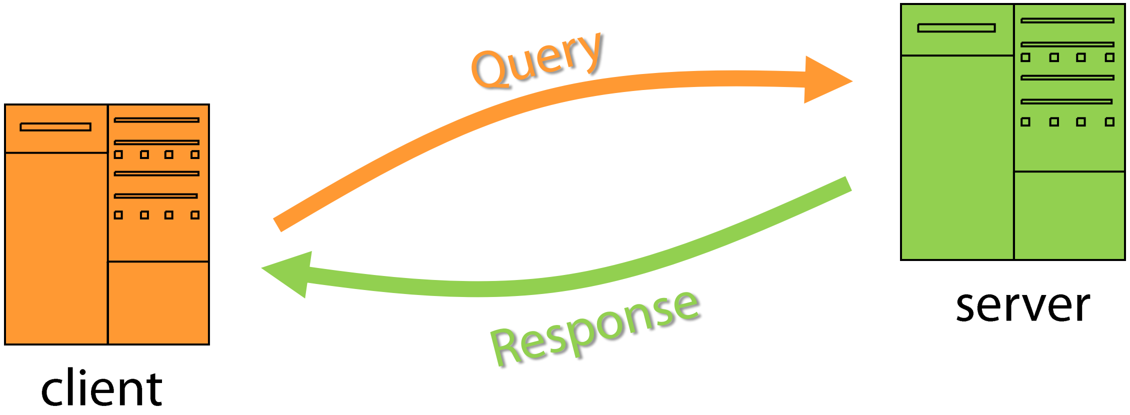
Technion Summer School in Computer Security, September 2016

Attacking the Network Time Protocol (NTP)



BOSTON UNIVERSITY

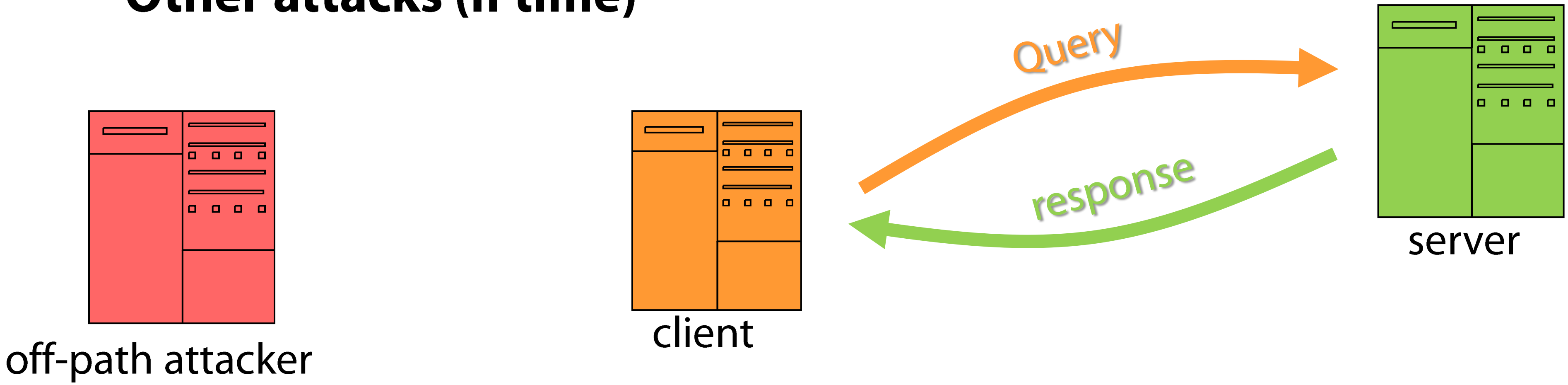
Aanchal Malhotra
Isaac E. Cohen, Erik Brakke
Sharon Goldberg

outline of the talk

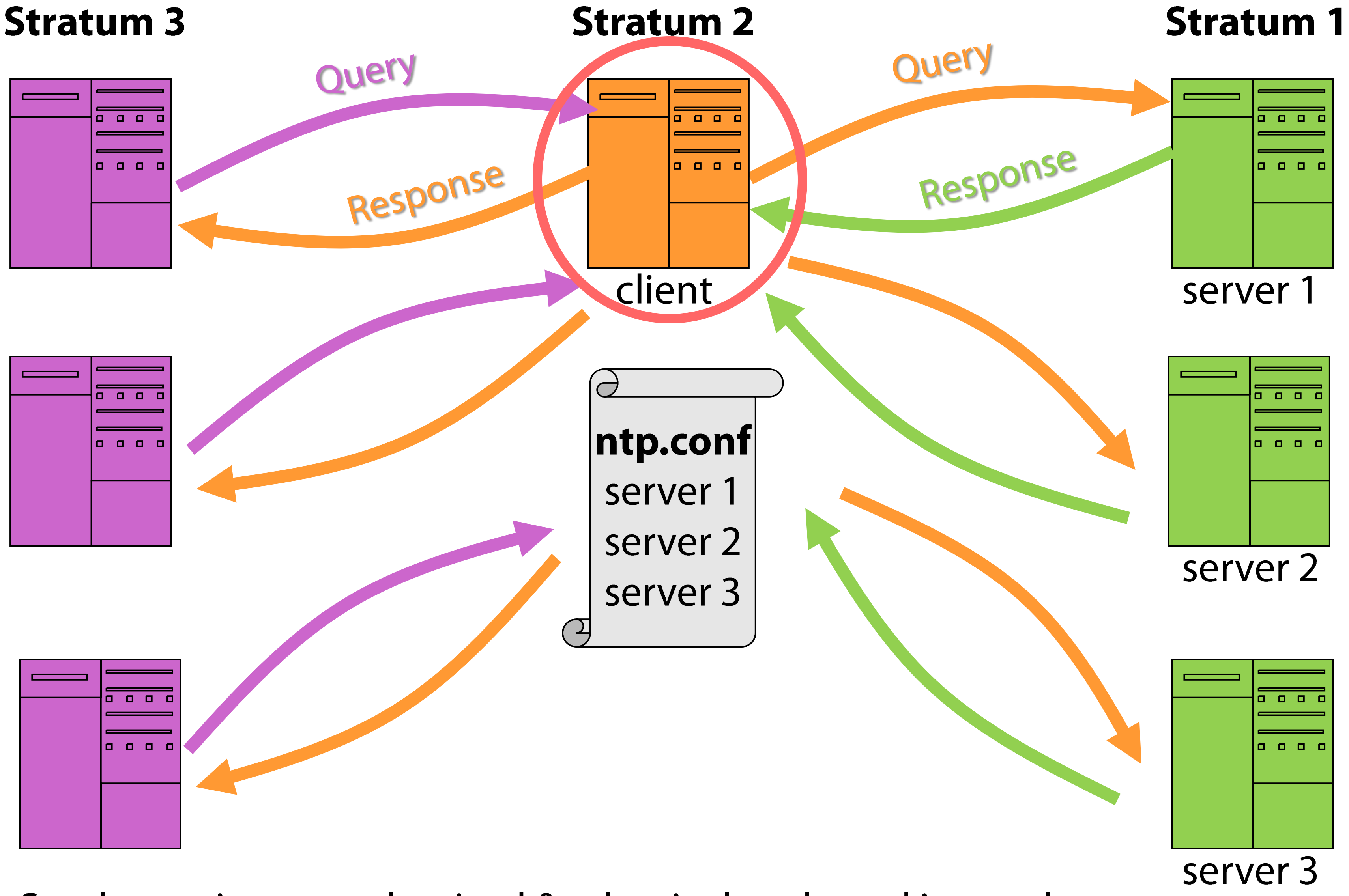
- **Background**
  - How does NTP work?
  - How does NTP client take time?

