Device Tracking via Linux's New TCP Source Port Selection Algorithm

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Seminar

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Introduction

Motivation

Meltdown and Spectre

MELTDOWN [3]

SPECTRE [4]

- Exploited performance features of modern CPUs
- Side effects of out-of-order and speculative execution
- Allows to read innaccesible data from memory

Device Tracking via Linux's New TCP Source Port Selection Algorithm (Extended Version) *

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- Exploited Linux's TCP source port selection algorithm
- Side effects of hash collisions
- Allows to track devices through device ID tied to device-specific key

Browser-based device tracking

Definition and Problem

information

- Information collected through web browser
- Privacy risk

Browser-based device tracking

Goldene image challenge

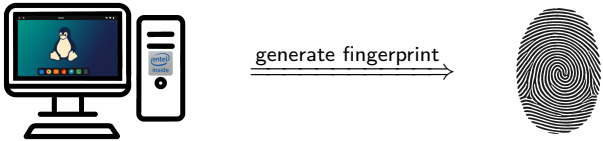
- Golden image challenge: Distinguish identical devices with same hardware and software configuration ☑ ⇒ device-specific key

Browser-based device tracking

Types of techniques

- Tagging techniques: Insert an ID

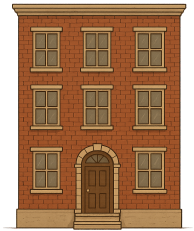
- Fingerprinting techniques: Measure characteristics



Source Port Selection

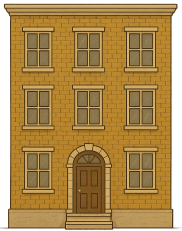
4-Tuple

- 4-tuple: $(IP_{Src}, Port_{Src}, IP_{Dest}, Port_{Dest})$



(123 Maple St., Apt. 5B) → (456 Oak St., Apt. 9D)

(192.0.2.123, 55'555) → (203.0.113.456, 49'999)



- (192.0.2.123, 55'555, 203.0.113.10, 49'999)
- (123 Maple St., Apt. 5B, 456 Oak St., Apt. 9D)

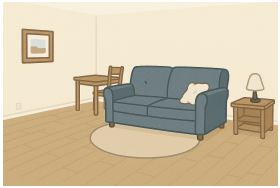
- Chooses TCP source port $Port_{Src}$ for 3-tuple: $(IP_{Src}, IP_{Dest}, Port_{Dest})$

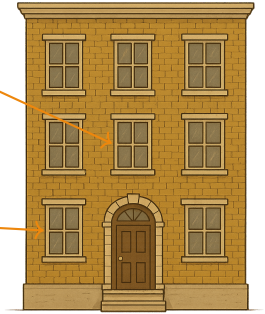
Source Port Selection

Goals

- Functionality: Reusing soure ports can cause failures

  $\Rightarrow$ Earlier connections might be active (`TIME_WAIT` state)

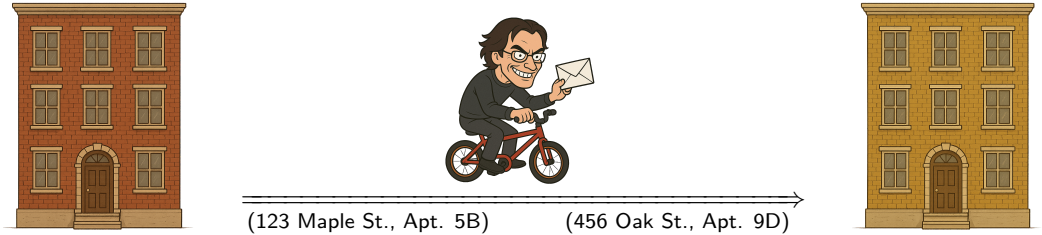




Source Port Selection

Goals

- Security:
  - Off-path attacks
  - Determine Device activity (number TCP connections per time)



Double-Hash Port Selection Algorithm (DHPS)

Algorithm Overview

- TCP source ports divided into ranges:

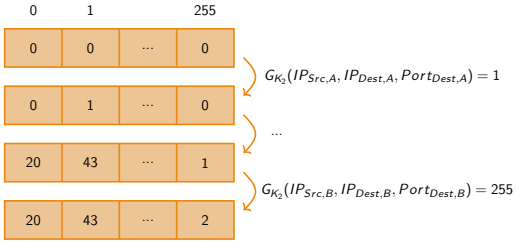
Port Range Type	Typical Range	Usage
Well-known ports	0–1023	Specific services, e.g. HTTP (80), HTTPS (443) etc.
Registered ports	1024–49151	User applications or services, not ephemeral
Ephemeral ports	49152–60999	Dynamically allocated by OS for short-lived client-side connections

Double-Hash Port Selection Algorithm (DHPS)

Algorithm Overview

- Complete 3-tuple to 4-tuple with cryptographic keyed-hash functions:
  - F_{K_1} : 3-Tuples $\xrightarrow{K_1}$ $\{0, \ldots, 2^{32}\}$
  - G_{K_2} : 3-Tuples $\xrightarrow{K_2}$ $\{0, \ldots, T\}$ where T is length of perturbation table

- Incrementation of port numbers separated into T different spaces
  $\Rightarrow$ Port-reuse frequency lower[2]
  $\Rightarrow$ Harder to analyse device activity



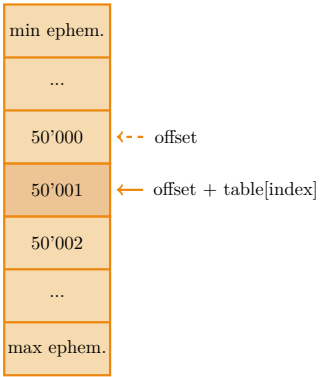
Double-Hash Port Selection Algorithm (DHPS)

Pseudocode

Algorithm 1 DHPS Source Port Selection

```
1  procedure SelectEphemeralPort
2      num_ephemeral ← max_ephemeral − min_ephemeral + 1
3      offset ← F_K1(IP_SRC,IP_DST,PORT_DST)
4      index ← G_K2(IP_SRC,IP_DST,PORT_DST)
5      count ← num_ephemeral
6      repeat
7          port ← min_ephemeral +
8              ((offset + table[index]) mod num_ephemeral)
9          table[index] ← table[index] + 1
10         if CheckSuitablePort(port) then
11             return port
12         count←count − 1
13     until count = 0
14     return Error
```

- Source port calculation:
  - $offset = 50'000$
  - $index = 255$



Double-Hash Port Selection Algorithm (DHPS)

Pseudocode

Algorithm 2 DHPS Source Port Selection

```
1  procedure SelectEphemeralPort
2      num_ephemeral ← max_ephemeral − min_ephemeral + 1
3      offset ← F_K1(IP_SRC,IP_DST,PORT_DST)
4      index ← G_K2(IP_SRC,IP_DST,PORT_DST)
5      count ← num_ephemeral
6      repeat
7          port ← min_ephemeral +
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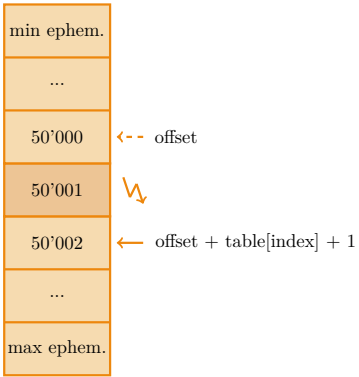

Double-Hash Port Selection Algorithm (DHPS)

Pseudocode

Algorithm 3 DHPS Source Port Selection

```
1  procedure SelectEphemeralPort
2      num_ephemeral ← max_ephemeral − min_ephemeral + 1
3      offset ← F_K1(IP_SRC,IP_DST,PORT_DST)
4      index ← G_K2(IP_SRC,IP_DST,PORT_DST)
5      count ← num_ephemeral
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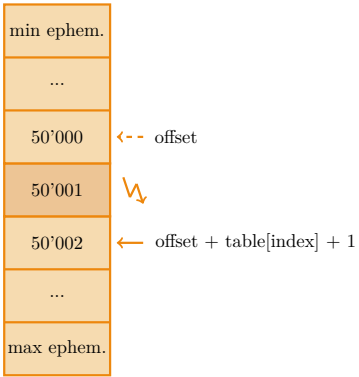

