### Announcements

- This is the last lecture!
- No lectures next week
- Let me know if you want to meet about project
- Final on Wednesday 12/7

### Plan for project:

- Replace poster by short presentations on the last day of classes
- Project report due Monday 12/12
  - 6-8 pages

### Overview

- Routing privacy
- Web Privacy
- Wireless Privacy

### Randomized Routing

- Hide message source by routing it randomly
  - Popular technique: Crowds, Freenet, Onion routing
  - Routers don't know for sure if the apparent source of a message is the true sender or another router
**Onion Routing**

- Sender chooses a random sequence of routers
  - Some routers are honest, some controlled by attacker
  - Sender controls the length of the path

**Route Establishment**

Routing info for each link encrypted with router’s public key
Each router learns only the identity of the next router

**Tor**

- Second-generation onion routing network
  - [http://tor.eff.org](http://tor.eff.org)
  - Developed by Roger Dingledine, Nick Mathewson and Paul Syverson
  - Specifically designed for low-latency anonymous Internet communications
  - Running since October 2003
  - 100s nodes on four continents, thousands of users
  - “Easy-to-use” client proxy
    - Freely available, can use it for anonymous browsing

**How does Tor work?**

1. How Tor Works: 1

   - Alice
   - Step 1: Alice’s Tor client obtains a list of Tor nodes from a directory server.
   - Dave
   - Jane
   - Bob
How does Tor work?

Tor Circuit Setup (1)
• Client proxy establish a symmetric session key and circuit with Onion Router #1

Tor Circuit Setup (2)
• Client proxy extends the circuit by establishing a symmetric session key with Onion Router #2
  • Tunnel through Onion Router #1 (don’t need)

Tor Circuit Setup (3)
• Client proxy extends the circuit by establishing a symmetric session key with Onion Router #3
  • Tunnel through Onion Routers #1 and #2
Using a Tor Circuit

- Client applications connect and communicate over the established Tor circuit

Location Hidden Servers

- Goal: deploy a server on the Internet that anyone can connect to without knowing where it is or who runs it
- Accessible from anywhere
- Resistant to censorship
- Can survive full-blown DoS attack
- Resistant to physical attack
  - Can’t find the physical server!

Creating a Location Hidden Server

- Client obtains service descriptor and intro point address from directory
- Server creates onion routes to "introduction points"
- Server gives intro points’ descriptors and addresses to service lookup directory

Using a Location Hidden Server

- Client sends address of the rendezvous point and any authorization, if needed, to server through intro point
- Rendezvous point mates the circuits from client & server
- If server chooses to talk to client, connect to rendezvous point
Overview
- Routing privacy
- Web Privacy
- Wireless Privacy

An “Old” Problem
- Many governments/companies trying to limit their citizens’ access to information
  - Censorship (prevent access)
  - Punishment (deter access)
  - China, Saudi Arabia, HP
- How can we defeat such attempts?
  - Circumvent censorship
  - Undetectably

Proxy-Based Web Censorship
- Government manages national web firewall
  - Not optional---catches ALL web traffic
- Block certain requests
  - Possibly based on content
  - More commonly on IP address/publisher
  - China: Western news sites, Taiwan material
- Log requests to detect troublemakers
  - Even without blocking, may just watch traffic
- But they don’t turn off the whole net
  - Creates a crack in their barrier

Goal
- Circumvent censor via innocent web activity
  - Normal web server and client cooperate to create covert channel
  - Without consequence for client
  - And without consequence for server
  - Broad participation increases system robustness
  - Ensure offering service doesn’t lead to trouble
    - e.g., loss of business through being blocked
  - Also, “law knows no boundaries”
The Big Picture

Requirements
- Client deniability
  - Detection could be embarrassing or worse
- Client statistical deniability
  - Even suspicion could be a problem
- Server covertness/statistical deniability
  - If server detected, can be blocked
- Communication robustness
  - Even without detecting, censor could scramble covert channel
- Performance (bandwidth, latency)