- **Our client/server mode attacks**
  - Denial of Service by Spoofed Kiss-of-Death (off-path)
  - Denial of Service by Priming the Pump (off-path)
  - Timeshifting by IPv4 Packet Fragmentation (off-path)

- **Broadcast mode attacks**
- **Other attacks (if time)**

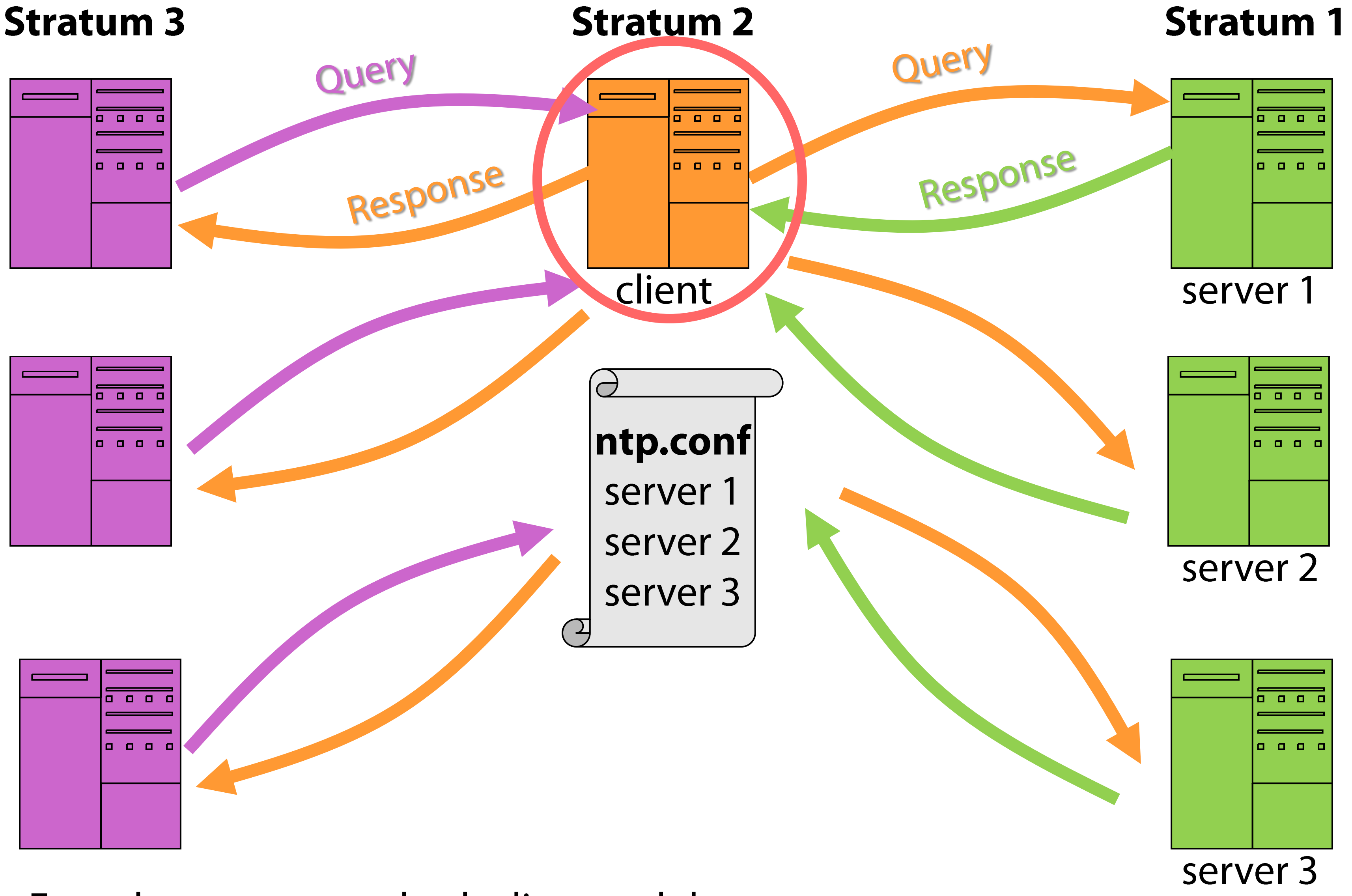


background: how does NTP work?



- Sends queries at randomized & adaptively-selected intervals
- Requires certain number of self-consistent responses to update its clock

background: how does NTP work?



- Every host can act as both client and the server
- My laptop will answer queries from public Internet

the state of crypto in NTP

NTP’s crypto is rarely used in practice

- Symmetric crypto
  - Uses *MD5(key||message*) [RFC 5905] (insecure!)
  - No in-band mechanism for key distribution
- Asymmetric crypto
  - Autokey Protocol [RFC 5906] is not a standards-track doc
  - Crypto is badly broken [S. Röttger’ 2012]

Our zmap scan (July 2016) found 3.9M IPs revealing NTP crypto state

- Only 78K systems have all associations authenticated (2%)

IETF: Lots of activity lately in IETF to develop a secure NTP

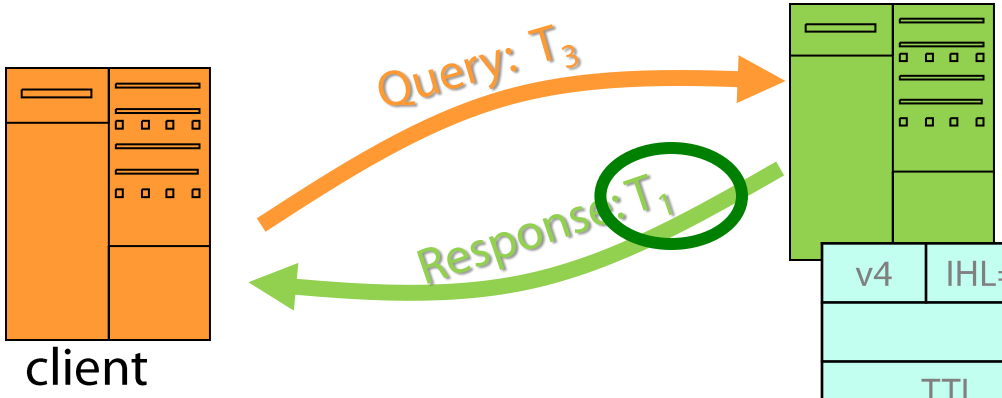
- NTS (Network Time Security)
- Very fluid right now, but potentially based on DTLS.

We attack the NTPv4 spec [RFC 5905]

and its reference implementation
(ntpd v4.2.8p2 & ntpd v4.2.6p5)

We assume NTP messages are
not cryptographically authenticated.

non-crypto authentication with origin timestamp (T_1)



Analogous to
- UDP source port randomization
- TCP sequence no randomization

<table>
<tr><td colspan="2">v4</td><td>IHL=20</td><td>TOS</td><td colspan="5">Total length = 76</td></tr>
<tr><td colspan="4">IPID</td><td>x</td><td>DF</td><td>MF</td><td colspan="2">Frag Offset</td></tr>
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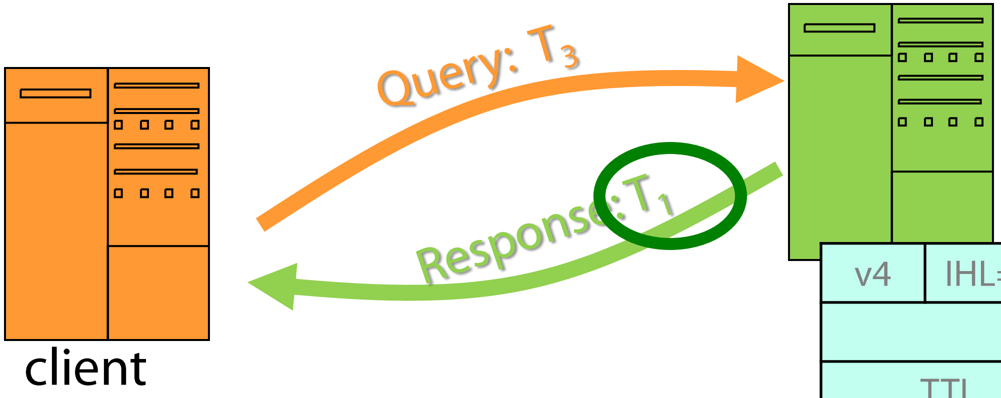
TEST2: Match
T3 in Query to **T1 in Response**.

seconds
fractional seconds

64 bits

*ntpd does not randomize source port!

non-crypto authentication with origin timestamp (T_1)



Analogous to
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TEST2: Match
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<tr><td colspan="2"><b>seconds</b></td></tr>
<tr><td><b>precision</b></td><td><b>randomness</b></td></tr>
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64 bits

*ntpd does not randomize source port!