Double-Hash Port Selection Algorithm (DHPS)

Pseudocode

Algorithm 4 DHPS Source Port Selection

```
1  procedure SelectEphemeralPort
2      num_ephemeral ← max_ephemeral − min_ephemeral + 1
3      offset ← F_K1(IP_SRC,IP_DST,PORT_DST)
4      index ← G_K2(IP_SRC,IP_DST,PORT_DST)
5      count ← num_ephemeral
6      repeat
7          port ← min_ephemeral +
8              ((offset + table[index]) mod num_ephemeral)
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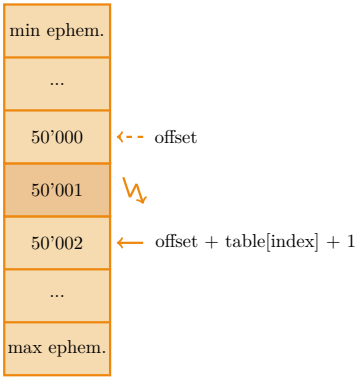
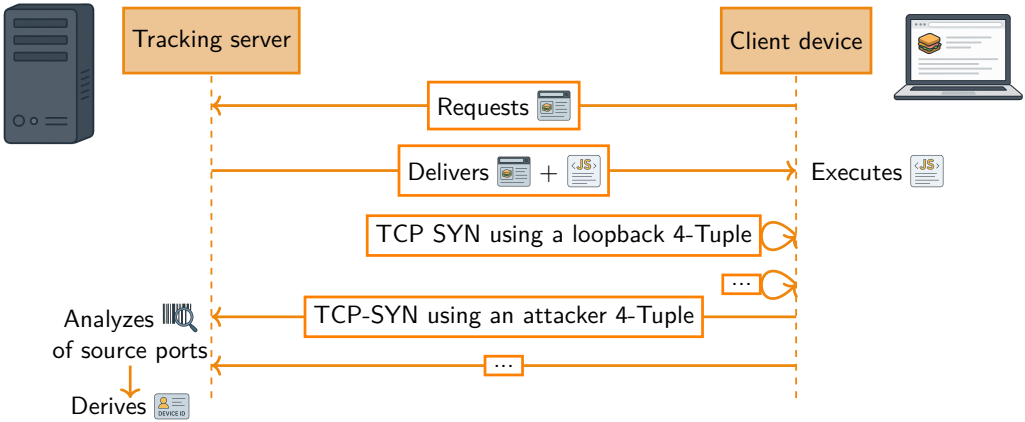


Attack

Attack Overview

Parties



Attack Overview

2 Types of 3-tuples

- Attacker 3-tuples:

$$DHPS(IP_{Src} = 192.0.2.123, IP_{Dst} = 203.0.113.10, Port_{Dst} = 456)$$

$$=$$

$$(192.0.2.123, 55'555, 203.0.113.10, 456)$$

$$(IP_{Src}, Port_{Src}, IP_{Dest}, Port_{Dest})$$

- Loopback 3-tuples:

$$DHPS(IP_{Src} = 127.0.0.1, IP_{Dst} = 127.0.0.3, Port_{Dst} = 11'111)$$

$$=$$

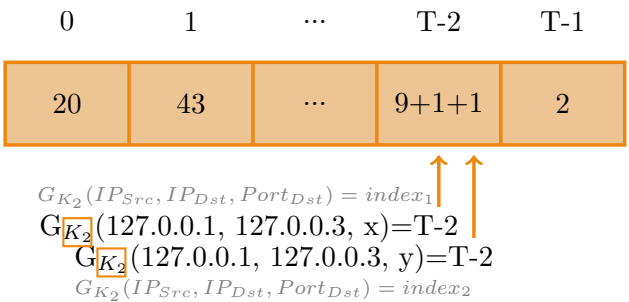
$$(127.0.0.1, 49'999, 127.0.0.3, 11'111)$$

$$(IP_{Src}, Port_{Src}, IP_{Dest}, Port_{Dest})$$

Device ID

Collisions

- Structure formed by collisions of loopback 3-tuples via G_{K_2}:



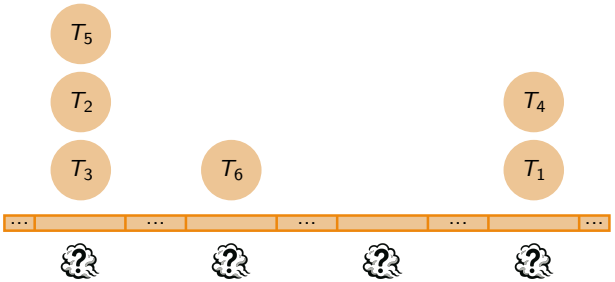
- Collisions depend on K_2
- K_2 randomly generated at
  - ⇒ Persists across and
  - ⇒ Also persists

Device ID

Independent pairs

- Consists of set of all such colliding independent pairs:

$\{(T_3, T_2), (T_3, T_5)\}$ $\{(T_1, T_4)\}$



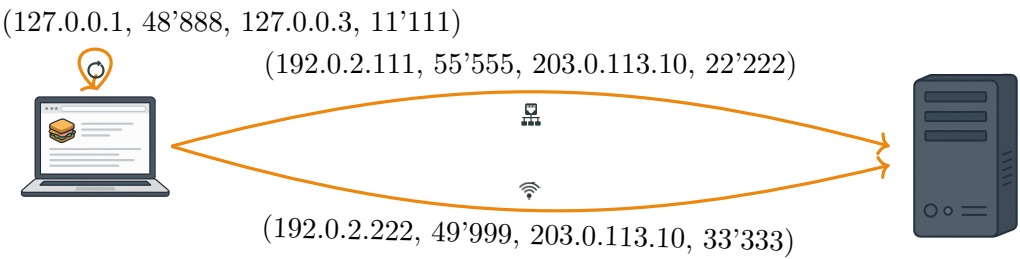
- #i: 6 = Device ID
- 💥: 3, evidence how K_2 maps into perturbation table cells

- Why?
  - $\binom{3}{2}$ pairs of $\{T_3, T_2, T_5\}$
    - $3 - 1$ are independent
  - $\{(T_3, T_2), (T_3, T_5)\}$ imply (T_2, T_5)

Device ID

Why loopback 3-tuples?

- Attacker 3-tuples not consistent across
- Loopback 3-tuples don't have this problem

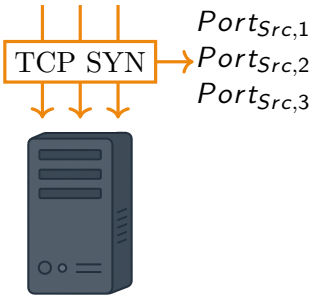


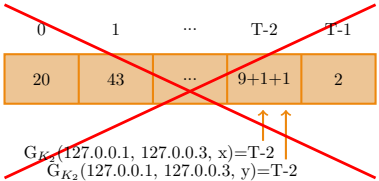
⇒ Loopback 3-tuples used for generating

Sandwiching Technique

Cannot directly observe collisions

- no access to kernel internals





- side effect: predictable increment

$$\texttt{table[index]} \leftarrow \texttt{table[index]} + 1$$

- analyse source port increments via
- ⇒ derive DEVICE ID

Sandwiching Technique

General principle

Step	Calculation
Wrapper	$i = G_{K_2}(\mathsf{IP}_{\mathsf{Src},X}, \mathsf{IP}_{\mathsf{Dst},X}, \mathsf{Port}_{\mathsf{Dst},X})$
Filling	$j = G_{K_2}(\mathsf{IP}_{\mathsf{Src},Y}, \mathsf{IP}_{\mathsf{Dst},Y}, \mathsf{Port}_{\mathsf{Dst},Y})$
Wrapper	$i = G_{K_2}(\mathsf{IP}_{\mathsf{Src},X}, \mathsf{IP}_{\mathsf{Dst},X}, \mathsf{Port}_{\mathsf{Dst},X})$

Sandwiching Technique

General principle

Step	Calculation
Wrapper	$i = G_{K_2}(\mathrm{IP}_{\mathrm{Src},X}, \mathrm{IP}_{\mathrm{Dst},X}, \mathrm{Port}_{\mathrm{Dst},X})$ $\mathrm{offset}_X = F_{K_1}(\mathrm{IP}_{\mathrm{Src},X}, \mathrm{IP}_{\mathrm{Dst},X}, \mathrm{Port}_{\mathrm{Dst},X})$
Filling	$j = G_{K_2}(\mathrm{IP}_{\mathrm{Src},Y}, \mathrm{IP}_{\mathrm{Dst},Y}, \mathrm{Port}_{\mathrm{Dst},Y})$ $\mathrm{offset}_Y = F_{K_1}(\mathrm{IP}_{\mathrm{Src},Y}, \mathrm{IP}_{\mathrm{Dst},Y}, \mathrm{Port}_{\mathrm{Dst},Y})$
Wrapper	$i = G_{K_2}(\mathrm{IP}_{\mathrm{Src},X}, \mathrm{IP}_{\mathrm{Dst},X}, \mathrm{Port}_{\mathrm{Dst},X})$ $\mathrm{offset}_X = F_{K_1}(\mathrm{IP}_{\mathrm{Src},X}, \mathrm{IP}_{\mathrm{Dst},X}, \mathrm{Port}_{\mathrm{Dst},X})$

Sandwiching Technique

General principle

Step	Calculation
Wrapper	$i = G_{K_2}(\mathrm{IP}_{\mathrm{Src},X}, \mathrm{IP}_{\mathrm{Dst},X}, \mathrm{Port}_{\mathrm{Dst},X})$ $\mathrm{offset}_X = F_{K_1}(\mathrm{IP}_{\mathrm{Src},X}, \mathrm{IP}_{\mathrm{Dst},X}, \mathrm{Port}_{\mathrm{Dst},X})$ $\mathrm{Port}_{\mathrm{Src},1} = \mathrm{min\_ephemeral} + (\mathrm{offset}_X + \mathrm{table}[i]) \bmod \mathrm{num\_ephemeral}$
Filling	$j = G_{K_2}(\mathrm{IP}_{\mathrm{Src},Y}, \mathrm{IP}_{\mathrm{Dst},Y}, \mathrm{Port}_{\mathrm{Dst},Y})$ $\mathrm{offset}_Y = F_{K_1}(\mathrm{IP}_{\mathrm{Src},Y}, \mathrm{IP}_{\mathrm{Dst},Y}, \mathrm{Port}_{\mathrm{Dst},Y})$ $\mathrm{Port}_{\mathrm{Src},2} = \mathrm{min\_ephemeral} + (\mathrm{offset}_Y + \mathrm{table}[j]) \bmod \mathrm{num\_ephemeral}$
Wrapper	$i = G_{K_2}(\mathrm{IP}_{\mathrm{Src},X}, \mathrm{IP}_{\mathrm{Dst},X}, \mathrm{Port}_{\mathrm{Dst},X})$ $\mathrm{offset}_X = F_{K_1}(\mathrm{IP}_{\mathrm{Src},X}, \mathrm{IP}_{\mathrm{Dst},X}, \mathrm{Port}_{\mathrm{Dst},X})$ $\mathrm{Port}_{\mathrm{Src},3} = \mathrm{min\_ephemeral} + (\mathrm{offset}_X + \mathrm{table}[i]) \bmod \mathrm{num\_ephemeral}$

