Reflection Scan: an Off-Path Attack on TCP

Jan Wróbel
wrr@mixedbit.org

Abstract

The paper demonstrates how traffic load of a shared packet queue can be exploited as a side channel through which protected information leaks to an off-path attacker. The attacker sends to a victim a sequence of identical spoofed segments. The victim responds to each segment in the sequence (the sequence is reflected by the victim) if the segments satisfy a certain condition tested by the attacker. The responses do not reach the attacker directly, but induce extra load on a routing queue shared between the victim and the attacker. Increased processing time of packets traversing the queue reveal that the tested condition was true. The paper concentrates on the TCP, but the approach is generic and can be effective against other protocols that allow to construct requests which are conditionally answered by the victim. A proof of concept was created to asses applicability of the method in real-life scenarios.

1 Introduction

The TCP protocol without an additional encryption and authentication layer is inherently vulnerable to man-in-the-middle attacks. An attacker that has a way to intercept network traffic between TCP end points, can easily read and alter the communication. Off-path attacks, in which the attacker can not intercept network traffic, are much harder to execute. Along the years several weaknesses in the protocol or particular implementations that made off-path attacks easier were disclosed. Protocol specification was improved and many vendors fixed implementations to close discovered holes. A TCP connection between hosts that implement the newest recommendations ([3], [4], [5]) is believed to be reasonably well protected against off-path attacks.

A TCP session is protected by three secret numbers: a 16-bit ephemeral port and two 32-bit sequence numbers, one for each side of the connection. Other fields, such as IP addresses of end points and a server port, are easy to determine in many scenarios. Each TCP segment exchanged within an established connection carries all three secret values. For a segment to be accepted, it must contain a correct ephemeral port number, its sequence number must be within receiver's window and a sequence number the segment is acknowledging (acknowledge number) must be acceptable. According to the recent recommendations, an ephemeral port should be randomly picked from a 1025-65535 range and an acknowledge number should be accepted only if it is equal to the next octet to be sent or lower by at most 'largest sender window seen'. If an end point follows these recommendations, the attacker needs

$$\frac{(2^{16}-1025)\times 2^{32}\times 2^{32}}{\text{window size A}\times\text{window size B}}$$

attempts to generate an acceptable segment. Assuming both windows have 65kB, about 2^{48} attempts are needed. If the end point follows strict RST validation rules, which require RST segment to have a sequence number equal to the next expected sequence number, the attacker needs $(2^{16}-1025)\times 2^{32}$ attempts to blindly reset the connection, which is also about 2^{48}. The number is large enough to make blind attacks impractical in most scenarios. The attacker would need to push segments for 500 hours at 100Gb/s rate to have one segment accepted. Even if a segment is accepted, the probability that it lines up with a start of a window is only $\frac{1}{\text{window size}}$. Thus, a successful blind attack can corrupt or reset the session, but it has low chances of inserting a meaningful payload in a correct place.

While the risk of accepting spoofed TCP segments as valid is recognized and well studied, the recommendations and implementations overlook the risk of responding to rejected segments. A TCP layer can either silently drop a rejected segment or respond to it (with an ACK or a RST). The action to perform differs between different implementations of the protocol. It was originally specified in the 'Event Processing' section of RFC 793 [1], but new systems, especially firewalls, do not fully follow the RFC, but implement stricter filtering rules, as for example described in [2]. These new rules are carefully specified to preserve interoperability between different implementations.

If for a particular TCP implementation conditional response to a rejected segment depends on one of secret values set in the segment, and if an attacker can discover that a system responded to a spoofed segment, the TCP session can be compromised. The attacker can determine if a tested secret value satisfied certain condition (an ephemeral port was correct, a sequence number was in window, an acknowledge number was acceptable). The secrets can be revealed in separate steps, each of the steps requires relatively small resources.

Congestion of a queue shared between the off-path attacker and the targeted TCP stream is a side channel through which the attacker can determine if the TCP layer responded to spoofed segments. Detecting negligible load caused by a single response would be hard in practice, but the attacker can send a sequence of segments of any desired length. If each segment from the sequence is answered, the answers can cause a substantial traffic spike or even queue overflow. Figure 1 illustrates the technique.