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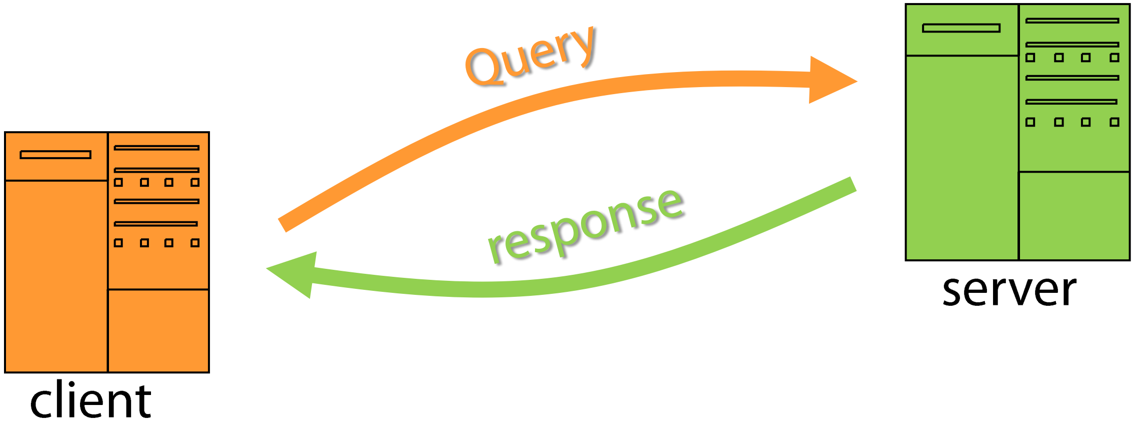
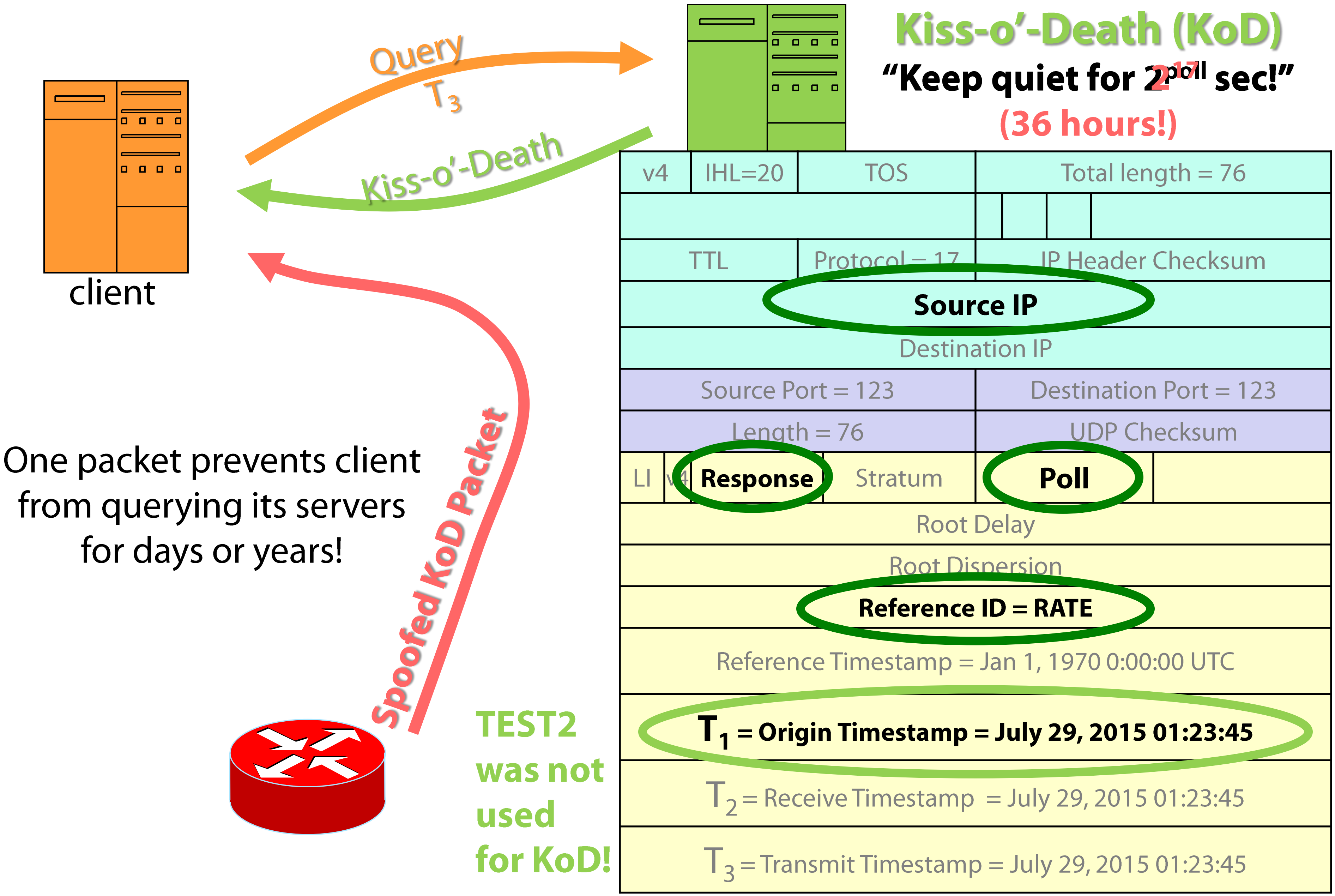
  - ➢ **Denial of Service** by Spoofed Kiss-of-Death (off-path)
  - ➢ **Denial of Service** by Priming the Pump (off-path)
  - ➢ Timeshifting by IPv4 Packet Fragmentation (off-path)

- Broadcast mode attacks



denial of service via spoofed kiss-o-death (KoD)



Kiss-o'-Death (KoD)

“Keep quiet for 2^{poll} 2^{17} sec!”

(36 hours!)

One packet prevents client from querying its servers for days or years!

TEST2 was not used for KoD!

v4 | IHL=20 | TOS | Total length = 76

TTL | Protocol = 17 | IP Header Checksum

Source IP

Destination IP

Source Port = 123 | Destination Port = 123

Length = 76 | UDP Checksum

LI | v4 | **Response** | Stratum | **Poll**

Root Delay

Root Dispersion

Reference ID = RATE

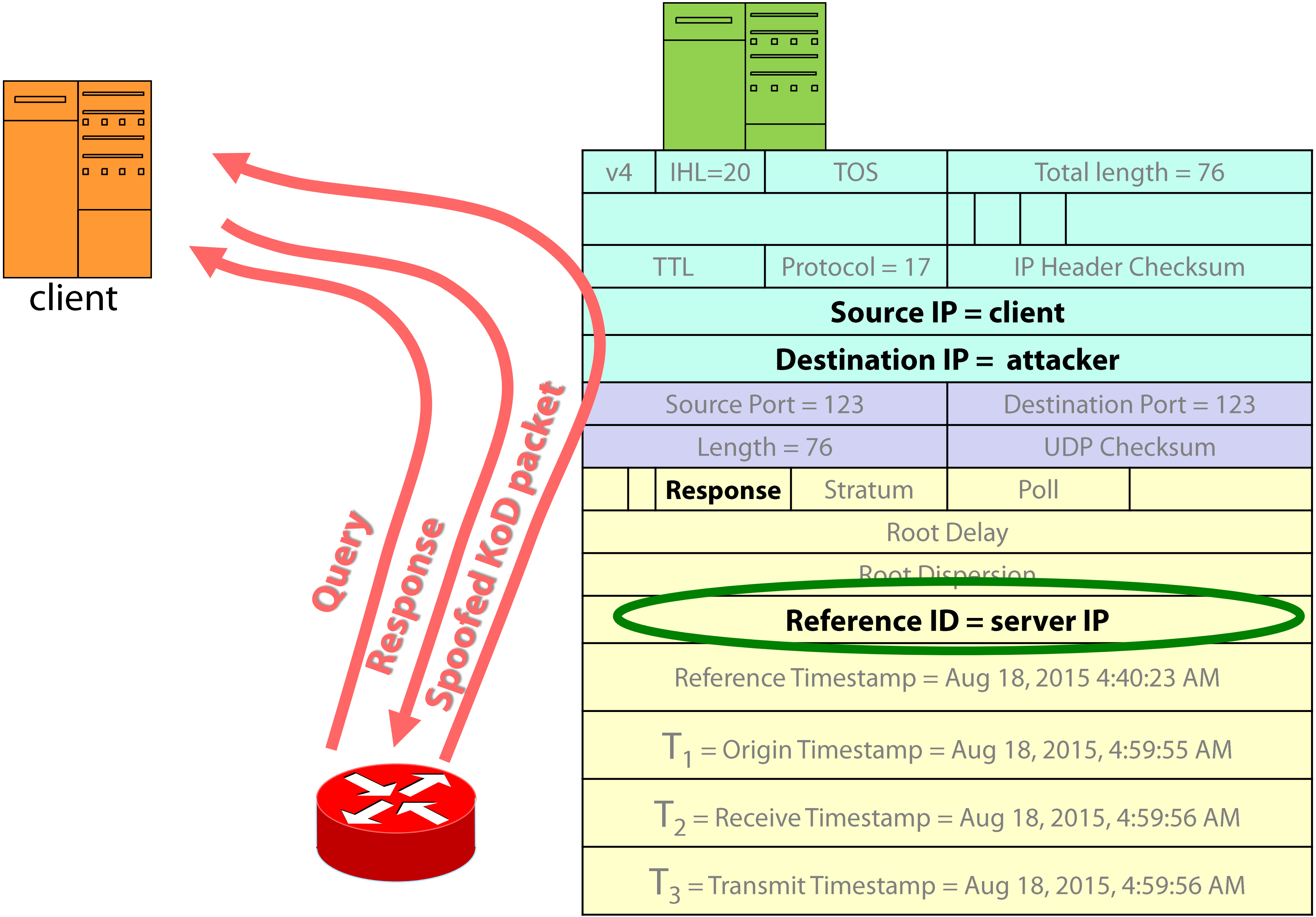
Reference Timestamp = Jan 1, 1970 0:00:00 UTC