Sandwiching Technique

General principle

Step	Calculation
Wrapper	$i = G_{K_2}(\text{IP}_{\text{Src},X}, \text{IP}_{\text{Dst},X}, \text{Port}_{\text{Dst},X})$ $\text{offset}_X = F_{K_1}(\text{IP}_{\text{Src},X}, \text{IP}_{\text{Dst},X}, \text{Port}_{\text{Dst},X})$ $\text{Port}_{\text{Src},1} = \text{min\_ephemeral} + (\text{offset}_X + \text{table}[i]) \bmod \text{num\_ephemeral}$ $\text{table}[i] = \text{table}[i] + 1$
Filling	$j = G_{K_2}(\text{IP}_{\text{Src},Y}, \text{IP}_{\text{Dst},Y}, \text{Port}_{\text{Dst},Y})$ $\text{offset}_Y = F_{K_1}(\text{IP}_{\text{Src},Y}, \text{IP}_{\text{Dst},Y}, \text{Port}_{\text{Dst},Y})$ $\text{Port}_{\text{Src},2} = \text{min\_ephemeral} + (\text{offset}_Y + \text{table}[j]) \bmod \text{num\_ephemeral}$ $\text{table}[j] = \text{table}[j] + 1$
Wrapper	$i = G_{K_2}(\text{IP}_{\text{Src},X}, \text{IP}_{\text{Dst},X}, \text{Port}_{\text{Dst},X})$ $\text{offset}_X = F_{K_1}(\text{IP}_{\text{Src},X}, \text{IP}_{\text{Dst},X}, \text{Port}_{\text{Dst},X})$ $\text{Port}_{\text{Src},3} = \text{min\_ephemeral} + (\text{offset}_X + \text{table}[i]) \bmod \text{num\_ephemeral}$ $\text{table}[i] = \text{table}[i] + 1$

Sandwiching Technique

General principle

$$table[j] = \begin{cases} rand(j) + 0, & \text{if } i \neq j, \text{ meaning perturbation table cell } i \text{ was not used,} \\ rand(j) + 1, & \text{if } i = j, \text{ meaning perturbation table cell } i \text{ was used} \end{cases}$$

$$table[i] = \begin{cases} rand(i) + 1, & \text{if } i \neq j, \text{ meaning perturbation table cell } i \text{ was not used,} \\ rand(i) + 2, & \text{if } i = j, \text{ meaning perturbation table cell } i \text{ was used} \end{cases}$$

Step	Calculation
Filling	$j = G_{K_2}(\text{IP}_{\text{Src},Y}, \text{IP}_{\text{Dst},Y}, \text{Port}_{\text{Dst},Y})$ $\text{offset}_Y = F_{K_1}(\text{IP}_{\text{Src},Y}, \text{IP}_{\text{Dst},Y}, \text{Port}_{\text{Dst},Y})$ $\text{Port}_{\text{Src},2} = \text{min\_ephemeral} + (\text{offset}_Y + \boxed{\text{table}[j]}) \bmod \text{num\_ephemeral}$ $\text{table}[j] = \text{table}[j] + 1$
Wrapper	$i = G_{K_2}(\text{IP}_{\text{Src},X}, \text{IP}_{\text{Dst},X}, \text{Port}_{\text{Dst},X})$ $\text{offset}_X = F_{K_1}(\text{IP}_{\text{Src},X}, \text{IP}_{\text{Dst},X}, \text{Port}_{\text{Dst},X})$ $\text{Port}_{\text{Src},3} = \text{min\_ephemeral} + (\text{offset}_X + \boxed{\text{table}[i]}) \bmod \text{num\_ephemeral}$ $\text{table}[i] = \text{table}[i] + 1$

Sandwiching Technique

General principle

Step	Calculation
Wrapper	$i = G_{K_2}(\text{IP}_{\text{Src},X}, \text{IP}_{\text{Dst},X}, \text{Port}_{\text{Dst},X})$ $\text{offset}_X = F_{K_1}(\text{IP}_{\text{Src},X}, \text{IP}_{\text{Dst},X}, \text{Port}_{\text{Dst},X})$ $\boxed{\text{Port}_{\text{Src},1}} = \text{min\_ephemeral} + (\text{offset}_X + \text{table}[i]) \bmod \text{num\_ephemeral}$ $\text{table}[i] = \text{table}[i] + 1$

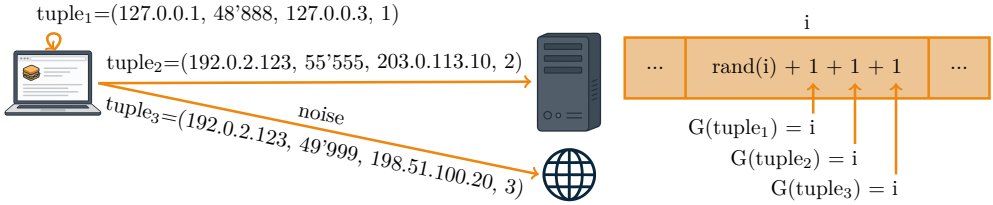
Collision between 3-tuples X and Y
$\Leftrightarrow$ G_{K_2} maps 3-tuples X and Y to same perturbation table cell
$\Leftrightarrow$ $\text{Port}_{\text{Src},3}$ is greater than $\text{Port}_{\text{Src},1} + 1$

Wrapper	$i = G_{K_2}(\text{IP}_{\text{Src},X}, \text{IP}_{\text{Dst},X}, \text{Port}_{\text{Dst},X})$ $\text{offset}_X = F_{K_1}(\text{IP}_{\text{Src},X}, \text{IP}_{\text{Dst},X}, \text{Port}_{\text{Dst},X})$ $\boxed{\text{Port}_{\text{Src},3}} = \text{min\_ephemeral} + (\text{offset}_X + \text{table}[i]) \bmod \text{num\_ephemeral}$ $\text{table}[i] = \text{table}[i] + 1$

Sandwiching Technique

To consider in practise

- Background noise

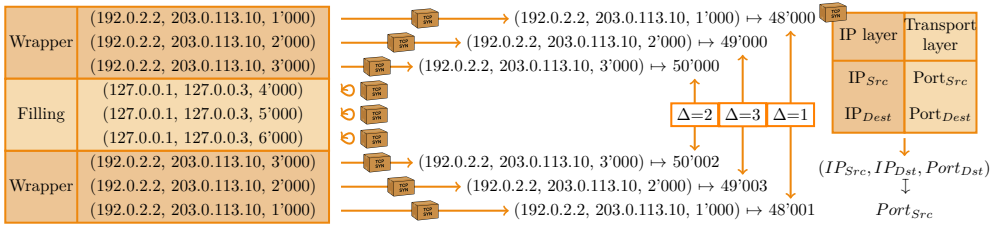


- Multiple 3-tuples used in steps
- Limitations of client device

Sandwiching Technique

To consider in practise

- Background noise
- Multiple 3-tuples used in steps

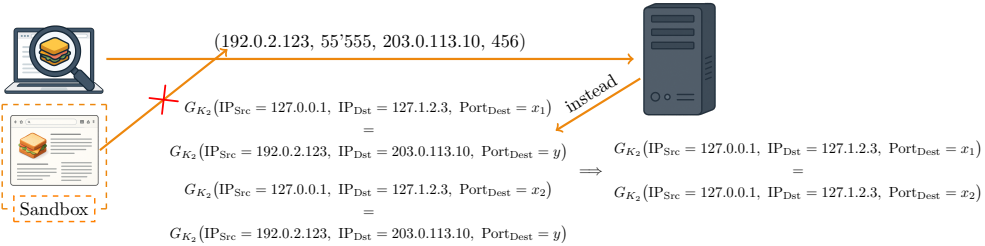


- Limitations of client device

Sandwiching Technique

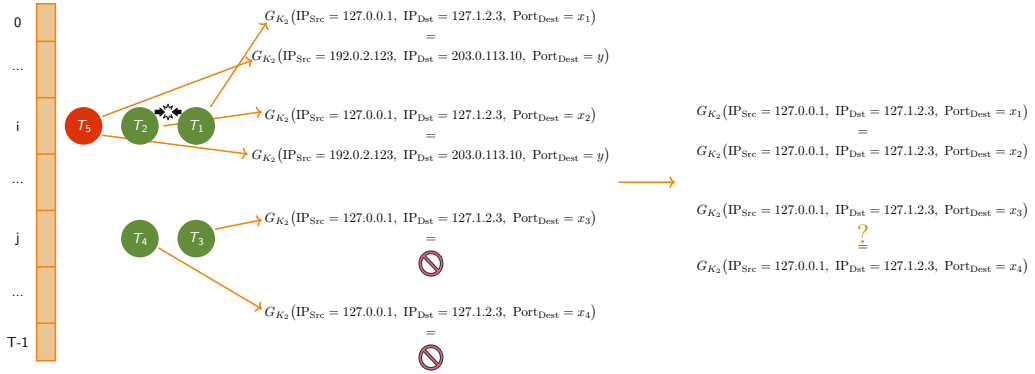
To consider in practise

- Background noise
- Multiple 3-tuples used in steps
- Limitations of client device



Phase 1

Reason for Phase 1



- Every cell should be testable for collisions

$\Rightarrow$ Set of unique attacker 3-tuples that collectively cover all cells

Phase 1

Pseudocode

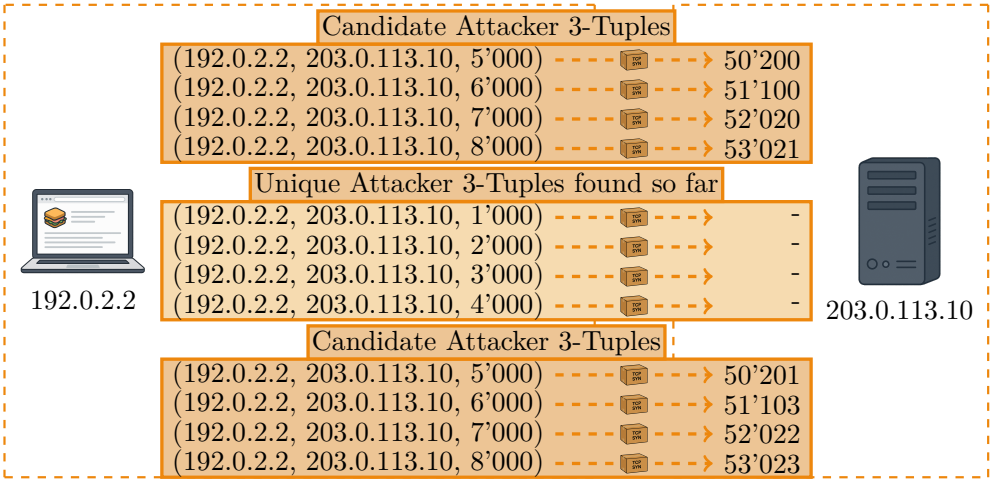
Algorithm 5 Finding Attacker 3-Tuple per Cell (Phase 1)

