Covert channels in TCP/IP: attack and defence

The creation and detection of TCP/IP steganography for covert channels and device fingerprinting

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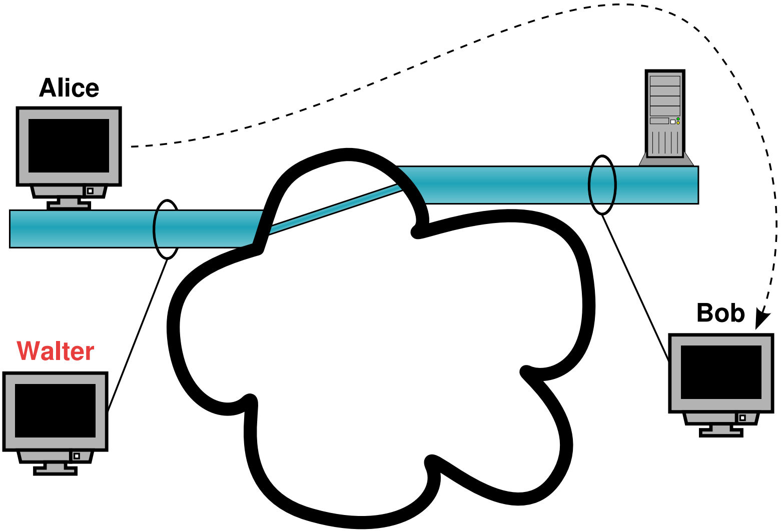
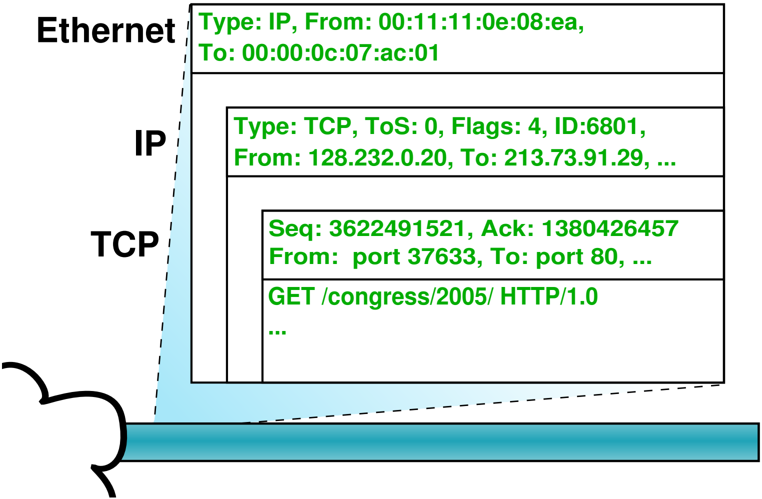
Scenario



Threat model

- Walter is a *passive warden*, trying to detect unauthorised communication from Alice to Bob
  - To break this policy, Alice uses a *covert channel*
- Walter knows which OS Alice is running
- Alice sends message hidden in *cover-text*
- The cover-text must be received intact
- Alice requires *indistinguishability*
- Subject to these constraints, Alice would like to maximise the available *bandwidth*
- Techniques to achieve these goals are known as *steganography*

Protocol stack



Why TCP/IP

- Lower levels (Ethernet) will not reach Bob
- Alice might not be able to control which applications she runs
- So higher level protocols might not be available
- Almost all network applications use TCP/IP
- So Alice can use this without raising suspicion

IP

0 3	4 7	8 15	16 18	19 23	24 31
Version	IHL	*Type of Service*	Total Length		
Identification			*Flags*	*Fragment Offset*	
Time to Live		Protocol	Header Checksum		
Source Address					
Destination Address					
Options					Padding

Fragmentation

- If IP packets are too large to fit into the lower layer, they can be fragmented
- Data could be encoded by changing
  - The size of fragments
  - The order of fragments
- IP gives no guarantees of in-order delivery
  - So IP packets can be re-ordered
- All these are predictable, so while the cover-text will get through, Walter can see the steganography