(Un)related Work
- SSL
  - Encrypted connection---can’t tell content
  - Suspicious!
  - Doesn’t help reach blocked servers
  - Govt. can require revealing SSL keys
- Anonymizing Proxies
  - Prevent servers from knowing identity of client
  - But proxy inside censor can’t reach content
  - And proxy outside censor can be blocked
  - And use of proxy is suspicious

Safeweb/Triangle boy
- Operation
  - Client contacts triangle-boy “reflector”
  - Reflector forwards requests to blocked server
  - Server returns content to client (IP spoof)
- Circumvents censorship
- But still easily detected
  - “Local monitoring of the user only reveals an encrypted conversation between User and Triangle Boy machine.” (Safeweb manual)
Summary

• Easy to hide what you are getting
  • Just use SSL
• And easy to circumvent censors
  • Safeweb
• But hard to hide that you are doing it

Infranet: Circumventing Censors

• Censors allow certain traffic
• Use to construct a covert channel
  • Talk to normal servers
  • Embed requests for censored content in normal-seeming requests
  • Receive censored content hidden in normal-seeming responses
• Requester: client asking for hidden content
• Responder: server covertly providing it

System Architecture

Receiving Content is Easier Half

• Responder is a normal web server, serving images (among other things)
• Encrypt data using requestor key
• Embed in “unimportant, random” bits of images
  • E.g., high order color bits
  • Watermarking
• Encrypted data looks random---only requestor can tell it isn’t (and decrypt)
**Example**

- One image has embedded content
- You can’t tell which (shows it’s working)

**Goals Analysis**

- Client looks innocent (receives images)
  - Infranet users & nonusers indistinguishable
- Server less so
  - Any one image seems innocent
  - But same image with different “random bits” in each copy is suspicious
  - Evasion: never use same image-URL twice
    - Justify: per-individual customized web site
    - Human inspection might detect odd URL usage
  - Evasion: use time-varying image (webcam)
- Performance: 1/3 of image bits

**Upstream (Requests) is Harder**

- No “random content bits” that can be fiddled to send messages to responder
- Solution: let browsing pattern itself be the message
- Suppose web page has $k$ links.
  - GET on $i^{th}$ link signifies symbol “$i$” to requestor
  - Result: $\log_2(k)$ message bits from link click
- Can be automated
- To prevent censor from seeing message, encrypt with responder key

**Goals Analysis**

- Deniability: requestor generates standard http GETs to allowed web sites
  - Fact of GETs isn’t itself proof of wrongdoing
  - Known rule for translating GETs to message, but message is encrypted, so not evidence
- Statistical deniability
  - Encrypting message produces “random” string
  - Sent via series of “random” GETs
  - Problem: normal user browsing not random
    - Some links rare
    - Conditional dependence of browsing on past browsing
Performance vs. Deniability

- Middling deniability, poor performance
  - Request URL may be (say) 50 characters
  - 16 Links/Page (say) means 4 bits
  - So need 100 GETs to request one URL!
  - And still poor statistical deniability

- Can we enhance deniability?
  - Yes, by decreasing performance further

- Can we enhance performance?
  - Yes, and enhance deniability at same time

Paranoid Alternative

- Settle for one message bit per GET
  - Odd/even links on page
  - Or generalize to “mod k” for some small k

- User has many link choices for each bit
  - Can choose one that is reasonable
  - Incorporate error correcting code in case no reasonable next link sends correct bit

- Drawback: user must be directly involved in sending each message bit
  - Very low bandwidth vs time spent

Higher Performance

- Idea: arithmetic coding of requests
  - If request $i$ has probability $p_i$, then entropy of request distribution is $\sum p_i \log p_i$
  - Arithmetic coding encodes request $i$ using $\log p_i$ bits
  - Result: expected request size equals entropy
  - Optimal

- Problem: requestor does not know the probability distribution of requests
  - Does not have info needed for encoding