```
1  procedure SendBurst(X)
2      for all x ∈ X do
3          AttemptConnectTCP(x)
4  procedure GetSourcePorts(U)
5      SendBurst(U)
6      R ← ReceiveAttackerTupleToPortMap()
7      return R
8  procedure Phase1
9      S' ← ∅
10     while |S'|< T do
11         S ← GetNewExternalDestinations()
12         P ← GetSourcePorts(S) // 1st burst
13         SendBurst(S') // 2nd burst
14         P' ← GetSourcePorts(S) // 3rd burst
15         S' ← S' ∪ {x | P'(x) − P(x) = 1}
16     return S'
```

- S: New candidate attacker 3-tuples
- S': Unique attacker 3-tuples found so far
- P, P': Functions of $(IP_{Src}, IP_{Dest}, Port_{Dest}) \mapsto Port_{Src}$ for new candiate attacker 3-tuples
- x: Candidate attacker 3-tuple

Phase 1

Overview



Phase 1

Pseudocode

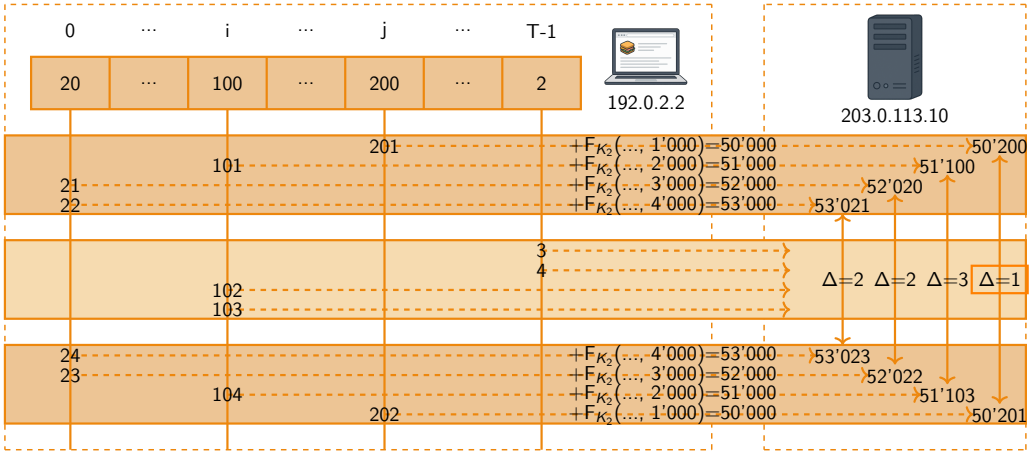
Algorithm 6 Finding Attacker 3-Tuple per Cell (Phase 1)