Seldom used IP options

- ToS: Used for altering quality of service
  - Almost never used, so easily detectable
- Flags: Used to signal fragmentation
  - Predictable based on context, so easily detectable
- IP options (different from TCP options)
  - Seldom used now, so easily detectable

IP ID

- Unique value associated with each IP packet
- Used to re-assemble fragments
- Commonly implemented (e.g. Linux) as a per-destination counter
  - This is to prevent *idle-scanning*
  - Linked to TCP (details later)
- Violating this would result in easy detection
- Respecting this dramatically reduces bandwidth

TCP

<table>
<tr><th>0 3</th><th>4 9</th><th>10 15</th><th>16 23</th><th>24 31</th></tr>
<tr><td colspan="3">Source Port</td><td colspan="2">Destination Port</td></tr>
<tr><td colspan="5">Sequence Number</td></tr>
<tr><td colspan="5">Acknowledgement Number</td></tr>
<tr><td>Offset</td><td>Reserved</td><td>Flags</td><td colspan="2">Window</td></tr>
<tr><td colspan="3">Checksum</td><td colspan="2">Urgent Pointer</td></tr>
<tr><td colspan="4">Options (including timestamp)</td><td>Padding</td></tr>
</table>

TCP timestamp

- Option available in TCP packets which allows hosts to measure round-trip-time
- Available in most modern operating systems, but off by default in Windows
- Stores the time packet was sent, according to a 1 Hz–1 kHz clock
- Predictable, but packets can be delayed to force this value to be odd or even, allowing 1 bit per packet to be sent
- With high-bandwidth connections, where many packets with the same timestamp are normally sent out, this scheme can be detected

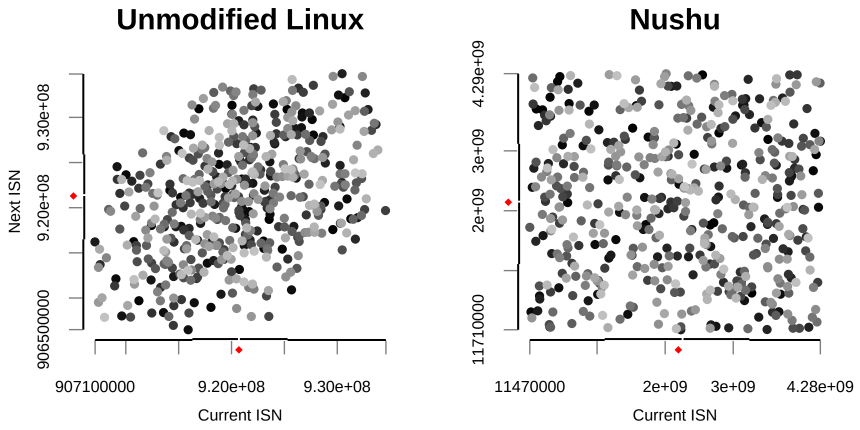
TCP initial sequence number

- When TCP connection is first built, each side picks an *initial sequence number (ISN)*, used for reliability and flow control.
- To prevent IP address spoofing, this number should be hard to guess
- While there have been problems in the past, all modern operating systems now do this
- It is large (32 bits), and because it is unpredictable to outsiders, including Walter, this field is the most useful for steganography.
- However using it properly is far from simple

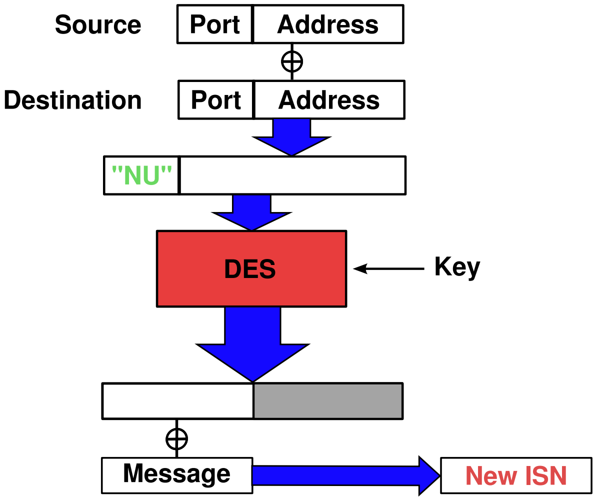
Nushu

- Presented by Joanna Rutkowska at 21C3
- Steganographic covert channel implemented for Linux
- Also includes error recovery
- Uses clever kernel tricks to hide from local detection (outside the scope of this talk)
- Replaces ISN with encrypted message (so should look random)