Solution: Range Mapping

- Adler-Maggs
- Exploit asymmetric bandwidth
- Responder sends probability distribution to requester using easy, downstream path
- Requestor uses this “dictionary” to build arithmetic code, send encoded result
- Variation for non-binary
  - Our messages aren’t bits, they are clicks
  - And server knows different clicks should have different probabilities
Toy Example

- Suppose possible requests fewer than links on page
- Responder sends dictionary:
  - “link 1 means http://mit.edu”
  - “link 2 means http://stanford.edu”
- Assigns common requests to common GETs
- Requestor GETs link matching intended request
- One GET sends full (possibly huge) request
- Problem: in general, $\infty$ possible requests
  - Can’t send a dictionary for all

Overview

- Routing privacy
- Web Privacy
- Wireless Privacy
  - Slides Jamie

Our Wireless World

Best Security Practices

- Bootstrap
- Username: Alice
  - Key: 0x348190...
- SSID: Bob’s Network
  - Key: 0x2384949...
- Out-of-band (e.g., password, WiFi Protected Setup)
- 802.11 probe
  - Is Bob’s Network here?
- 802.11 beacon
  - Bob’s Network is here
- Discover
- Authenticate and Bind
  - 802.11 auth
    - Proof that I’m Alice
  - 802.11 auth
    - Proof that I’m Bob
- Send Data
  - 802.11 header
  - 802.11 header
  - Confidentiality
  - Authentication
  - Integrity
Privacy Problems Remain

Many exposed bits are (or can be used as) identifiers that are linked over time

Discover

802.11 probe Is Bob’s Network here?
802.11 beacon Bob’s Network is here

Authenticate and Bind

802.11 auth Proof that I’m Alice
802.11 auth Proof that I’m Bob

Send Data

• Confidentiality
• Authenticity
• Integrity

Problem: Long-Term Linking

Linking enables location tracking, user profiling, inventorying, relationship profiling, …
[Greenstein, HotOS ’07; Jiang, MobiSys ’07; Pang, MobiCom ’07, HotNets ’07]

Problem: Short-Term Linking

3-9 data streams overlap each 100 ms, on average

Easy to identify and relate devices over time

Easy to isolate distinct packet streams
Problem: Short-Term Linking

Isolated data streams are more susceptible to side-channel analysis on packet sizes and timing
- Exposes keystrokes, VoIP calls, webpages, movies, ...

[Liberatore, CCS '06; Pang, MobiCom '07; Saponas, Usenix Security '07; Song, Usenix Security '01; Wright, IEEE S&P '08; Wright, Usenix Security '07]

Fundamental Problem

Many exposed bits are (or can be used as) identifiers that are linked over time

Discover
- 802.11 probe
- 802.11 beacon

Authenticate and Bind
- 802.11 auth
  - Proof that I'm Alice
- 802.11 auth
  - Proof that I'm Bob

Send Data
- MAC addr, seqno, ...

Goal: Make All Bits Appear Random

Bootstrap

SSID: Bob’s Network
Key: 0x2384949...

Username: Alice
Key: 0x348190...

Challenge: Filtering without Identifiers

Which packets are mine?

Which packets are mine?
Design Requirements

• When $A$ generates Message to $B$, she sends:

\[
PrivateMessage = F(A, B, Message)
\]

where $F$ has these properties:

– **Confidentiality**: Only $A$ and $B$ can determine Message.
– **Authenticity**: $B$ can verify $A$ created PrivateMessage.
– **Integrity**: $B$ can verify Message not modified.
– **Unlinkability**: Only $A$ and $B$ can link PrivateMessages to same sender or receiver.
– **Efficiency**: $B$ can process PrivateMessages as fast as he can receive them.