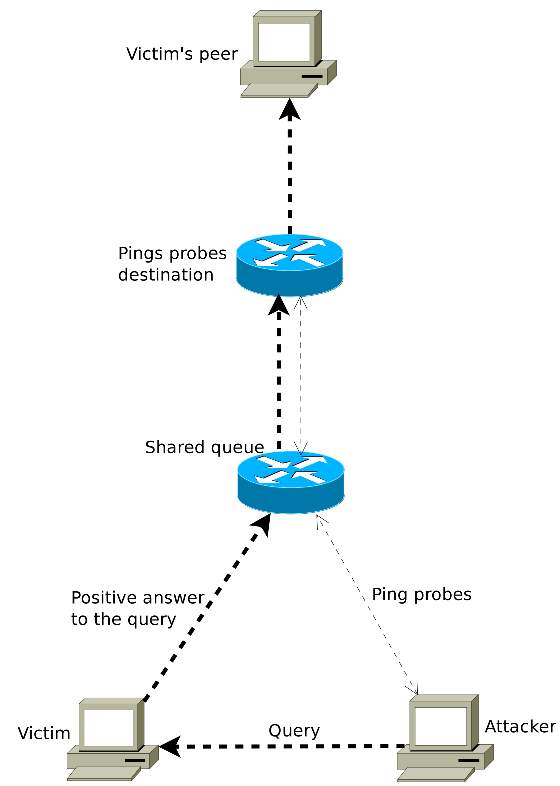


Figure 1: High level attack scheme. The attacker sends a query to the victim in a form of a sequence of spoofed segments. If the answer to the query is positive, the victim responds with a sequence of segments addressed to its peer. At the same time, the attacker sends ping probes that share an outbound queue with segments from the victim. Increased round trip time reveals the positive answer to the query.

2 Related work

A high correlation between traffic patterns of users sharing a routing resource was demonstrated in [6]. The authors monitored ping round trip time to a router that connected a user to the Internet and compared the measurements with traffic patterns generated by the user's online activities. In this technique the eavesdropper was passive and did not send any packets to trigger traffic spikes and gain additional information.

The attack described in this paper shares a lot of similarities with well known off-path techniques that exploit weak implementations of IP ID generation mechanism. Some legacy systems increase the ID field of subsequent IP packets that leave a machine by one. This provides a side channel to determine if a host sent a packet in response to incoming traffic. The channel can be used to perform stealth port scans [7] or to execute off-path attacks against established TCP connections [8]. Contrary to the technique described in this paper, the exploitation of IP ID channel requires an attacker to establish a legitimate, bidirectional communication channel to a vulnerable host. Today firewalls commonly disallow creation of such channels to client machines. This document concentrates on compromising TCP session, but the technique can also be used to perform a stealth port scan analogous to the one described in [7].

The authors of [9] showed that TCP congestion control mechanism can be exploited by a malicious receiver to improve performance of his/her connection at the cost of others. Applicability of such technique for a Denial of Service attack was studied in [10]. In simulated environment the authors were able to significantly decrease the bandwidth of participating TCP connections. Security Assessment of the TCP [5] explains that such attacks can be executed blindly by an off-path attacker. Congestion control mechanism is driven by ACK segments and TCP layer can be easily tricked to generate ACKs by spoofed segments with incorrect sequence numbers.

3 Requirements and applicability

As in case of most off-path attacks, the attacker must be able to send spoofed IP packets to one end of the targeted connection. It is also assumed that IP addresses of both ends and a port number of a server are known to the attacker. Throughout the paper, the end point to which spoofed segments are addressed is called 'the victim', the second end point is called 'the victim's peer'.

In addition to these usual requirements, the attacker must be able to send legitimate traffic probes through (or to) one of the machines (a router or an end point) on the path of the targeted TCP traffic. Ideally, the machine should be a bottleneck for the TCP connection. As described in [6], a good candidate is an edge router connecting the victim to the Internet. The probes can be ICMP pings, but also segments exchanged within a legitimate TCP connection, anything that would allow to detect changes in traffic load of the bottleneck.