T_1 = Origin Timestamp = July 29, 2015 01:23:45

T_2 = Receive Timestamp = July 29, 2015 01:23:45

T_3 = Transmit Timestamp = July 29, 2015 01:23:45

how to learn the server’s IP for the spoofed KoD?



v4 | IHL=20 | TOS | Total length = 76

TTL | Protocol = 17 | IP Header Checksum

Source IP = client

Destination IP = attacker

Source Port = 123 | Destination Port = 123

Length = 76 | UDP Checksum

Response | Stratum | Poll

Root Delay

Root Dispersion

Reference ID = server IP

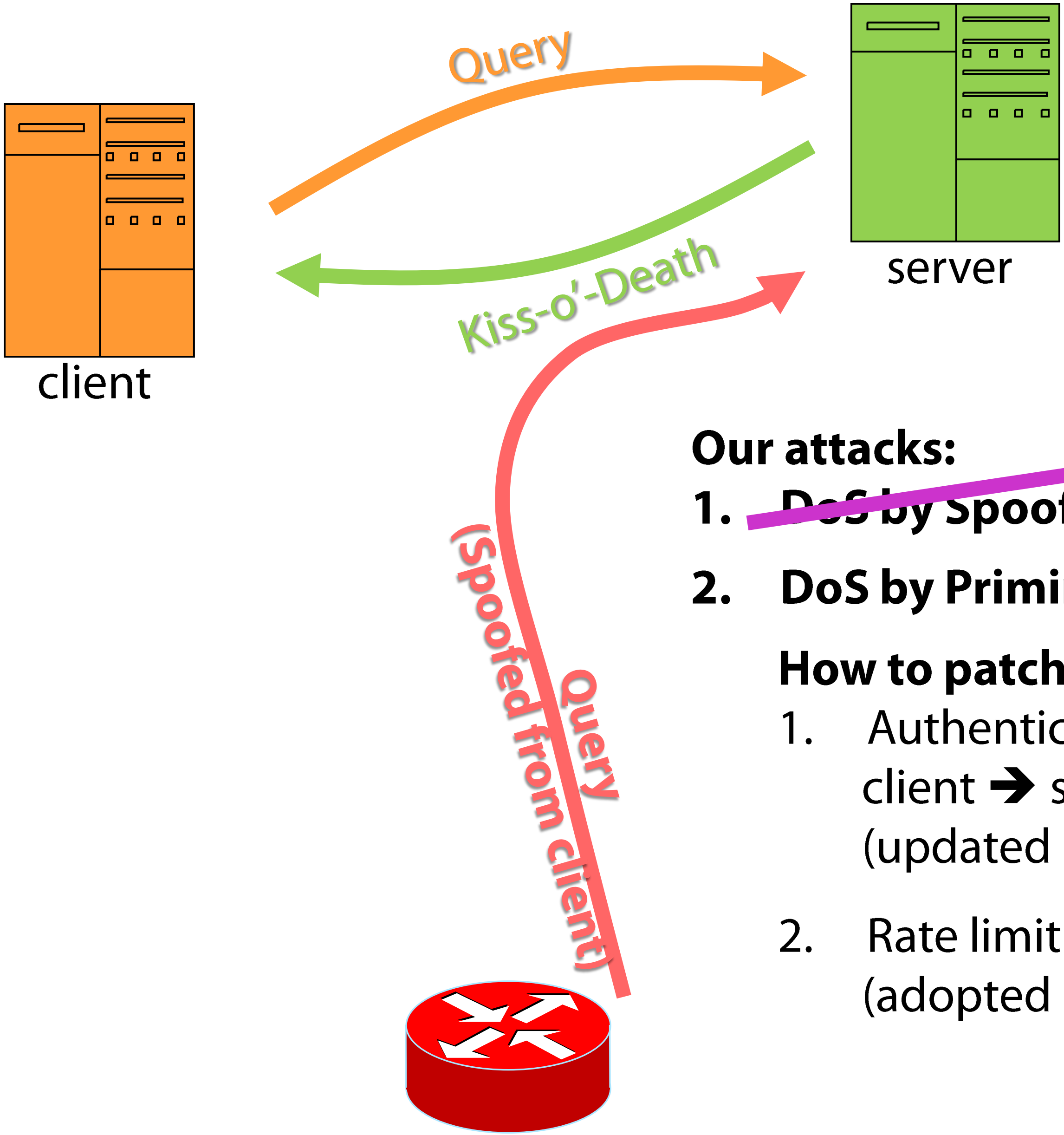
Reference Timestamp = Aug 18, 2015 4:40:23 AM

T_1 = Origin Timestamp = Aug 18, 2015, 4:59:55 AM

T_2 = Receive Timestamp = Aug 18, 2015, 4:59:56 AM

T_3 = Transmit Timestamp = Aug 18, 2015, 4:59:56 AM

denial of service by priming the pump



Patched!

TEST2 for KoD

ntpd 4.2.8p4

Our attacks:

1. ~~**DoS by Spoofed KoD (off-path)**~~
2. **DoS by Priming the Pump (off-path)**

How to patch?