Straw man: MAC Pseudonyms

• **Idea**: change MAC address periodically
  • Per session or when idle [Gruteser ’05, Jiang ’07]
  • Other fields remain (e.g., in discovery/binding)
    • No mechanism for data authentication/encryption
    • Doesn’t hide network names during discovery or credentials during authentication
  • **Pseudonyms are linkable in the short-term**
    • Same MAC must be used for each association
    • Data streams still vulnerable to side-channel leaks

Solution Summary

802.11 WPA

<table>
<thead>
<tr>
<th></th>
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**Straw man: Encrypt Everything**

**Bootstrap**

SSID: Bob’s Network
Key: 0x2384949...

Username: Alice
Key: 0x348190...

**Idea:** Use bootstrapped keys to encrypt everything

- **Discover**
- **Authenticate**
- **and Bind**
- **Send Data**

**Straw man: Public Key Protocol**

**Client**

Prove "Bob"

**Check signature:** $K_{Alice}^3$

**Key-private encryption** (e.g., ElGamal)

Try to decrypt

$K_{Bob}$

**Service**

Check signature: $K_{Alice}^3$

Slow! ($>100ms$)

Based on [Abadi ‘04]

**Straw man: Symmetric Key Protocol**

**Client**

Prove “Bob”

$K_{AB}$

**Service**

$K_{AB}$

**Symmetric encryption** (e.g., AES w/ random IV)

Can’t identify the decryption key in the packet or else it is linkable

$K_{AB}$

Try to decrypt with each shared key

**Solution Summary**

<table>
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SlyFi

• Symmetric key almost works, but tension between:
  • Unlinkability: can’t expose the identity of the key
  • Efficiency: need to identify the key to avoid trying all keys

• Idea: Identify the key in an unlinkable way

• Approach:
  • Sender A and receiver B agree on tokens: $T_1^A$, $T_2^A$, $T_3^A$, ...
  • A attaches $T^A_i$ to encrypted packet for B

SlyFi: Data Transport

• Data messages:
  • Only sent over established connections
    - Expect messages to be delivered
    - Use implicit transmission number to synchronize $i$

  \[ T^A_i = AES_{K^A}(i) \quad \text{where } i = \text{transmission #} \]
SlyFi: Discovery/Binding

• Discovery & binding messages:
  • **Infrequent**: only sent when trying to associate
  • **Narrow interface**: single application, few side-channels
  ⇒ Linkability at short timescales is usually OK
  ⇒ Use loosely synchronized time to synchronize $T_i$

  \[ T_i^{AB} = \text{AES}_{K_{AB}}(i) \quad \text{where } i = \left\lfloor \text{current time}/5 \text{ min} \right\rfloor \]

  • At the start of time interval $i$ compute $T_i^{AB}$
  • Handling clock skew:
    – Receiver $B$ saves $T_{i+1}^{AB}, \ldots, T_{i+5}^{AB}$ in table
    – Tolerates clock skew of 5-2 minutes

Answer:

- **Discovery & binding messages:**
  - Infrequent: only sent when trying to associate
  - Narrow interface: single application, few side-channels
  - Can’t expect most messages to be delivered
  - Can’t rely on transmission reception to synchronize
  - Linkability at short timescales is usually OK
  - Use loosely synchronized time to synchronize

- **Solution Summary**

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Next Lecture…

- No next lecture 😊
- Exam
  - Much like the midterm
  - 1.5hrs on Dec 1st
  - Mostly on 2nd half of semester but with some coverage of 1st half
- Project
  - 6-8pg writeup – due Dec 5th
  - 10min presentation – on Dec 2nd or 3rd
    - Incorporate feedback into final writeup

Overview

- P2P Privacy

Freenet

- Addition goals to file location:
  - Provide publisher anonymity, security
  - Resistant to attacks – a third party shouldn’t be able to deny the access to a particular file (data item, object), even if it compromises a large fraction of machines
- Files are stored according to associated key
- Core idea: try to cluster information about similar keys
- Messages
  - Random 64bit ID used for loop detection
  - TTL
    - TTL 1 are forwarded with finite probability
    - Helps anonymity
  - Depth counter
    - Opposite of TTL – incremented with each hop
    - Depth counter initialized to small random value
Data Structure