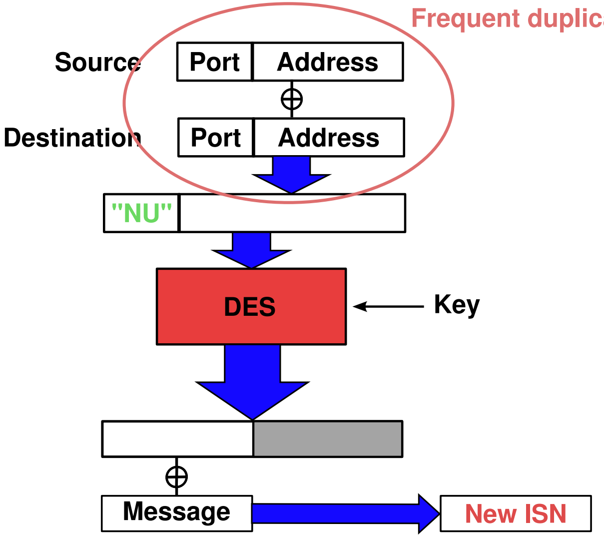
Catching Nushu



Nushu encryption



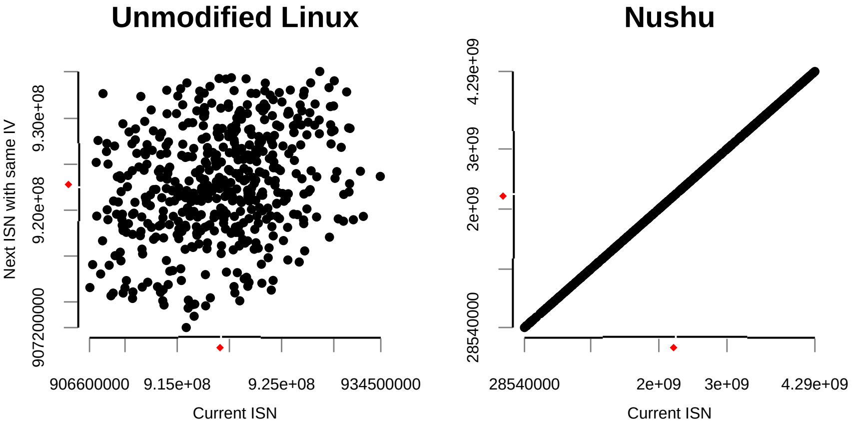
Nushu encryption



Attacking the cryptography

- There will be frequent duplications of this
  - Source IP is fixed; destination IP will not vary much
  - Destination port will not vary much and source port does not use anywhere near all of the 2^{16} possibilities
- Whenever there is a duplication, the output of DES will be the same
- $X = (M_1 \oplus K) \oplus (M_2 \oplus K) = M_1 \oplus M_2$
- If $M_1 = M_2$ then $X = 0$
- Even if $M_1 \neq M_2$, X will still show patterns