There are various factors that influence applicability of the attack:

- Available bandwidth and time. The bigger the bandwidth between the attacker and the victim the better. The smaller the bandwidth between the victim and its peer the better.
- Bottleneck's natural traffic patterns. The attack is harder if the traffic traversing the bottleneck is large or has variable characteristic.
- Network topology. The attack is easier if spoofed segments from the attacker to the victim do not traverse the bottleneck, and thus do not disturb traffic probes send by the attacker.
- Bottleneck's queuing policy. Good isolation of traffic coming from different users can impede the attack.
- Traffic measuring and analyzing technique. Advanced techniques can increase the attack feasibility in adverse scenarios.

It is beyond the scope of this paper to determine the practical limits of the technique. The results of performed experiments can provide a reference point for analyzing applicability of the attack in different scenarios. The proof of concept can be used a starting point for further experiments. The attack requires much fewer resources than truly blind off-path attack, but the requirements are still significant enough to make it impractical in many real-life scenarios.

4 Experimental setup

The experiments were performed in favorable for the attacker, but not improbable conditions. The attacker was sharing an edge router with the victim. The router had 2500kb/s downlink and 320kb/s uplink connection to the Internet. The attacker was connected to the victim with 100Mb/s link, but did not have direct access to the victim's traffic. Three different scenarios were considered:

- Idle TCP connection with negligible natural traffic traversing the bottleneck. This scenario was the easiest one, induced responses constituted substantial part of bottleneck's traffic.
- The victim downloading data at full speed (saturated downlink).
- The victim uploading data at full speed (saturated uplink).

The attacker sent ping requests to a router one hop beyond the edge router. This ensured ping packets and segments sent by the victim in response to spoofed traffic shared an outgoing queue of the edge router. When the link to the outside world was idle, the ping Round Trip Time was about 20ms, when the link was saturated, the RTT increased to about 700ms.

Two systems were analyzed. Windows XP SP3 with firewall enabled and Linux 3.0.0. Linux had Netfilter firewall enabled with following commands:

```
iptables -A INPUT -m state \
  --state ESTABLISHED -j ACCEPT;
iptables -A INPUT -j DROP;
```

This is a common configuration for a client machine. All incoming traffic that it not directed to connections initiated by the protected machine is dropped.

The two tested systems implement different rules for processing TCP segments. To determine how a host protected by a firewall responds to an incoming segment two steps need to be analyzed: is firewall going to drop the segment and if not, how TCP layer is going to handle the segment? The differences between the two tested systems come from the first step - Netfilter imposes stricter filtering rules ([2]) than Windows XP firewall. The second step for both systems is the same (in respect to processing rules exploited by the attack) and closely follows RFC 793. Processing rules that are important from the attack perspective are briefly explained in following sections.

The proof of concept that was used to obtain experimental results can be found at [16]. The paper does not discuss low level details of the implementation, an interested reader is encouraged to study a documentation accompanying the code.

It is important to note that no bugs in TCP implementations of targeted systems were exploited.

5 Attack details

Assuming a shared router implements FIFO queuing policy, delay introduced by a series of N packets of equal size is:

$$\frac{N * \text{packet size}}{\text{bandwith}}$$

The victim is tricked to generate ACK segments, which have about 80 bytes (assuming about 40B for layer two header, 20B for IP and about 20B for TCP headers). Applying the formula to the experimental setup, a theoretical delay introduced by 30 ACK segments should be $\frac{30*80*8}{320000}\text{s} = 0.06\text{s}$. It is three times more than the ping RTT for the idle link (20ms), and should be easily detectable in the easiest experimental scenario. 1000 ACKs should introduce a delay of $\frac{1000*80*8}{320000}\text{s} = 2.0\text{s}$. This is about three times more than the ping RTT for the saturated link (700ms), and should be easily detectable in the download and upload experiments.

5.1 Ephemeral port number

'Event Processing' section of RFC 793 requires an ACK segment to be sent in response to any segment that belongs to an established connection (has correct IP addresses and ports) but is outside of a window (has an incorrect sequence number). If a host adheres to this specification, and is protected by a firewall that silently drops segments not belonging to any connection (a common case), the attacker can use segments with an incorrect sequence number to determine a client port number.