```
1  procedure SendBurst(X)
2      for all x ∈ X do
3          AttemptConnectTCP(x)
4  procedure GetSourcePorts(U)
5      SendBurst(U)
6      R ← ReceiveAttackerTupleToPortMap()
7      return R
8  procedure Phase1
9      S' ← ∅
10     while |S'|< T do
11         S ← GetNewExternalDestinations()
12         P ← GetSourcePorts(S) // 1st burst
13         SendBurst(S') // 2nd burst
14         P' ← GetSourcePorts(S) // 3rd burst
15         S' ← S' ∪ {x | P'(x) − P(x) = 1}
16     return S'
```

- S: New candidate attacker 3-tuples
- S': Unique attacker 3-tuples found so far
- P, P': Functions of $(IP_{Src}, IP_{Dest}, Port_{Dest}) \mapsto Port_{Src}$ for new candiate attacker 3-tuples
- x: Candidate attacker 3-tuple

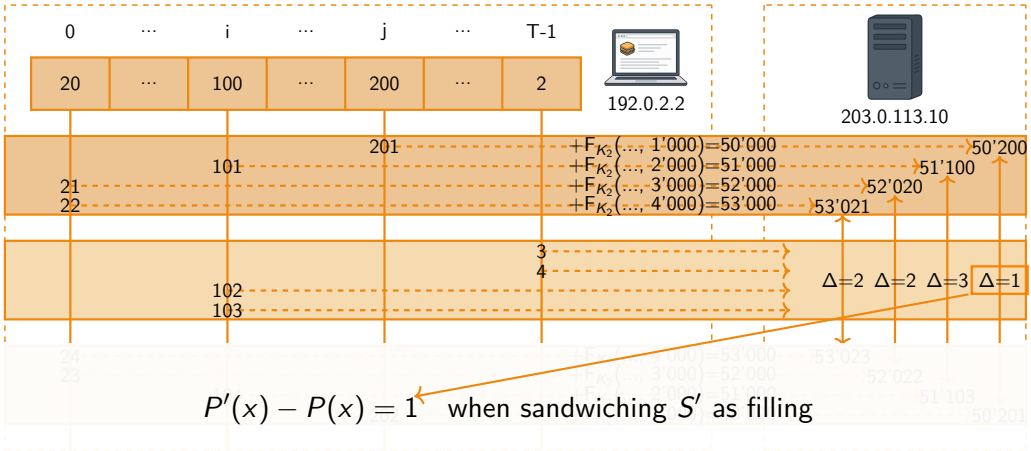
Phase 1

Condition for unique attacker 3-tuple



Phase 1

Condition for unique attacker 3-tuple



Phase 1

Pseudocode

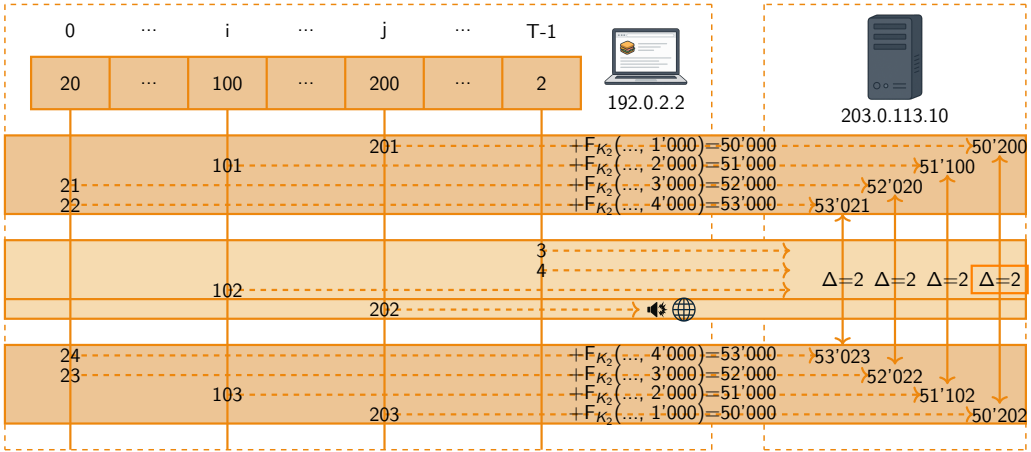
Algorithm 7 FINDING ATTACKER 3-TUPLE PER CELL (PHASE 1)

```
1  procedure SendBurst(X)
2      for all x ∈ X do
3          AttemptConnectTCP(x)
4  procedure GetSourcePorts(U)
5      SendBurst(U)
6      R ← ReceiveAttackerTupleToPortMap()
7      return R
8  procedure Phase1
9      S' ← ∅
10     while |S'|< T do
11         S ← GetNewExternalDestinations()
12         P ← GetSourcePorts(S) // 1st burst
13         SendBurst(S') // 2nd burst
14         P' ← GetSourcePorts(S) // 3rd burst
15         S' ← S' ∪ {x | P'(x) − P(x) = 1}
16     return S'
```

- S: New candidate attacker 3-tuples
- S': Unique attacker 3-tuples found so far
- P, P': Functions of $(IP_{Src}, IP_{Dest}, Port_{Dest}) \mapsto Port_{Src}$ for new candiate attacker 3-tuples
- x: Candidate attacker 3-tuple

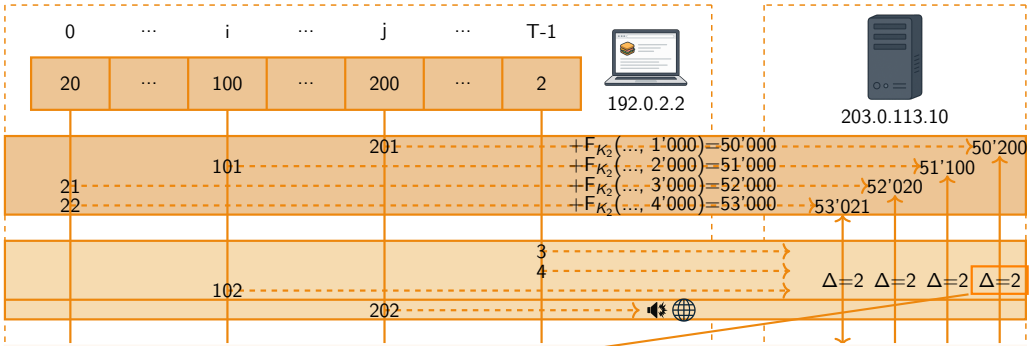
Phase 1

Influence of noise



Phase 1

Influence of noise



- Noise can hide a unique attacker 3-tuple, but it can't fabricate one

Phase 2

Pseudocode

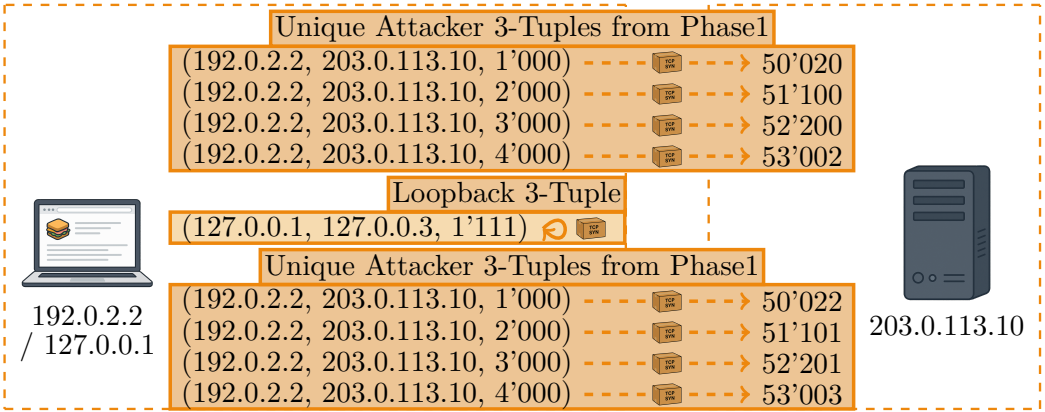
Algorithm 8 Finding a Device ID (Phase 2)