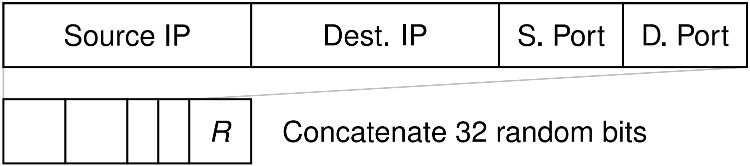
Nushu revealed



Linux ISN generation

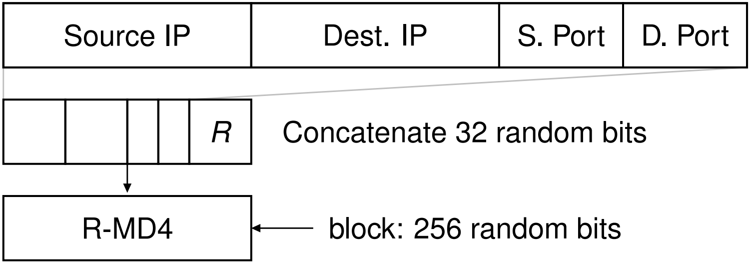
Source IP	Dest. IP	S. Port	D. Port

Linux ISN generation

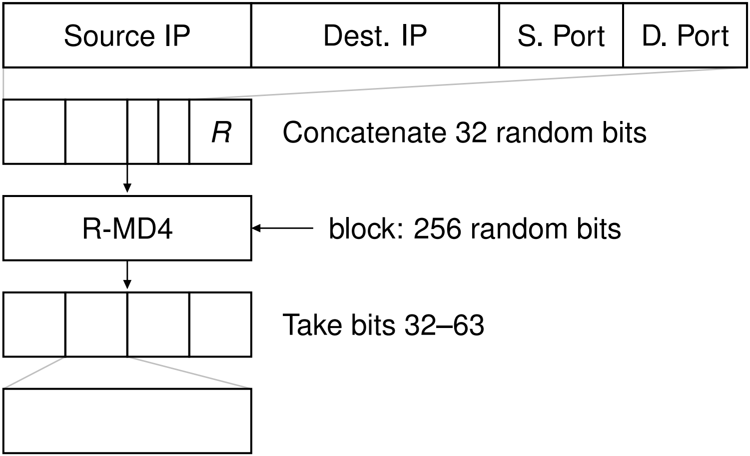


Concatenate 32 random bits

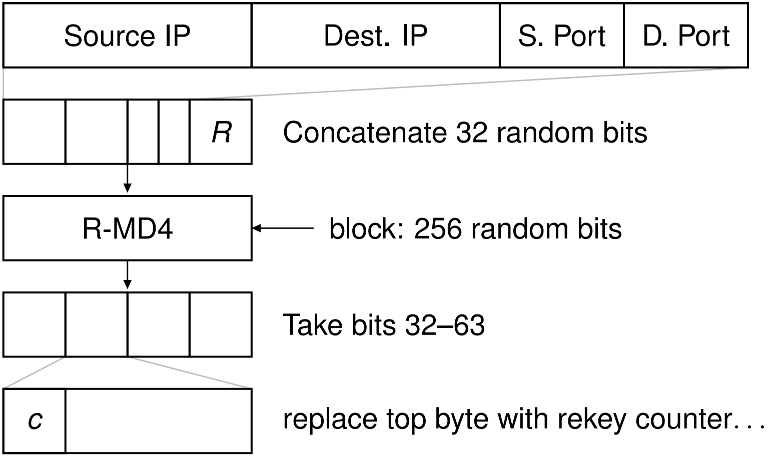
Linux ISN generation



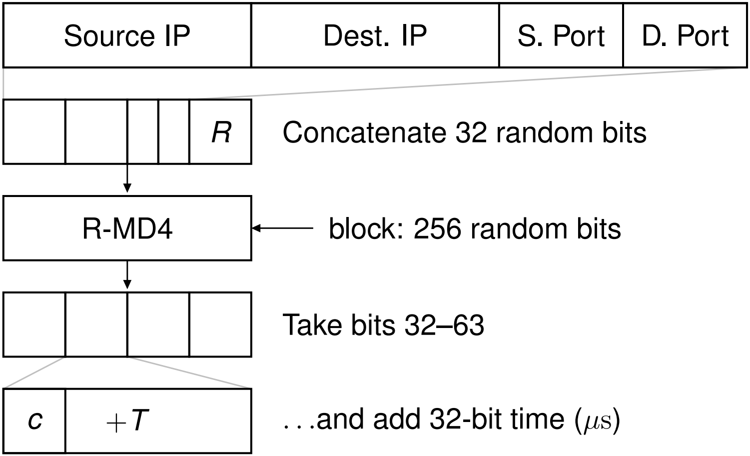
Linux ISN generation



Linux ISN generation



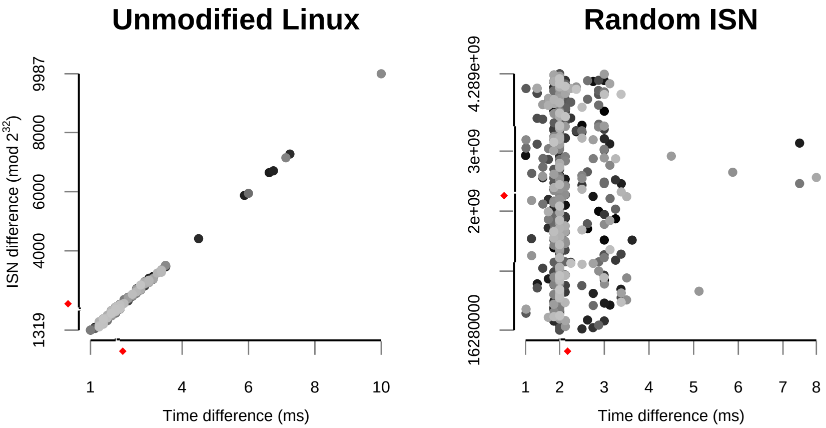
Linux ISN generation



Patterns with the Linux ISN

- Within a rekey period, multiple connections with the same source/destination, IP address/port number will have the same input to MD4
- The difference between the ISNs for two connections will be the time difference in microseconds
- The Nushu problem could be prevented by not repeating IVs
  - Use more randomness (hash as much of the header as possible)
  - In case there is a collision, use a 32-bit block cipher
  - Never send the same plaintext with the same IV
- This would hide any patterns, but Linux introduces patterns of its own

