/

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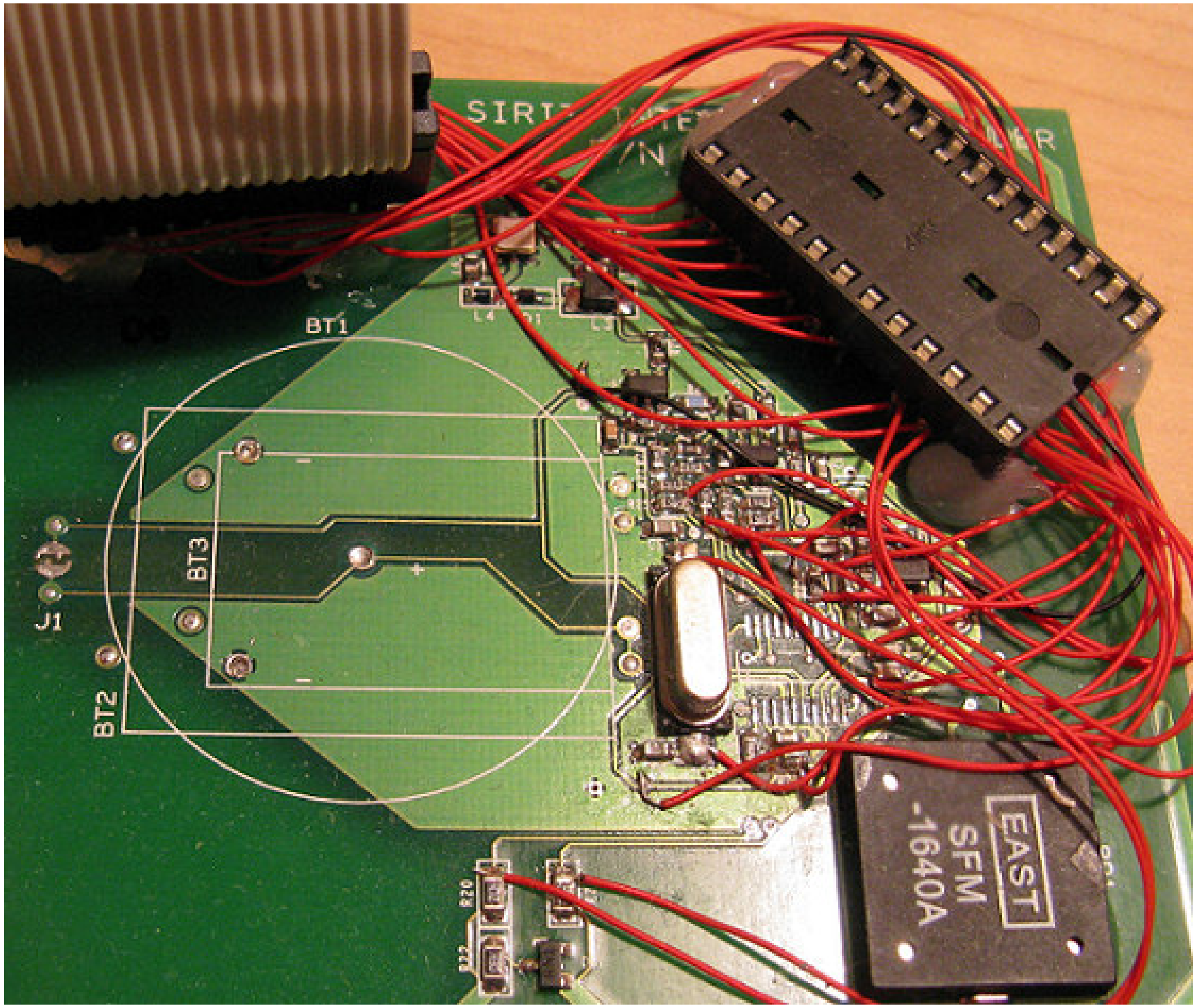
Monitoring transponder IO