```
1  procedure Phase2
2      C ← ∅; n ← 0; i ← 0
3      repeat
4          i ← i + 1
5          P ← GetSourcePorts(S') // 1st burst
6          AttemptConnectTCP({L_i}) // 2nd burst
7          P' ← GetSourcePorts(S') // 3rd burst
8          w ← ιw(P'(w) − P(w) > ε)
9          if Defined(B_w) then // A collision was found
10             C ← C ∪ {(L_i, B[w])}
11             n ← n + 1
12         else
13             B[w] ← L_i
14     until n ≥ n*[i] // This is equiv. to P_D^i(n) ≤ p*
15     return (C,i)
```

- i: Number of iterations
- n: Number of independent pairs / collisions of loopback 3-tuples
- L_i: Single loopback 3-tuple
- S': Unique attacker 3-tuples from Phase 1
- w: The one unique attacker 3-tuple

Phase 2

Overview



Phase 2

Pseudocode

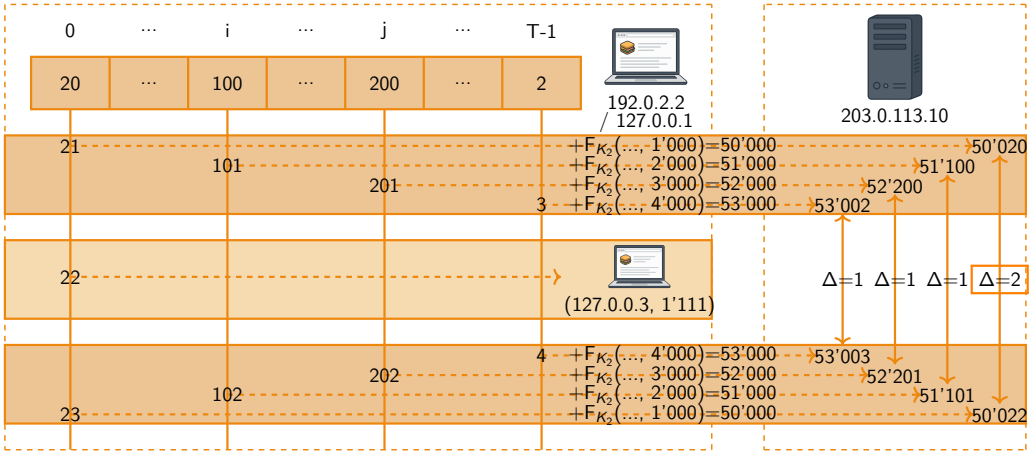
Algorithm 9 Finding a Device ID (Phase 2)

```
1  procedure Phase2
2      C ← ∅; n ← 0; i ← 0
3      repeat
4          i ← i + 1
5          P ← GetSourcePorts(S') // 1st burst
6          AttemptConnectTCP({L_i}) // 2nd burst
7          P' ← GetSourcePorts(S') // 3rd burst
8          w ← ιw(P'(w) − P(w) > ε)
9          if Defined(B_w) then // A collision was found
10             C ← C ∪ {(L_i, B[w])}
11             n ← n + 1
12         else
13             B[w] ← L_i
14     until n ≥ n*[i] // This is equiv. to P_D^i(n) ≤ p*
15     return (C,i)
```

- i: Number of iterations
- n: Number of independent pairs / collisions of loopback 3-tuples
- L_i: Single loopback 3-tuple
- S': Unique attacker 3-tuples from Phase 1
- w: The one unique attacker 3-tuple
- ιw: Definite Description Operator, "the unique w" attacker 3-tuple

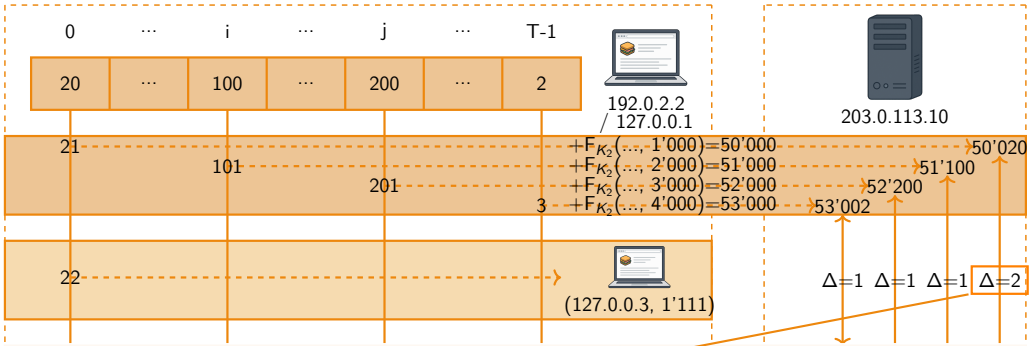
Phase 2

Condition for collision between attacker 3-tuple and loopback 3-tuple



Phase 2

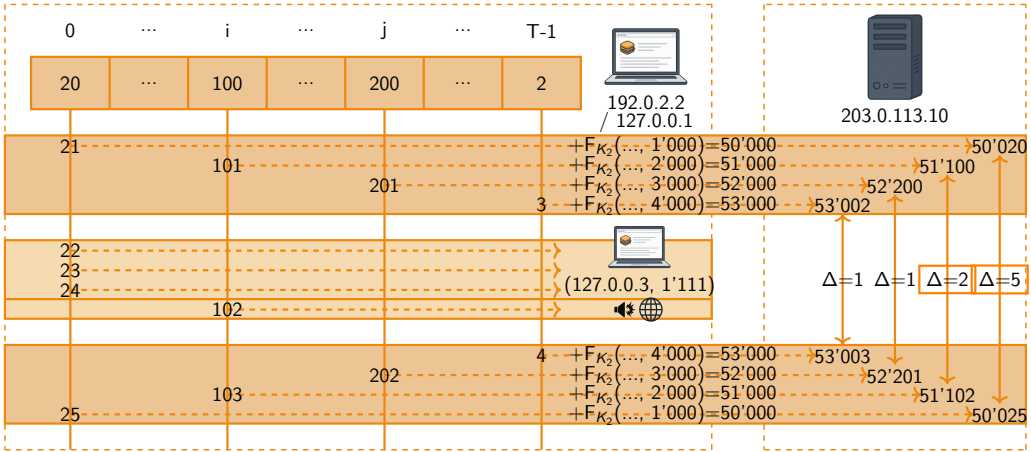
Condition for collision between attacker 3-tuple and loopback 3-tuple



$P'(w) - P(w) > 1$ when sandwiching L_i as filling

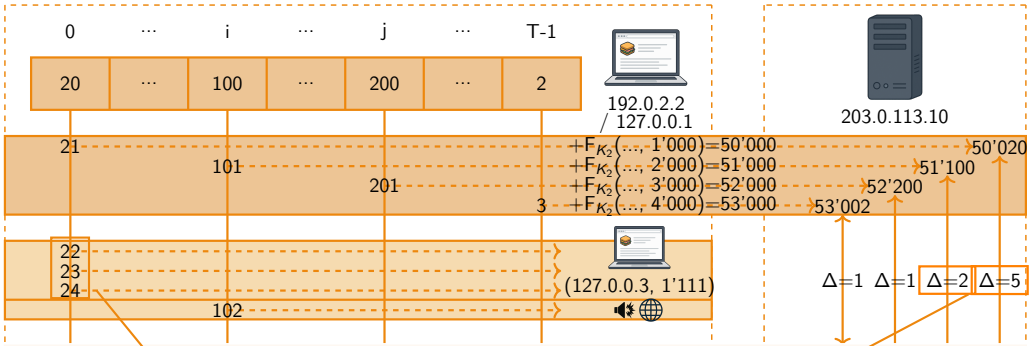
Phase 2

Influence of noise



Phase 2

Influence of noise

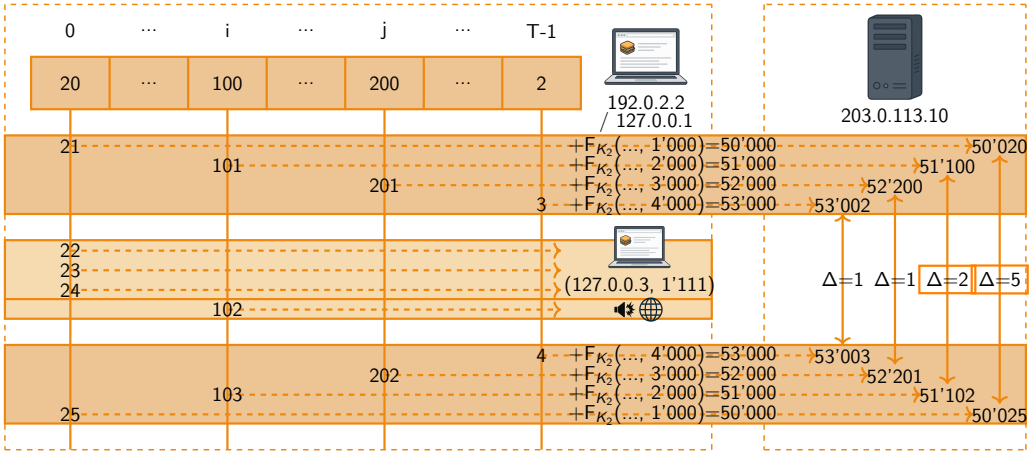


- Repeated connection attempts with same loopback 3-tuple

⇒ Any increments caused by noise are outweighed

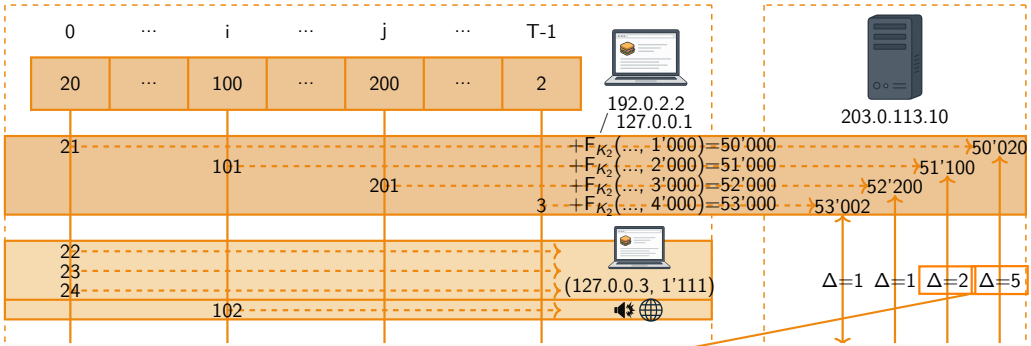
Phase 2

Condition for collision between attacker 3-tuple and loopback 3-tuple



Phase 2

Condition for collision between attacker 3-tuple and loopback 3-tuple



$P'(w) - P(w) > \varepsilon$ when sandwiching L_i as filling

Phase 2

Pseudocode

Algorithm 10 FINDING A DEVICE ID (PHASE 2)