1. Authenticate both directions
   client ➔ server & server ➔client
   (updated Network Time Security IETF ID)

2. Rate limit like DNS Response Rate Limit'g
   (adopted by chrony, ntpd)

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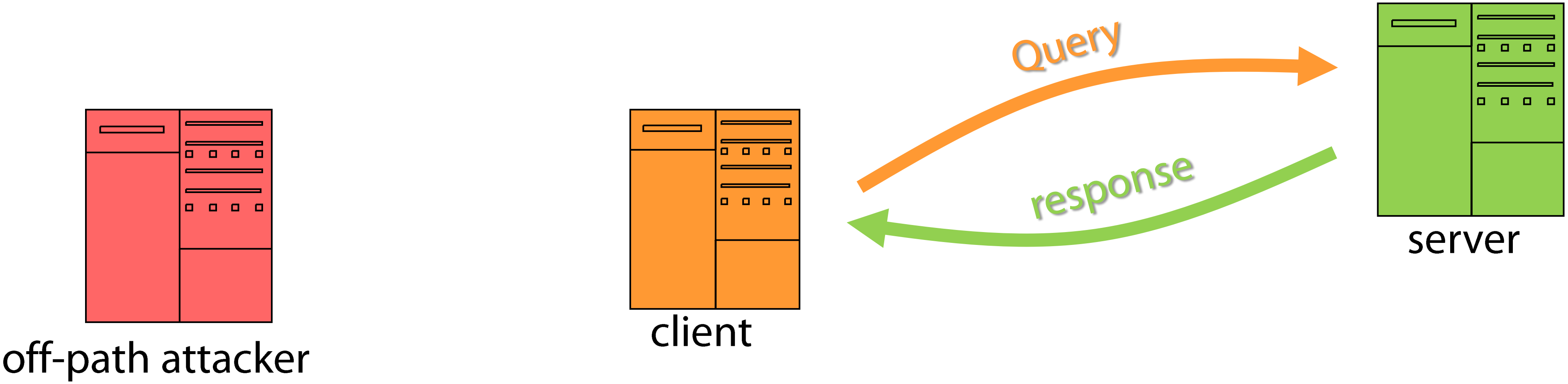
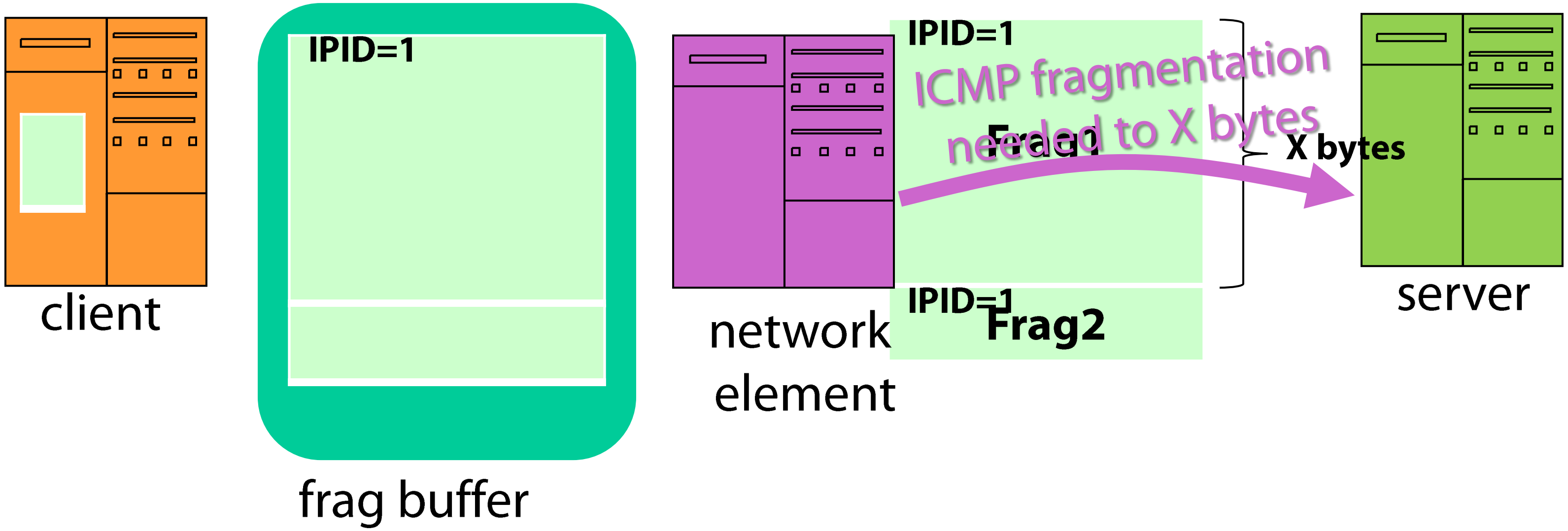
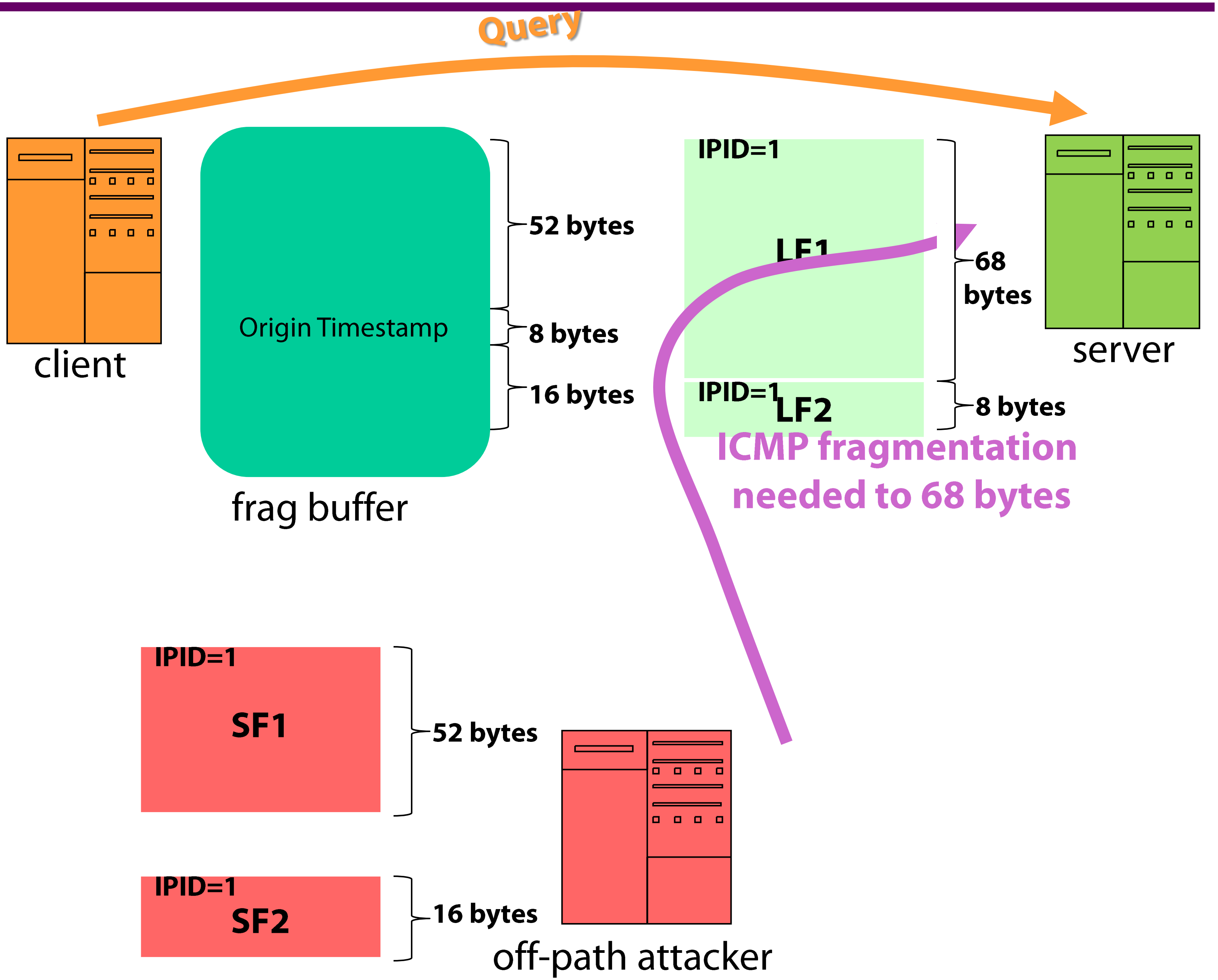
  - Denial of Service by Priming the Pump (off-path)
  - **Timeshifting** by IPv4 packet fragmentation (off-path)
- Broadcast mode attacks



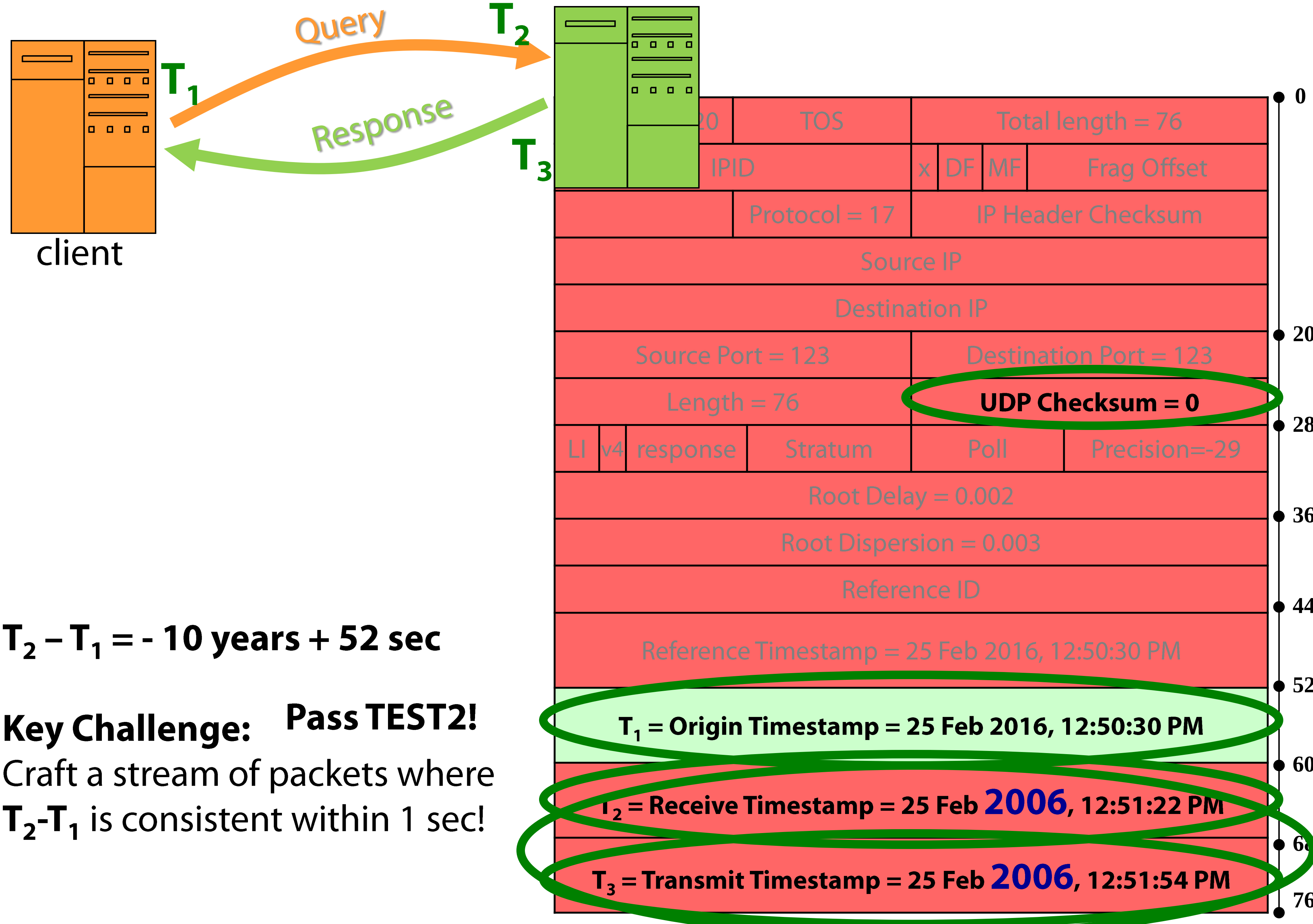
background: IPv4 fragmentation



exploiting IPv4 fragmentation to attack NTP



what does the reassembled packet look like?