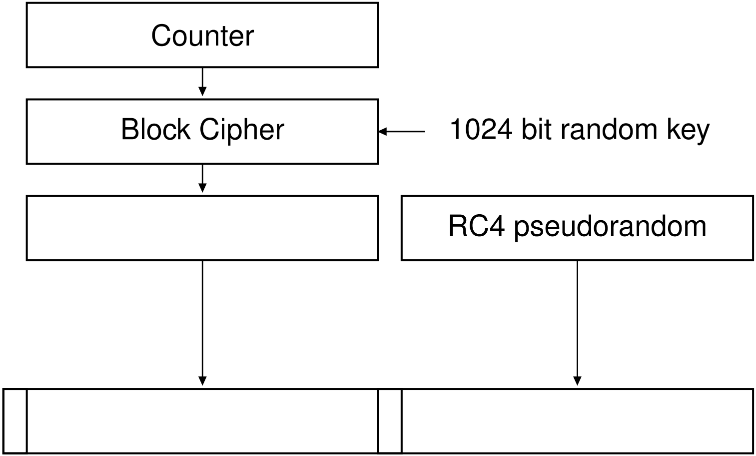
Better cryptography doesn't help



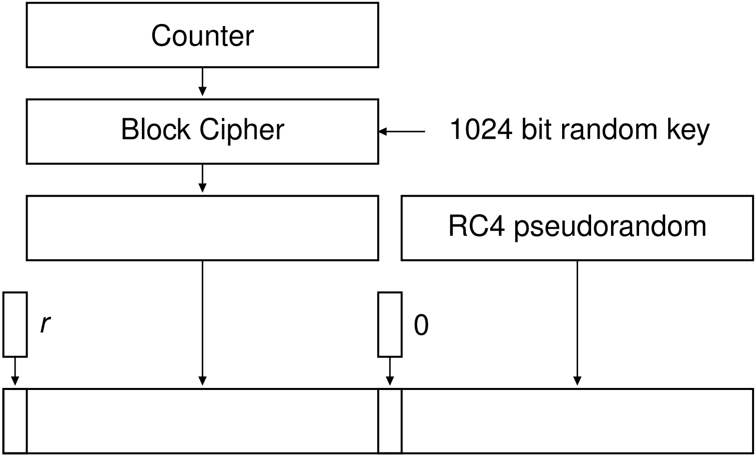
Steganography for Linux

- Replace the lower 3 bytes with our data
- Restore rekey counter
- Add one to rekey counter if carry bit is needed
  - Subtract current time in microseconds (mod 2^{32}) from our data
  - If this is negative, add one to they rekey counter, otherwise leave it alone
- Patch up the checksum and IP ID (depends on ISN)
- Can use the ACK from the remote host to get a good idea of whether the SYN packet was lost
- Freshness is achieved by xoring the plaintext with a hash of Source/Destination IP and Source/Destination Port
- One bit is reserved to cope with potential collisions

OpenBSD

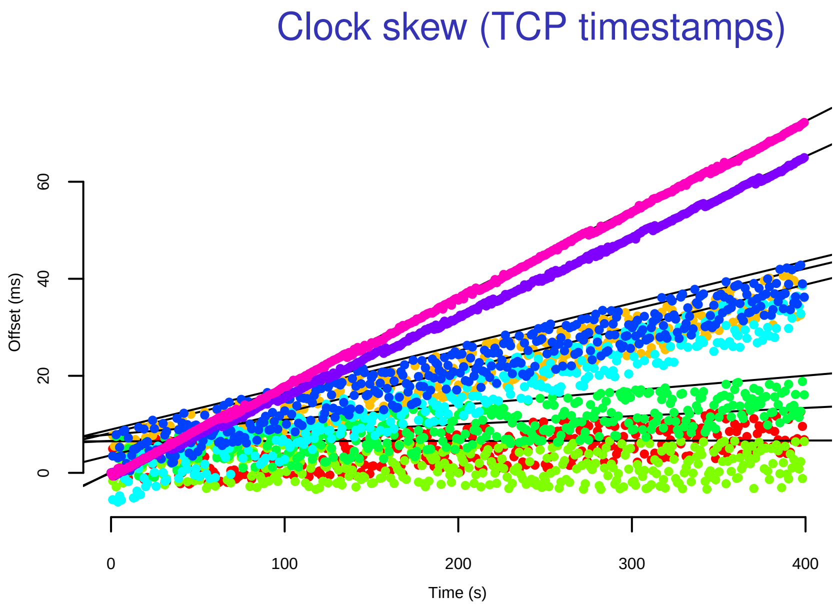


OpenBSD


Counter
Block Cipher
1024 bit random key
RC4 pseudorandom
r
0

Steganography with OpenBSD

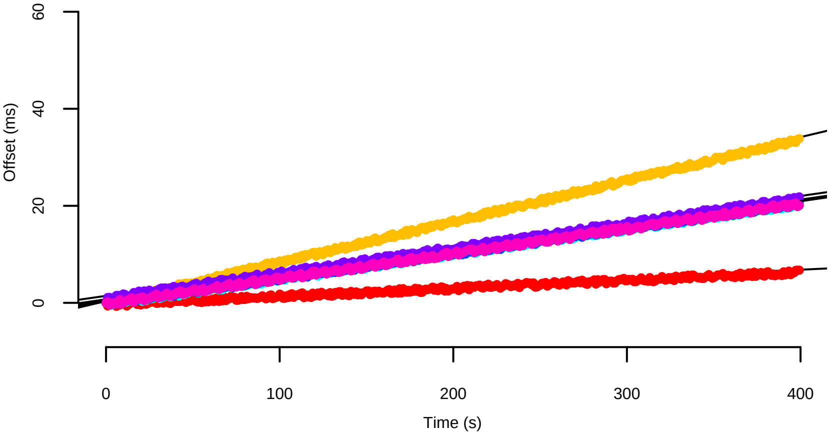
- Can code directly into the bottom 15 bits of the ISN (pre-shared key, with hash of other header fields for freshness)
- Need to code arbitrary data (with redundancy) onto a pseudorandom sequence of integers between 0 and 2^{15}
- For reliability, Bob needs to be able to cope with the loss of some of the elements in the sequence
- Elements of the sequence are encrypted using a block cipher before transmission, and thus appear exactly as a pseudorandom sequence to the warden