- Add header and socket for DIP CPU



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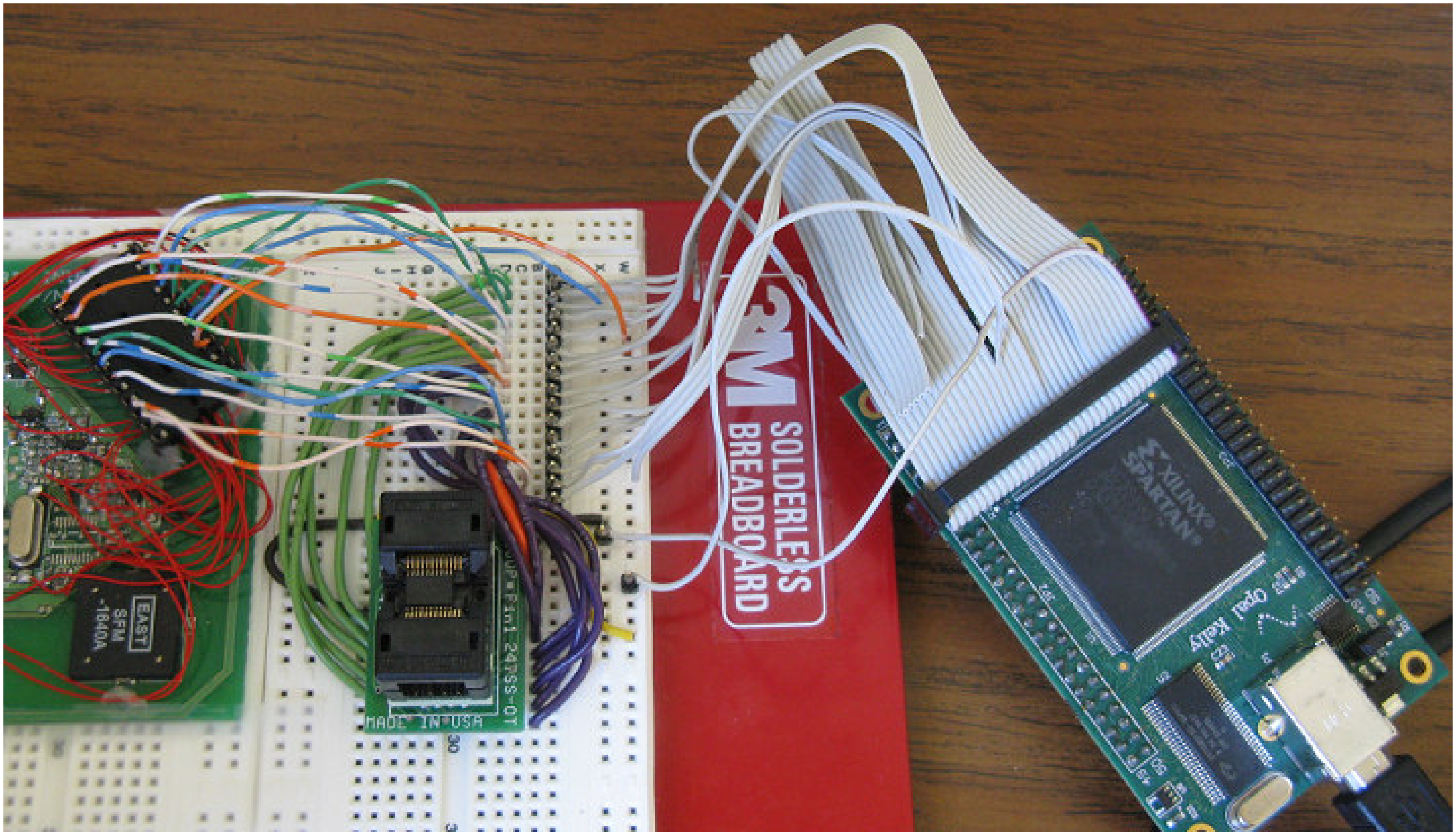
Monitoring transponder IO

- FPGA tap board and socket on breadboard



What's inside?

- Load code with IDA MSP430 plugin
  - Full reply messages with checksum laid out in order
  - Main loop: switch (packetLen); dispatch handler
  - Timer interrupts, comparator trigger
- Build a modified msp430simu
  - Cycle-accurate simulator in python
  - Breakpoint/log support routines
    - Checksum
    - Memcpy
    - Receive (poll) for packet
    - Transmit packet
    - Beep

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Reader request messages

- Standard
  - Request for ID (8000, 8 bytes)
- Reserved by spec but not supported by firmware
  - Encrypted ID request (80xx, 11 bytes)
    - Agency code (16 bits)
    - Proprietary TI encryption key (24 bits)
  - Encrypted unknown message (88xx, 13 bytes)
    - Transponder ID (32 bits)
    - Proprietary TI encryption key (24 bits)

Lengths include "AAC" header, rounded up to nearest byte.