```
1  procedure PHASE2
2      C ← ∅; n ← 0; i ← 0
3      repeat
4          i ← i + 1
5          P ← GETSOURCEPORTS(S') // 1st burst
6          ATTEMPTCONNECTTCP({L_i}) // 2nd burst
7          P' ← GETSOURCEPORTS(S') // 3rd burst
8          w ← ιw(P'(w) − P(w) > ε)
9          if DEFINED(B_w) then // A collision was found
10             C ← C ∪ {(L_i, B[w])}
11             n ← n + 1
12         else
13             B[w] ← L_i
14     until n ≥ n*[i] // This is equiv. to P'_D(n) ≤ p*
15     return (C,i)
```

- i: Number of iterations
- n: Number of independent pairs / collisions of loopback 3-tuples
- L_i: Single loopback 3-tuple
- S': Unique attacker 3-tuples from Phase 1
- w: The one unique attacker 3-tuple
- ιw: Definite Description Operator, "the unique w" attacker 3-tuple

---

- $B[w]$: Dictionary, keys = unique attacker 3-tuples, values = first loopback 3-tuple
- $\{T_3, T_2, T_5\} \Rightarrow \{(T_3, T_2), (T_3, T_5)\}$

Phase 2

Pseudocode

Algorithm 11 FINDING A DEVICE ID (PHASE 2)