20 | TOS | Total length = 76

IPID | x | DF | MF | Frag Offset

Protocol = 17 | IP Header Checksum

Source IP

Destination IP

Source Port = 123 | Destination Port = 123

Length = 76 | **UDP Checksum = 0**

LI | v4 | response | Stratum | Poll | Precision=-29

Root Delay = 0.002

Root Dispersion = 0.003

Reference ID

Reference Timestamp = 25 Feb 2016, 12:50:30 PM

T$_1$ = Origin Timestamp = 25 Feb 2016, 12:50:30 PM

T$_2$ = Receive Timestamp = 25 Feb 2006, 12:51:22 PM

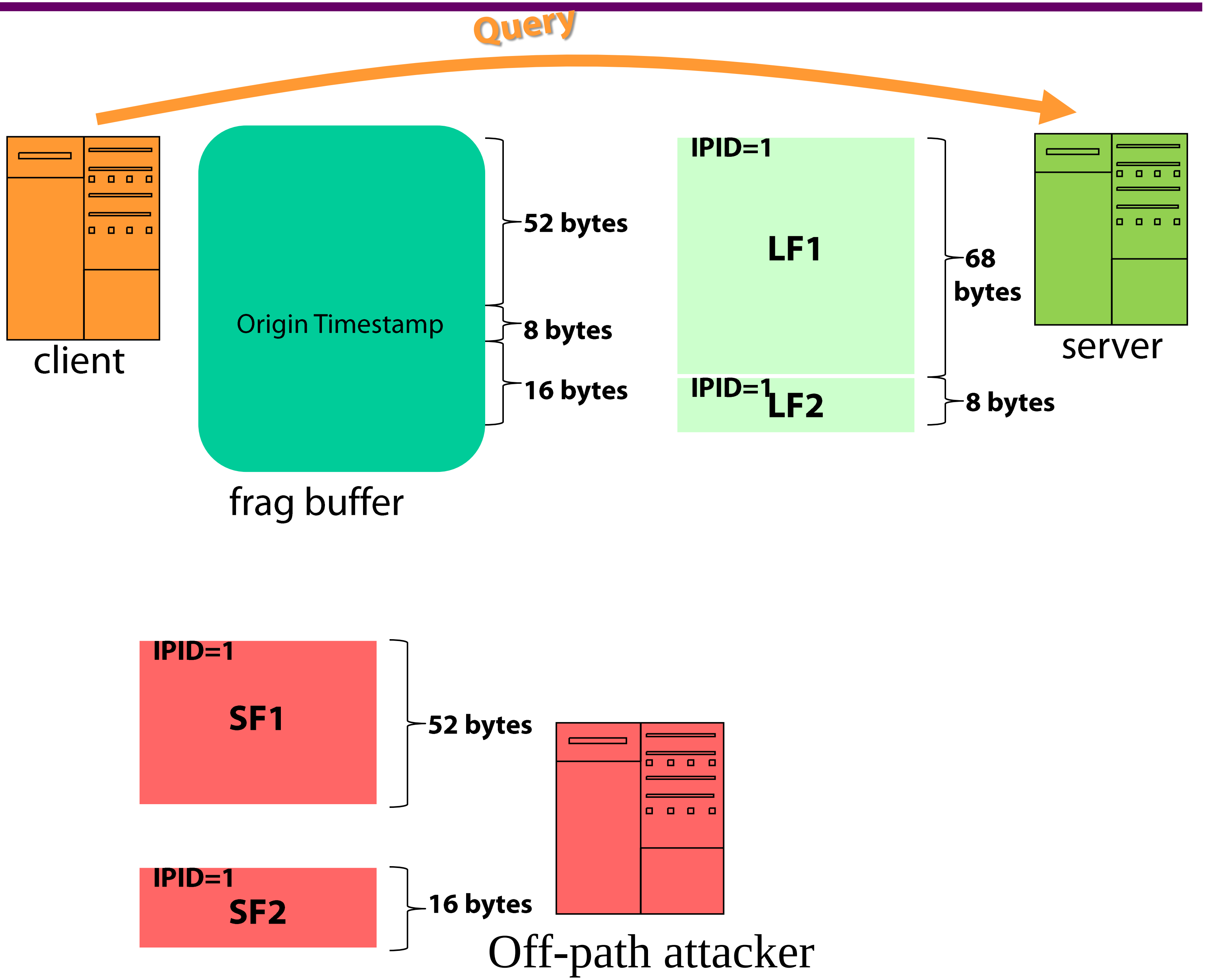
T$_3$ = Transmit Timestamp = 25 Feb 2006, 12:51:54 PM

T$_2$ – T$_1$ = - 10 years + 52 sec

Key Challenge: **Pass TEST2!**

Craft a stream of packets where T$_2$-T$_1$ is consistent within 1 sec!

challenge: construct a stream of consistent packets



Query

client

Origin Timestamp

frag buffer

52 bytes

8 bytes

16 bytes

IPID=1

LF1

IPID=1

LF2

68 bytes

8 bytes

server

IPID=1

SF1

52 bytes

IPID=1

SF2

16 bytes

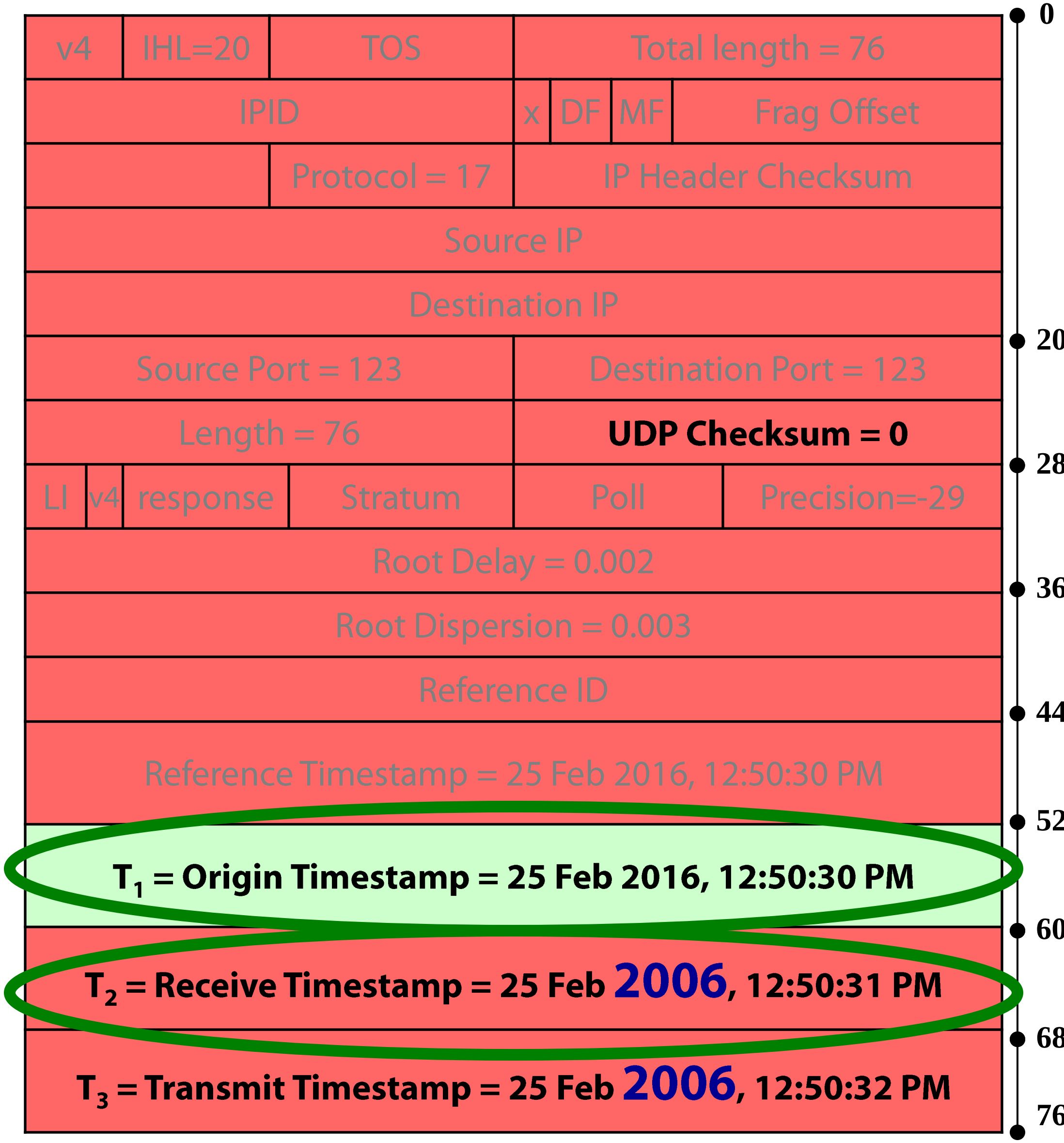
Off-path attacker

challenge: construct a stream of consistent packets

Why does this help?