- Each node maintains a common stack
  - \textit{id} – file identifier
  - \textit{next\_hop} – another node that stores the file \textit{id}
  - \textit{file} – file identified by \textit{id} being stored on the local node
- Forwarding:
  - Each message contains the file \textit{id} it is referring to
  - If \textit{file id} stored locally, then stop
    - Forwards data back to upstream requestor
  - Requestor adds file to cache, adds entry in routing table
  - If not, search for the “closest” \textit{id} in the stack, and forward the message to the corresponding \textit{next\_hop}

Query Example

<table>
<thead>
<tr>
<th>query(10)</th>
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<tbody>
<tr>
<td>4  n1  f4</td>
</tr>
<tr>
<td>12  n2  f12</td>
</tr>
<tr>
<td>5  n3</td>
</tr>
<tr>
<td>9  n3  f9</td>
</tr>
<tr>
<td>3  n1  f3</td>
</tr>
<tr>
<td>14  n4  f14</td>
</tr>
<tr>
<td>14  n5  f14</td>
</tr>
<tr>
<td>13  n2  f13</td>
</tr>
<tr>
<td>3  n6</td>
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</table>

Note: doesn’t show file caching on the reverse path

Freenet Requests

- Any node forwarding reply may change the source of the reply (to itself or any other node)
  - Helps anonymity
- Each query is associated a TTL that is decremented each time the query message is forwarded; to obscure distance to originator:
  - TTL can be initiated to a random value within some bounds
  - When TTL=1, the query is forwarded with a finite probability
- Each node maintains the state for all outstanding queries that have traversed it → help to avoid cycles
- If data is not found, failure is reported back
  - Requestor then tries next closest match in routing table

Freenet Request
**Freenet Search Features**

- Nodes tend to specialize in searching for similar keys over time
  - Gets queries from other nodes for similar keys
- Nodes store similar keys over time
  - Caching of files as a result of successful queries
- Similarity of keys does not reflect similarity of files
- Routing does not reflect network topology

**Freenet File Creation**

- Key for file generated and searched → helps identify collision
  - Not found (“All clear”) result indicates success
  - Source of insert message can be change by any forwarding node
- Creation mechanism adds files/info to locations with similar keys
- New nodes are discovered through file creation
- Erroneous/malicious inserts propagate original file further

**Cache Management**

- LRU Cache of files
- Files are not guaranteed to live forever
  - Files “fade away” as fewer requests are made for them
- File contents can be encrypted with original text names as key
  - Cache owners do not know either original name or contents → cannot be held responsible

**Freenet Naming**

- Freenet deals with keys
  - But humans need names
  - Keys are flat → would like structure as well
- Could have files that store keys for other files
  - File /text/philosophy could store keys for files in that directory → how to update this file though?
- Search engine → undesirable centralized solution
Freenet Naming - Indirect files

- Normal files stored using content-hash key
  - Prevents tampering, enables versioning, etc.
- Indirect files stored using name-based key
  - Indirect files store keys for normal files
  - Inserted at the same time as normal file
- Has same update problems as directory files
  - Updates handled by signing indirect file with public/private key
  - Collisions for insert of new indirect file handled specially → check to ensure same key used for signing
- Allows for files to be split into multiple smaller parts

How does Tor work?

**How Tor Works: 1**

1. Alice's Tor client obtains a list of Tor nodes from a directory server.
2. Alice's Tor client selects a random path to the destination server.
3. Data is encrypted at each hop, and the path is split into three parts:
   - Green links are in the clear.
   - Red links are encrypted.

**How Tor Works: 2**

1. Alice's Tor client selects a random path to the destination server.
2. Data is encrypted at each hop, and the path is split into three parts:
   - Green links are in the clear.
   - Red links are encrypted.
3. Data is then sent through the encrypted network, ensuring privacy and anonymity.
How does Tor work?

Building a circuit

Fetching a web page

Last onion router should get the IP address of Bob’s website to protect Alice’s anonymity.