Windows and Linux TCP stacks follow the RFC and respond with ACK to any segment with an incorrect sequence number. Linux Netfilter firewall uses stricter validation rules to drop segments that are not part of a connection:

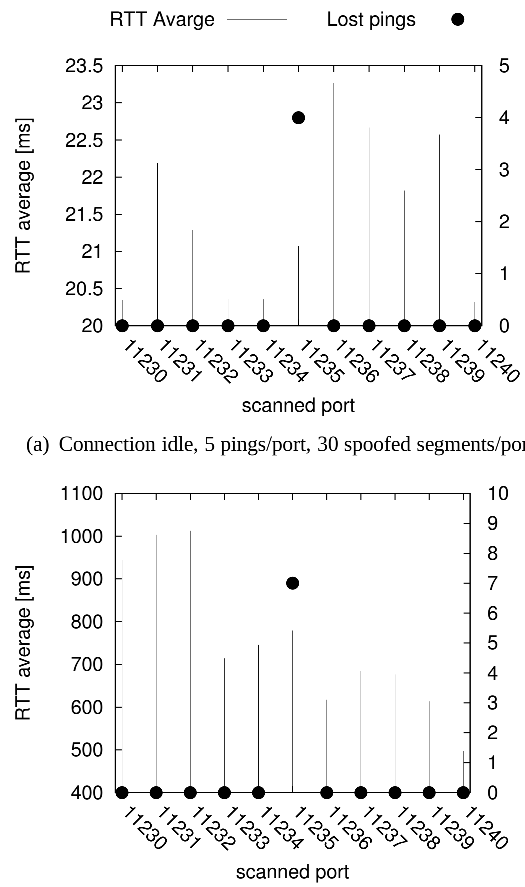
- Segments without ACK flag are dropped.
- Acknowledge number is validated. It is accepted only if it is equal to the next octet to be sent or lower by at most $\max(66000, \text{largest sender window seen})$.

Acknowledge number validation makes it much harder to use segments with an incorrect sequence number to search for a client port. But there is a hole:

- Segments that have both SYN and ACK flag set are always accepted and passed to the TCP layer.

TCP layer responds with ACK to such segments if their sequence number is outside of a window. This allows to discover an ephemeral port of a Netfilter protected host. The only drawback is that if a sequence number of SYN-ACK segment accidentally happens to be in-window, Linux responds with RST and the connection is closed. The probability of this is low: $\frac{\text{window size}}{2^{32}}$.

Figure 2 shows how ping RTT increases when a sequence of spoofed segments is directed at the correct ephemeral port. A spike in RTT occurs reliably, but usually it is not the only detected spike. Proof of concept code repeated all queries for which a spike was detected until a single query was left. This allowed to reveal an ephemeral port with a high success rate.



(a) Connection idle, 5 pings/port, 30 spoofed segments/port

(b) Connection downloading data, 10 pings/port, 1000 spoofed segments/port

Figure 2: The change in pings' loss rate reveal an ephemeral port in use (11235). Ping is considered lost if the response did not arrive within two RTTs of previous pings related to the same port.

The lower bound on a query time is a single ping RTT, because at least one ping needs to be sent to determine the query result. Even for a relatively short RTT of 20ms, if a full range of 64k ephemeral ports needs to be scanned, the sequential scan would require at least 21 minutes. When bandwidth from the attacker to the victim is large, continuous range of ports can be probed in each sequence of spoofed segments. Such sequence can be interpreted as a query 'Is the connection using a port between X and Y?'. If a part of the sequence is reflected, the answer is yes, and a sequential search can be used to find the exact port number. In the experimental setup such range queries worked well and considerably reduced time of the scan (see figure 3). Table 1 summarizes experimental results. The results were similar for both tested systems. The attacker can further improve performance if the targeted connection uses ephemeral port from a smaller range.

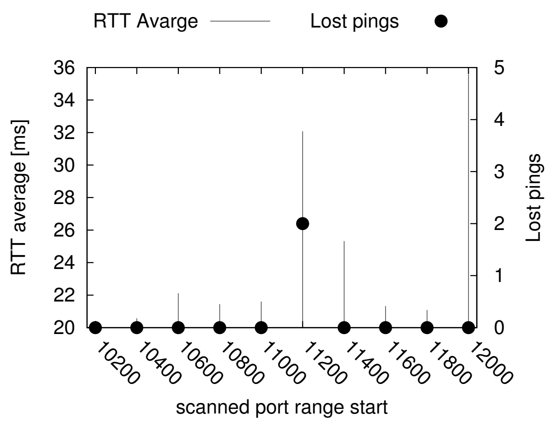


Figure 3: The range scan of an idle connection. Spoofed segments are covering 200 port ranges. 5 pings and 6000 spoofed segments (30 to each port) are sent for each range. RTT and loss rate spikes reveal the ephemeral port is somewhere between 11200 and 11400.