The second spoofed fragment sits in the fragment buffer for no longer than 1 sec

$T_2 - T_1 = -10 \text{ years} + 1\text{sec}$



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IPID | x | DF | MF | Frag Offset

Protocol = 17 | IP Header Checksum

Source IP

Destination IP

Source Port = 123 | Destination Port = 123

Length = 76 | **UDP Checksum = 0**

LI | v4 | response | Stratum | Poll | Precision=-29

Root Delay = 0.002

Root Dispersion = 0.003

Reference ID

Reference Timestamp = 25 Feb 2016, 12:50:30 PM

T_1 = Origin Timestamp = 25 Feb 2016, 12:50:30 PM

T_2 = Receive Timestamp = 25 Feb 2006, 12:50:31 PM

T_3 = Transmit Timestamp = 25 Feb 2006, 12:50:32 PM

attack surface for our NTP fragmentation attack

Conditions:

1. Server fragments NTP packets to 68 bytes
   - Out of 13M scanned NTP servers, 24K servers do this

2. Client reassembles overlapping fragments by the ”First” policy
   - Cannot safely measure due to teardrop [CA-1997-28]

3. Server uses incrementing IPID
   - Inferring globally-incrementing IPID is trivial (most vuln servers)
   - Infer per-destination IPID with **[Gilad-Herzberg’13]** and **[Knockell-Crandall’14]**

Recommendations:

- Servers should not fragment to 68 bytes (Test servers on our site!)
- Drop overlapping IPv4 fragments!

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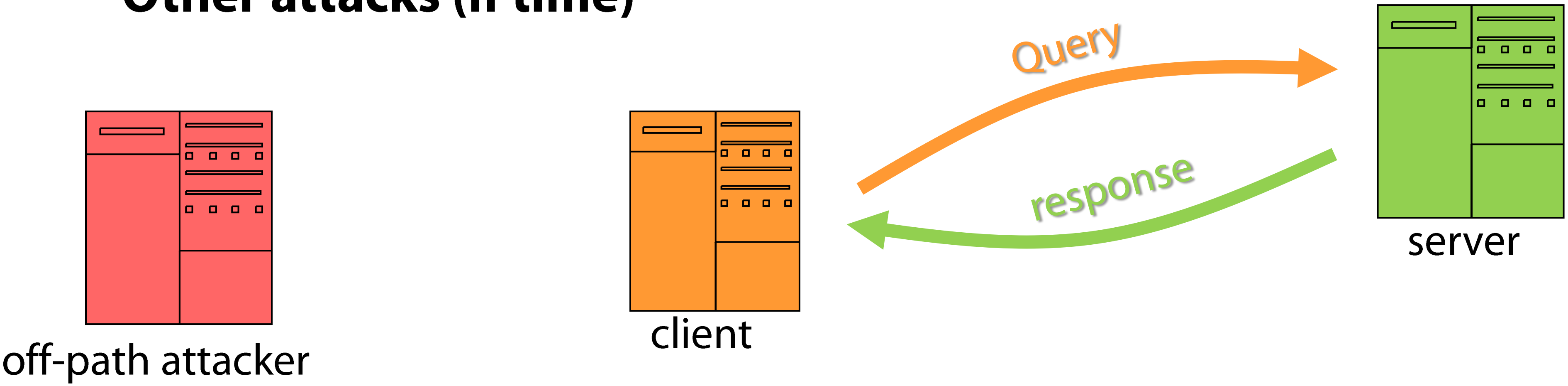


background: broadcast mode

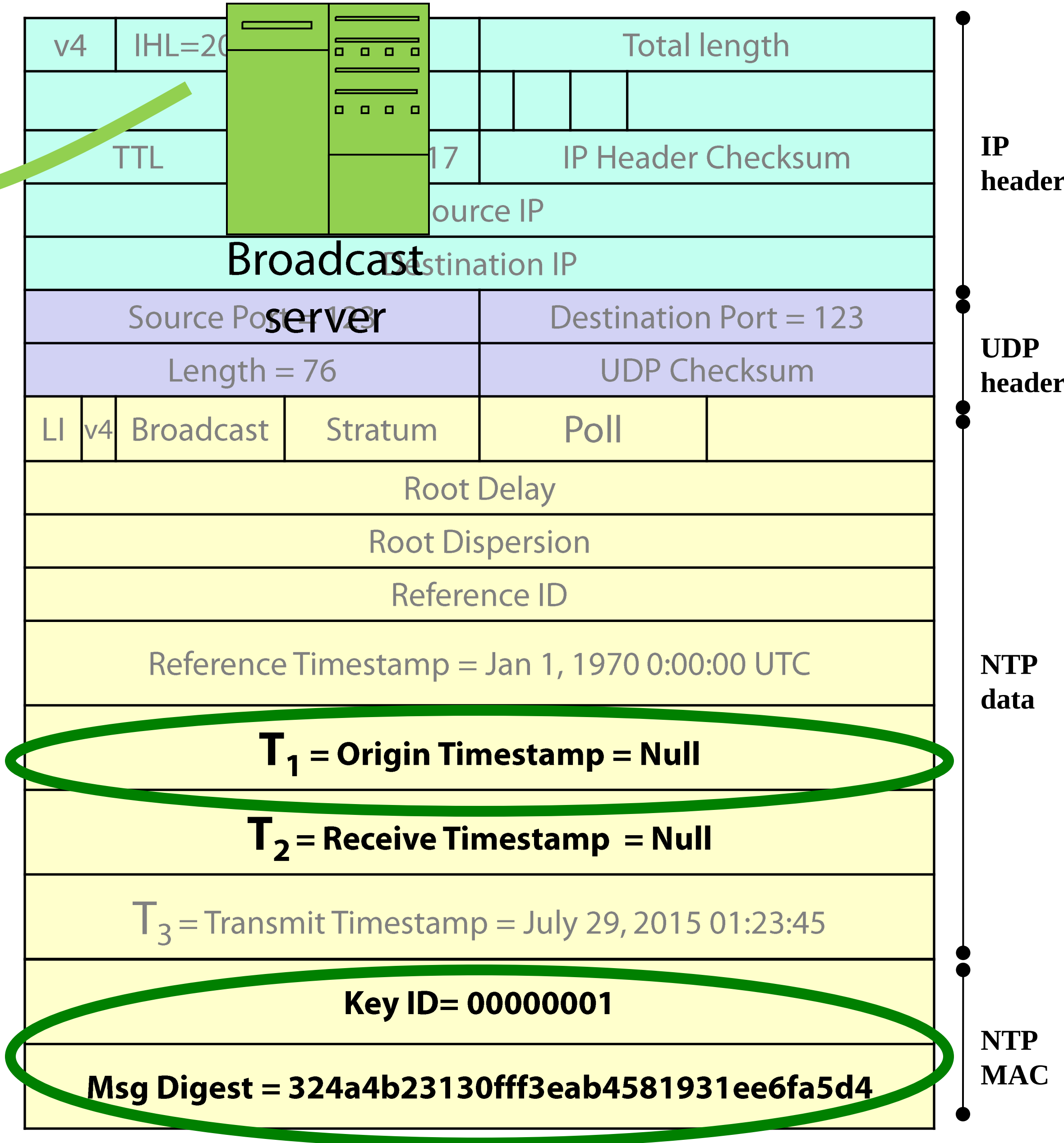
RFC5905 requires broadcast mode to be crypto authenticated

But why?

- TEST2 does not apply

RFC5905 says:

"If preconfigured to accept broadcast packets, the client accepts packets from ANY server that sends it broadcast packets."



v4 | IHL=20 | Total length

TTL | 17 | IP Header Checksum

Source IP

Destination IP

Source Port = 123 | Destination Port = 123

Length = 76 | UDP Checksum

LI | v4 | Broadcast | Stratum | Poll

Root Delay

Root Dispersion

Reference ID

Reference Timestamp = Jan 1, 1970 0:00:00 UTC

T_1 = Origin Timestamp = Null

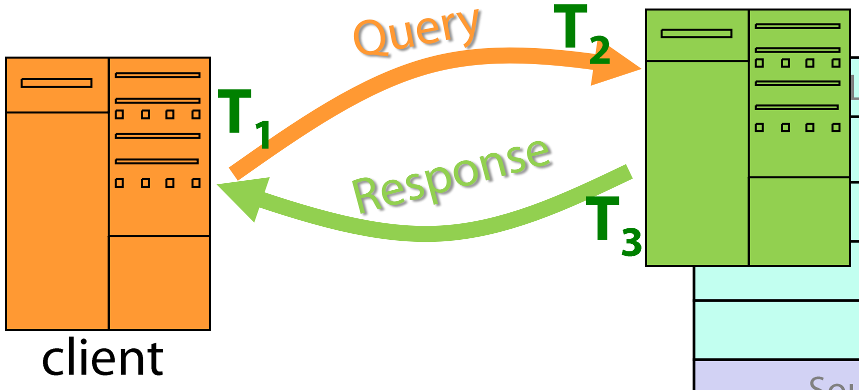
T_2 = Receive Timestamp = Null

T_3 = Transmit Timestamp = July 29, 2015 01:23:45

Key ID= 00000001

Msg Digest = 324a4b23130fff3eab4581931ee6fa5d4

how does a broadcast client detect replay attacks?