Reader request messages

- Supported by firmware but not specified
  - 11-byte requests
    - 00DE, 01DE, 02DE, 03DE, 0480, 04DE
  - 36-byte requests
    - 01DF, 05DF
  - 37-byte requests
    - 05DE

Transponder reply messages

- Standard
  - ID response (0001, 10 bytes)
- Reserved and supported by firmware
  - ID and serial response (0007, 22 bytes)
    - "Block A data" (128 bits) which is actually:
      - Unknown (16 bits)
      - Transponder ID (32 bits)
      - Unknown (16 bits)
      - Transponder serial number (BCD, 48 bits)
      - Padding (08FF)
- Reserved by spec but unsupported
  - "Block A and B, C, or D data" (000x, 38 bytes)

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Transponder reply messages

- Supported by firmware but not specified
  - Misc ID+serial messages
    - 0002, 38 bytes
      - 16 bytes empty
    - 0005, 38 bytes
      - Bits checked when processing other msgs
  - Empty messages (for future?)
    - 5F07, 30 bytes
    - 0003, 38 bytes
    - 0004, 38 bytes
    - 5F06, 38 bytes

Reader response messages

- Standard
  - Status reply (C000, 16 bytes)
    - Transponder ID (32 bits)
    - Reader ID (32 bits)
    - Status code (16 bits)
- Reserved but not supported by firmware
  - Unknown response 1 (C00x, 20 bytes)
  - Unknown response 2 (C00x, 36 bytes)
    - All the above + 128 bits “data”

What’s not inside?

CRYPTO.

Cloning attacks

- Passive cloning
  - Set up a receiver near a freeway
  - Record IDs as they are transmitted to reader
- Active cloning
  - Drive past parking lots, shopping centers, etc.
  - Use portable reader to scan and log IDs of parked cars
- Missing cryptographic property: replay resistance
  - Reader proves itself to transponder
  - Transponder proves itself to reader

Monetizing cloning attacks

- Create a subscription service
  - Users get customized transponders or hack existing ones
  - Device downloads new IDs from PC over the air
  - Each ID is used only once, preventing pattern analysis
- Low risk
  - Failure to read transponder = $29 fine
  - Service can pay penalty for subscribers
- Potential customers
  - Trucking companies
  - Drug couriers

Digging still deeper…

- Does FasTrak write data to your transponder?
  - “FasTrak is a read-only device. There's no memory to write anything to.” (John Goodwin, BATA)
  - Best interpretation: “We only use it in a read-only manner and are not aware our vendor used a flash device”
- But there is memory and it is writeable
  - MSP430F1111A is flash-based, only the BSL is in ROM
  - Supports in-system erase/rewrite

Firmware has ID update routine

- Flash write subroutine is present in firmware

```
mov    #0A550h, &FCTL2
mov    #0A500h, &FCTL3
mov.b @R14+, 0(R12)
```

- Called from multiple places in packet processing function
- Appears to be used to update the IDs of various message responses stored at 0x1000

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IDs can be wiped/overwritten from remote

- Flash update can be triggered with a couple messages
  - Packet 1: prepare to flash
  - Packet 2: data to write
- Update routine
  - Calculates checksum of data from packet
  - Writes it to various locations of IDs within pre-computed response messages stored in flash
- Caveat: update routine only tested in simulator so far

Alibi attack

- Establish presence elsewhere during crime
  - Read and save neighbor’s FasTrak ID from parked car
  - Send message to update his transponder with your ID
  - He goes to work at 9 am, you commit crime
  - Subpoena records: you were on the bridge at 9 am!
- Questions
  - Is FasTrak data really considered so indisputable?
  - Will this alibi hold up in court?

Contacting the vendors

- FasTrak is:
  - A technical standard ratified as law by the California legislature
  - Administered by CalTrans
  - Locally run by Metropolitan Transportation Commission (MTC), Bay Area Toll Authority (BATA), Orange County Transportation Corridor Agencies (TCA), etc.
  - With devices potentially provided by multiple vendors, but in practice, mostly Sirit
- No response after …
  - Email contact form on bayareafastrak.org
  - Sending business card with reporter who later talked to BATA
  - Speaking to CalTrans consultant

Conclusions

- Electronic toll collection needs improvement
  - Excessive loss of privacy in current usage
    - Please fix this before we move to license plate recognition
  - Clonable if no encryption
  - Untrustworthy for legal evidence
    - Transponder IDs can be overwritten over-the-air
- Found many surprises when opening the box, even with an established system
  - I’m happy to explain the details for free to any FasTrak authorities who contact me

Contact: nate@rootlabs.com Info/blog: rootlabs.com