A side note on Netfilter

It is interesting why Netfilter does not drop SYN-ACK segments arriving in a context of an already established connection. There are at least two signals that indicate a SYN-ACK segment is incorrect: 1. ACK number does not acknowledge any SYN segment, 2. Data was already exchanged in both directions, three way handshake must have had finished successfully. A comment in the Netfilter source code says *'Our connection entry may be out of sync, so ignore packets which may signal the real connection between the client and the server'* (ignore here means do not drop). The problem is that Netfilter is a completely separate layer from the Linux TCP stack. It does not have access to the real state of a TCP connection, but recreates it based on segments it has seen. It does not assume the protected end point is on the same machine and that segments it has accepted reached the destination. For these reasons, tracking state of a TCP connection and determining if a segment can be safely dropped is very complex. As demonstrated in [2], there are many corner cases to consider that can lead to hanged connections when handled incorrectly.

5.2 Sequence numbers

To inject data at the start of a window of a one end of the connection (the victim or its peer), the attacker needs to know the sequence number of the next octet to be sent (SND.NXT) by the other end. The exact value of the SND.NXT of the end point to which data is inserted does not need to be know, it is enough that the segment that injects data has an acceptable acknowledge number set. Injecting data is relatively easy if the end point is not actively receiving data from its peer. If it is not the case, the window and SND.NXT constantly change, introducing an additional obstacle that the attacker needs to overcome. The paper does not try to address these difficulties.

Steps needed to determine SND.NXTs significantly differ for the two tested systems. In both cases ACK segments with an ephemeral port determined in the previous step are used. Windows firewall never drops ACK segments that are exchanged withing an established connection (have correct IP addresses and ports), so only rules defined in RFC 793 need to be taken into account when analyzing Windows responses. Netfilter implements stricter filtering rules. The following subsections demonstrate that stricter filtering can significantly reduce resources needed by the attack.

Host strictly following RFC 793

The sequence number of the victim's peer needs to be determined first. If a sequence number of an incoming ACK segment is in window, and an acknowledge number is acceptable, the segment does not trigger any response. Otherwise, ACK segment is sent in response. According to RFC 793, acknowledge number is acceptable if it is equal to the next octet to be sent or lower by at most 2^{31}. In other words, an acceptable acknowledge number lies in range: [SND.NXT $-\ 2^{31}$, SND.NXT] (using the 'sequence space arithmetic'). Because of this, out of two acknowledge numbers that differ by 2^{31} one is guaranteed to be acceptable. The attacker needs to send

$$N = \frac{2 \times 2^{32}}{\text{window size}}$$

queries to find in-window sequence number. The risk of accidentally corrupting the session is negligible. The session would be corrupted only if the attacker happens to acknowledge data that was lost in transit. In such case the data won't be retransmitted.

The attacker does not need to know the size of the victim's window, although it can be often easily determined (see [11]). The attacker can first assume the maximum allowed window (1GB) and try sequence numbers that differ by 2^{30}. If none of such sequence numbers is in-window, the attacker can try sequence numbers in the

Table 1: Ephemeral port search. The full space of 65k ephemeral ports was searched.

connection type	scan time[s]	queries	pings	max ports per query	spoofed segments	reflected segments
idle	35	592	2960 5/query 0.25MB total 22ms avg RTT	200	2202780 30/port/query 171MB total	330 25kB
download	852	849	8490 10/query 0.7MB total 749ms avg RTT	100	73614000 1000/port/query 5741MB total	12000 0.9MB
upload	690	852	8520 10/query 0.7MB total 656ms avg RTT	100	74013000 1000/port/query 5773MB total	10000 0.8MB

middle of ranges probed in the previous step. If the victim uses 0.5GB window, one of such sequence numbers should be in-window. The steps can be repeated, each time the assumed window size is divided by two until in-window sequence number is found. Such search is described with more details in [8].