```
1  procedure PHASE2
2      C ← ∅; n ← 0; i ← 0
3      repeat
4          i ← i + 1
5          P ← GETSOURCEPORTS(S') // 1st burst
6          ATTEMPTCONNECTTCP({L_i}) // 2nd burst
7          P' ← GETSOURCEPORTS(S') // 3rd burst
8          w ← ιw(P'(w) − P(w) > ε)
9          if DEFINED(B_w) then // A collision was found
10             C ← C ∪ {(L_i, B[w])}
11             n ← n + 1
12         else
13             B[w] ← L_i
14     until n ≥ n*[i] // This is equiv. to P'_D(n) ≤ p*
15     return (C,i)
```

- i: Number of iterations
- n: Number of independent pairs / collisions of loopback 3-tuples
- L_i: Single loopback 3-tuple
- S': Unique attacker 3-tuples from Phase 1
- w: The one unique attacker 3-tuple
- ιw: Definite Description Operator, "the unique w" attacker 3-tuple

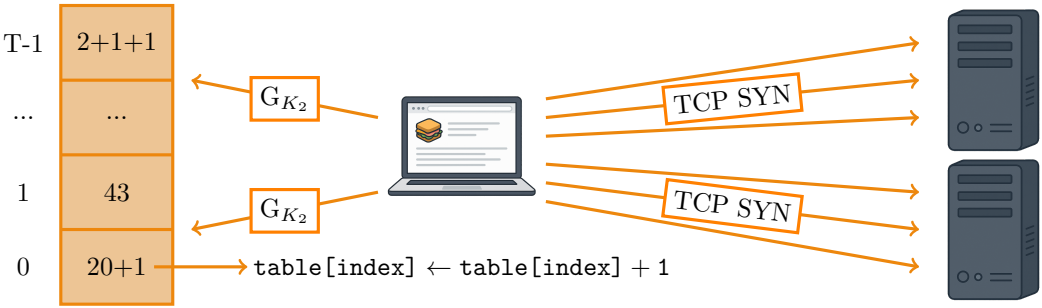
---

- $B[w]$: Dictionary, keys = unique attacker 3-tuples, values = first loopback 3-tuple
- $\{T_3, T_2, T_5\} \Rightarrow \{(T_3, T_2), (T_3, T_5)\}$

Countermeasures

Countermeasures Overview

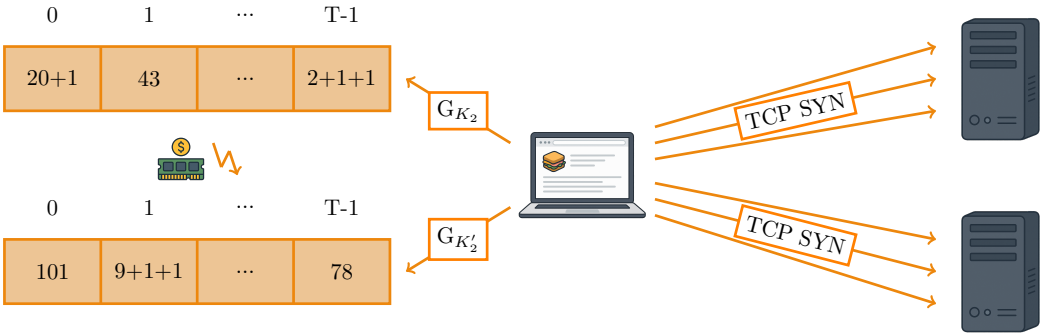
Root cause



- shared perturbation table ⇒ device-specific hash collisions
- predictable increment

Countermeasures Overview

Ideal solution



- separate perturbation table for each network context

$\Rightarrow$ high memory cost

Countermeasures Overview

General countermeasures

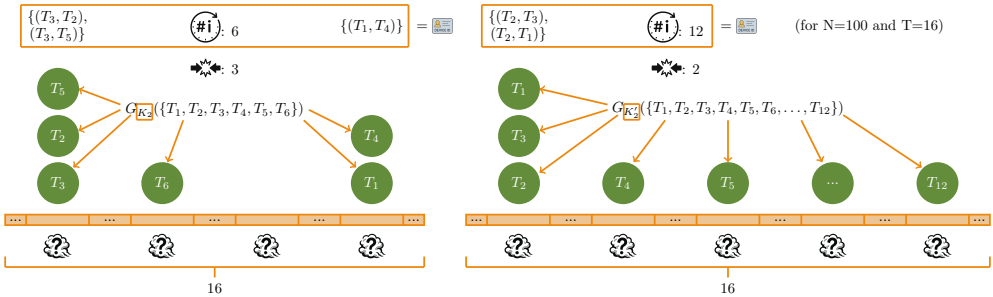
- make detecting hash collisions  and 
  - make it more time intensive:

  - limit time:

Countermeasures Overview

Implemented changes

- Periodic re-keying: Every 10 seconds

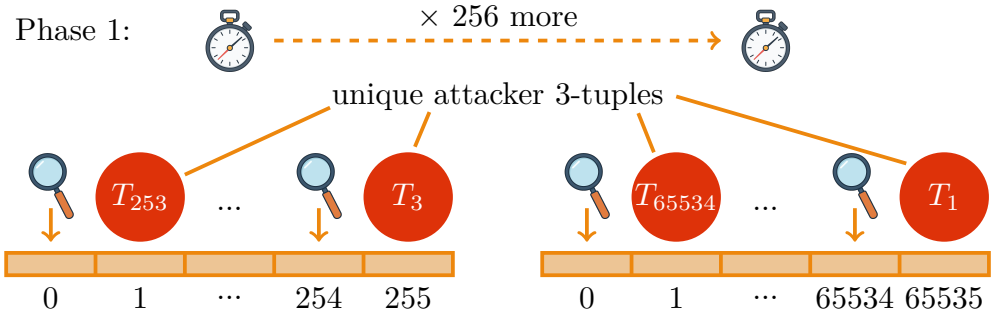


- Increase table size T: From 256 to 64 KiB
- Introduce more noise: Each increment randomly between 1 and 8

Countermeasures Overview

Implemented changes

- Periodic re-keying: Every 10 seconds
- Increase table size T: From 256 to 64 KiB



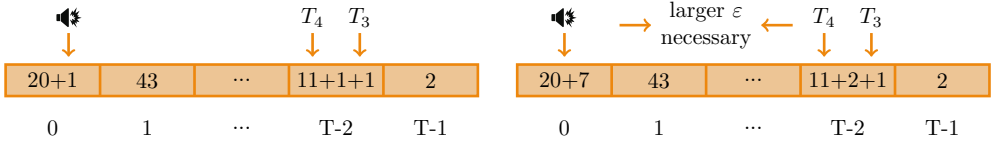
- Introduce more noise: Each increment randomly between 1 and 8

Countermeasures Overview

Implemented changes

- Periodic re-keying: Every 10 seconds
- Increase table size T: From 256 to 64 KiB
- Introduce more noise: Each increment randomly between 1 and 8

`table[index]` ← `table[index]` + 1 ⟶ `table[index]` ← `table[index]` + `rand(1, 8)`



Countermeasures

Thanks for your attention!

Questions?

Appendix

Appendix

Phase 2 termination condition script

- https://github.com/matthejue/Seminar-Device-Tracking/blob/main/phase2_termination_condition.py

Appendix

Demonstration of the attack

- https://youtu.be/pZbfV5nCQsA?feature=shared

Phase 2

Termination condition

Probabiliy that all non-first loopback 3-tuples go into the same buckets as in D

Combined probability of all first loopback 3-tuples in their buckets to match D's structure

Occupied (non-empty) buckets

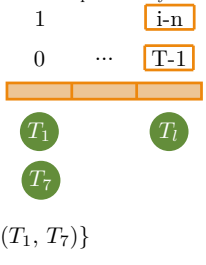
Correction because indices start at 0

Maximum acceptable probability that any pair of devices yields same device ID

$$P_D^i(n) = \frac{1}{T^n} \cdot \prod_{j=0}^{i-n-1} \left(1 - \frac{j}{T}\right) \quad < \quad p^* = \frac{c}{\binom{N}{2}}$$

probability that a random device yields same device ID as device D

threshold acceptance probability



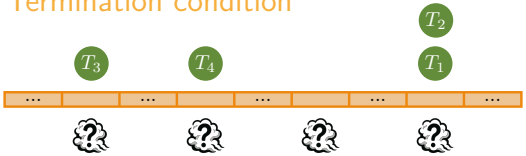
$$\frac{T-j}{T} = \frac{T}{T} - \frac{j}{T} = 1 - \frac{j}{T}$$

$\Rightarrow$ thus $n < i$

- T: Number of perturbation table cells
- N: Device population size
- c: Maximum average number of device ID collisions in a population
- i: Number of iterations
- n: Number of independent pairs / collisions

Phase 2

Termination condition



- Can only see which balls fall into same bucket
- Probability only depends on total number of independent collisions

- Correlations:

♦↑i $\Rightarrow$ $P_D^i(n)\downarrow$ $\Rightarrow$ $P_D^i(n) < p^*$ potentially closer to being satisfied

$$P_D^i(n) = \frac{1}{T^n} \cdot \prod_{j=0}^{\boxed{i}-n-1} \left(1 - \frac{j}{T}\right) \longrightarrow \text{multiply number} < 1 \text{ more often} \longrightarrow P_D^i(n)\downarrow$$

♦↑n $\Rightarrow$ $P_D^i(n)\downarrow$ $\Rightarrow$ $P_D^i(n) < p^*$ potentially closer to being satisfied

$$P_D^i(n) = \frac{1}{T^{\boxed{n}}} \cdot \prod_{j=0}^{i-\boxed{n}-1} \left(1 - \frac{j}{T}\right) \longrightarrow \begin{array}{l} \text{multiply number} < 1 \text{ less often} \longrightarrow P_D^i(n)\uparrow \\ \text{divide by large number} \longrightarrow P_D^i(n)\downarrow\downarrow \end{array} \longrightarrow P_D^i(n)\downarrow$$

Phase 2

Termination condition

n / i	1	2	3	4	5	6	7	8	9	10	11	12	13	14
5	1	2	3	4	5	6	7	8	9	10	11	12	13	14
4	1	2	3	4	5	6	7	8	9	10	11	12	13	14
3	1	2	3	4	5	6	7	8	9	10	11	12	13	14
2	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	1	2	3	4	5	6	7	8	9	10	11	12	13	14
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14

termination

20	···	2

N=100 0 ··· 15+1=16=T

- Precompute table $n^*[i] = \min\{n \mid P_D^i(n) < p^*\}$
- $n \geq n^*[i]$ replaces $P_D^i(n) < p^*$

$\Rightarrow$ Avoid repeated computation

i-range	n*[i]
4–5	4
6–11	3
12–12	2
13–13	1
14	0

Literature

Literature I

[1] Moshe Kol, Amit Klein, and Yossi Gilad. *Device Tracking via Linux's New TCP Source Port Selection Algorithm (Extended Version)*. 2022. arXiv: 2209.12993 [cs.CR]. URL: https://arxiv.org/abs/2209.12993.

[2] Michael Larsen and Fernando Gont. *Recommendations for Transport-Protocol Port Randomization*. Request for Comments RFC 6056. Internet Engineering Task Force, Jan. 2011. 29 pp. DOI: 10.17487/RFC6056. URL: https://datatracker.ietf.org/doc/rfc6056 (visited on 07/03/2025).

[3] *Meltdown (Security Vulnerability)*. In: *Wikipedia*. Dec. 26, 2024. URL: https://en.wikipedia.org/w/index.php?title=Meltdown_(security_vulnerability)&oldid=1265360095 (visited on 07/16/2025).

[4] *Spectre (Security Vulnerability)*. In: *Wikipedia*. June 16, 2025. URL: https://en.wikipedia.org/w/index.php?title=Spectre_(security_vulnerability)&oldid=1295923886 (visited on 07/16/2025).

Literature II

- All other images were generated using ChatGPT, which internally utilizes DALL-E 3
- The visualisations were created with TikZ and TikZiT