Clock skew (TCP timestamps)
Offset (ms)
0
20
40
60
0
100
200
300
400
Time (s)

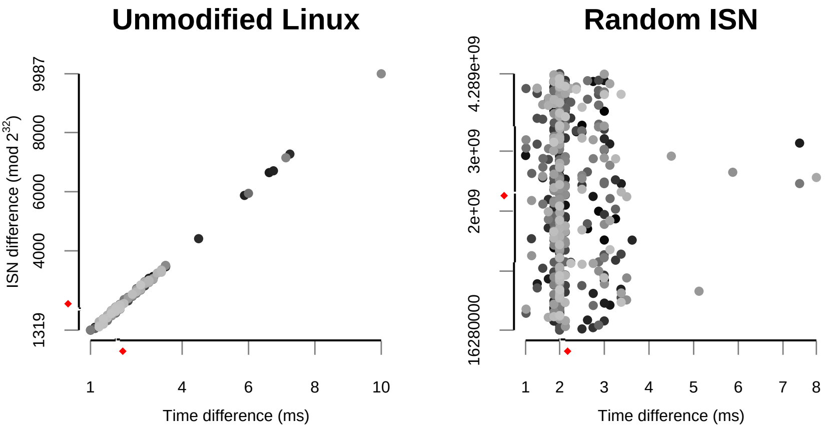
Timing information from ISNs

- All computers have a clock crystal to measure time, but imperfections cause some to run faster or slower than they should
- This error is very stable over time, and so can acts as an identity for a computer
- Even if the computer changes IP address or moves, its clock skew will stay the same and allows the computer to be tracked.
- There are several ways to extract clock skew information remotely
- TCP timestamp clocks run at 100 Hz or 1 kHz on Linux
- ICMP timestamp clocks run at 1 kHz
- On Linux, the TCP ISN clock runs at 1 MHz

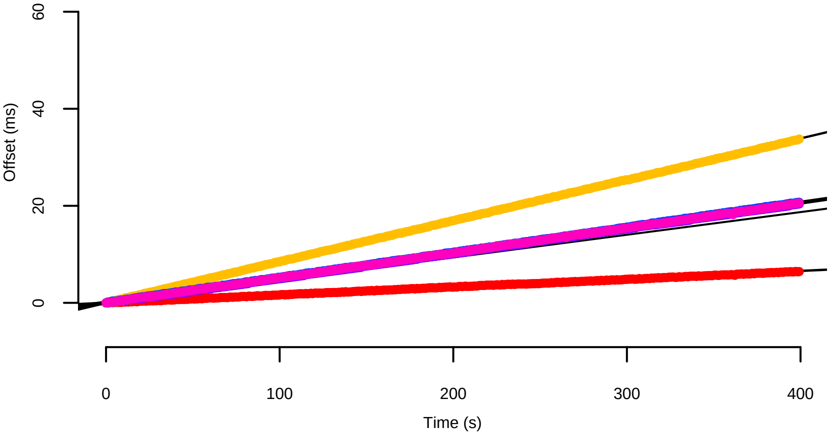
Clock skew (ICMP timestamps)



Timing patterns in the ISN



Clock skew (TCP ISN)



Conclusion

- Many proposed steganography schemes are detectable
- The common flaw is to assume that fields that *can* be random *are* random
- In fact, many fields in protocols are not random – sometimes for good reason, sometimes just through chance
- To build undetectable steganography schemes, you must examine exactly how fields are generated, before you can modify it safely
- If physical device fingerprinting is a concern, there are sources of time information which you might not expect