IP header:

L=20 | TOS | Total length

Protocol = 17 | IP Header Checksum

Source IP

Destination IP

UDP header:

Source Port = 123 | Destination Port = 123

Length = 76 | UDP Checksum

NTP data:

LI | v4 | Broadcast | Stratum | Poll

Root Delay

Root Dispersion

Reference ID

Reference Timestamp = Jan 1, 1970 0:00:00 UTC

T_1 = Origin Timestamp = NULL

T_2 = Receive Timestamp = NULL

T_3 = Transmit Timestamp = March 22, 2016 01:53:45

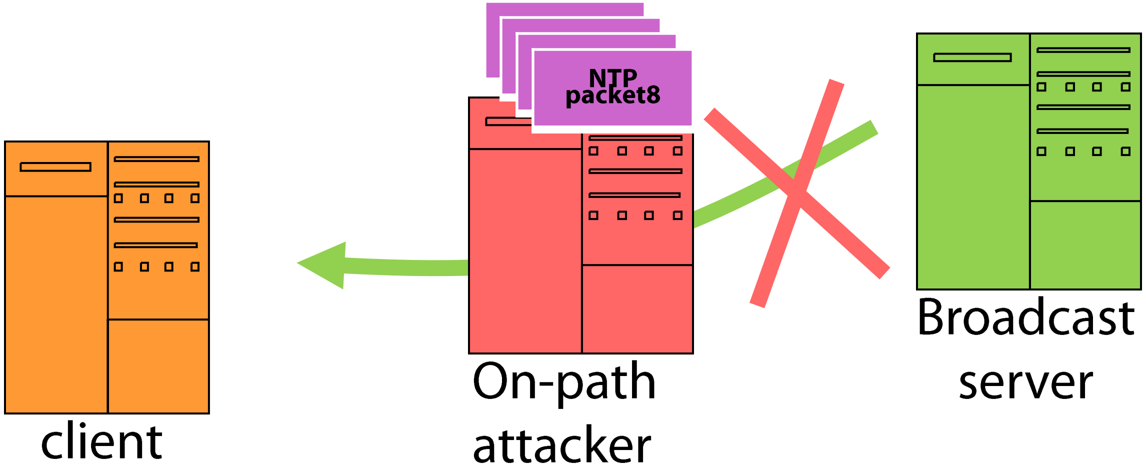
NTP MAC:

Key ID= 00000001

Message Digest = 324a4b23130fff3eab4581931ee6fa5d4

TEST1: Prevents replay of **most recent** packet!

déjà vu: time sticking attack via packet replay

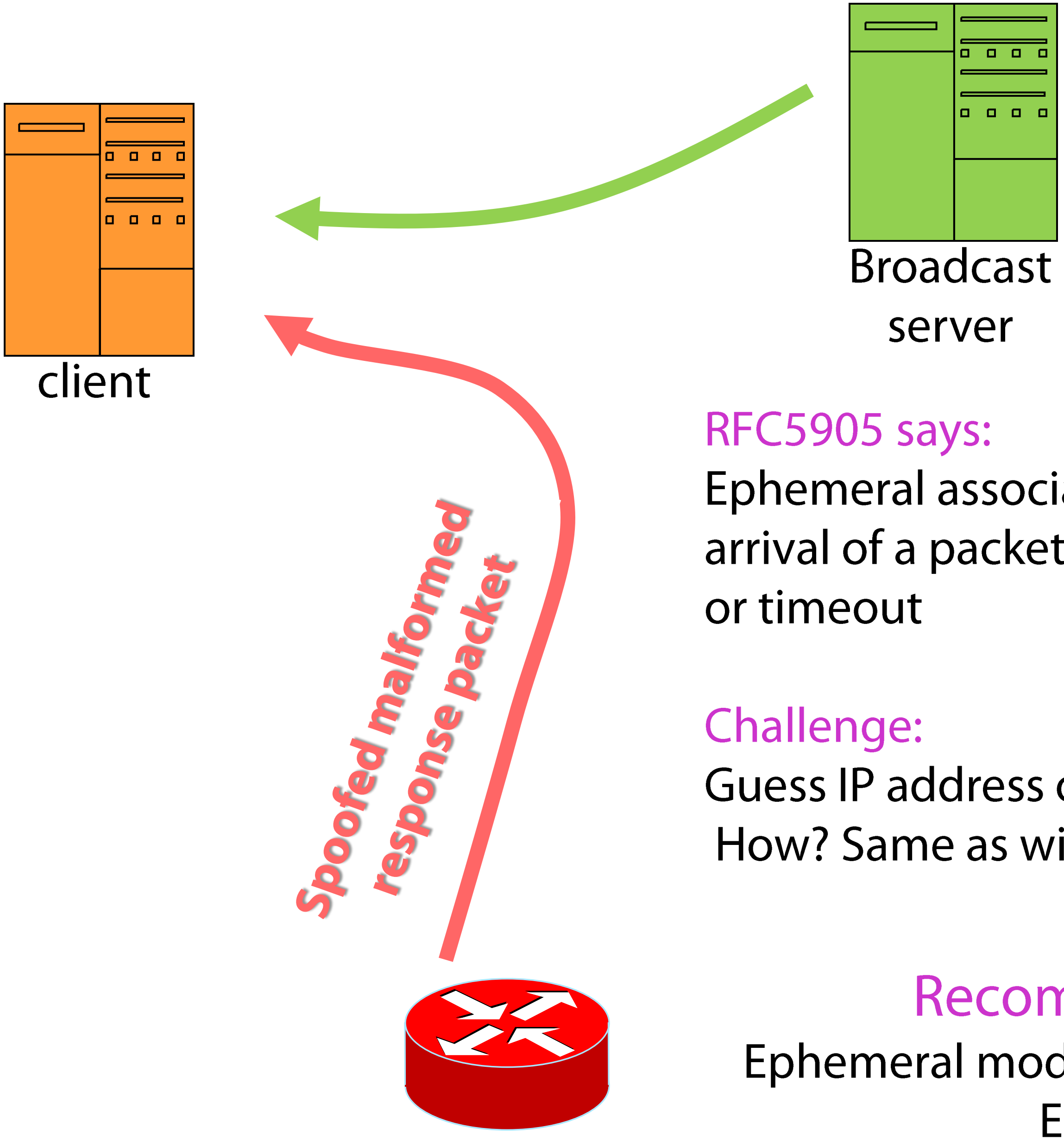


Attack: Replay, in order the eight most recent timestamps

Recommendation:

Add an incrementing counter to the (timestamp) fields that are null

off-path DoS attack using malformed crypto packets



RFC5905 says:

Ephemeral associations are mobilized upon arrival of a packet and demobilized upon error or timeout

Challenge:

Guess IP address of the server.

How? Same as with our KoD attacks

Recommendation:

Ephemeral modes considered harmful.

Eliminate.

other recent attacks

The dreaded NTP DDoS Reflection attack

- this is still a problem
- send the monlist control query to an NTP host (via UDP!)
- … get a list of last 600 IPs interacting with that host.

Cisco ASIG attacks on NTP

- zero origin timestamp attack (from RFC5905)
- NAK to the future (crypto NAK implementation flaw)
- crypto key misbinding leading to a sybil attack vulnerability
- origin timestamp leak vulnerability
  - Use NTP control queries to learn exact value of origin timestamp
  - … and bypass TEST2.

recommendations for NTP users

- **Firewall your NTP instances**.
  - End-hosts should not accept **anything** other than mode 4 packets from their preconfigured servers.
  - All hosts (incl. servers) should not accept **any** control queries (not just monlist) from arbitrary IPs. (Use the ntpd **`noquery`** option)
  - Firewalls should block KoD (mode 4) with high poll (eg poll >10)

- If ntpd is configured with the –g option, monitor for reboots
  - NTP is much more vulnerable to attacks when it reboots

- Don’t use broadcast mode except in a safe firewalled network
  - Even if your packets are authenticated, you are still vulnerable.
  - Make sure no broadcast packets come into your network from outside

- Don’t fragment NTP packets

longer recommendations for securing NTP

- Stop leaking so much information.
  - NTP packet leak the reference ID and reference time.
  - NTP control packets leak timestamps and lots of internal state
  - All this information can be collected using UDP
  - And in most cases is available by default

- Get rid of the KoD, use RRL style rate limiting instead

- Use a modern control protocol instead of leaky UDP control protocol

- Latest burst of bugs has shown that RFC5905 is underspecified

- Lots more work to be done to develop crypto for NTP

Questions?

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NDSS'16, San Diego, CA. Feb 2016.

Attacking the NTP's Authenticated Broadcast Mode
Aanchal Malhotra and Sharon Goldberg
SIGCOMM Computer Communication Review, April 2016.

http://www.cs.bu.edu/~goldbe/NTPattack.html