Out of N queries, a single one that does not generate a positive response needs to be found. The situation is opposite to the port scanning, where a single query that does generate a response was searched for. In practice, searching for a negative answer is more difficult:

- Bottleneck is constantly overloaded. Scanning needs to be done in sequence, with long enough intervals between subsequent queries for a bottleneck's queue to empty. Scanning several values at once is not possible - it is relatively easy to distinguish between a traffic spike and a lack of traffic spike, it is much harder to distinguish between a traffic spike and a slightly smaller traffic spike.
- Natural traffic may mask the lack of response. In contrast, when query to which the system responds is searched for, natural traffic can only magnify the traffic spike.

Figure 4 illustrates how RTT decreases when a probed sequence number is within window. Table 2 shows that even in case of an idle connection, the time needed for a scan to finish is significant. In the experimental setup, the PoC code would need roughly about 36 hours to complete a sequential scan of a connection uploading data.

Knowing in-window sequence number, the attacker can find the victim's peer SND.NXT by looking for the lowest sequence number that does not generate a response. Such value is at most window size before the in-window sequence number and can be found with binary search in $log(\text{window size})$ queries.

Also, if the value of the victim's SND.NXT is needed, it can be now easily determined. 31 queries are required to binary search for the highest acknowledge number that does not generate any response (is acceptable). This number is equal to the SND.NXT of the victim.

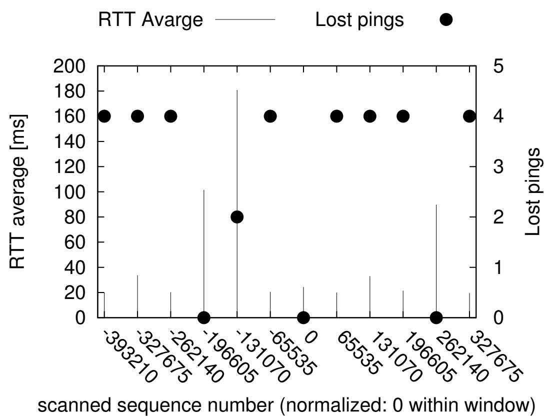
Host protected by Netfilter

The sequence number of the victim is determined first. The technique exploits acknowledge number validation rules described in section 5.1. An ACK segment is accepted only if its acknowledge number is equal to the next octet to be sent or lower by at most $\max(66000, \text{largest sender window seen})$. In other words, an acceptable acknowledge number lies in range: $[\text{SND.NXT} - \max(66000, \text{largest sender window seen}), \text{SND.NXT}]$ (using the 'sequence space arithmetic'). A segment with not acceptable acknowledge number is silently dropped by the firewall. Netfilter does not validate sequence numbers of ACKs. Linux TCP layer to which not dropped segments are passed, validates a sequence number and responds with ACK if it is out of a window.

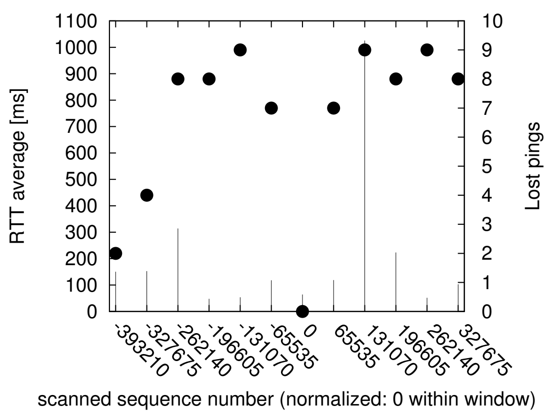
This allows to find an acceptable acknowledge number in $2^{32}/\max(66000, \text{largest sender window seen})$ tries. If the victim responds to a segment that had an incorrect sequence number, it means the acknowledge number was accepted by Netfilter. Searching for an acceptable acknowledge number is analogous to searching for an ephemeral port. At most $2^{32}/66000 = 65075$ values need to be probed and only one of these values generates a positive response, which allows to probe several values in a single query. See table 1 again for estimates of

Table 2: In-window sequence number search for the host strictly following RFC 793 processing rules. The host used a window of 65kB.

connection type	scan time[s]	queries	pings	spoofed segments	reflected segments
idle	16860 $\sim$5h	131338	394014 3/query 32MB total 85ms avg RTT	3940140 30/query 307MB total	3939930



(a) Connection idle, 5 pings/seq number, 30 spoofed segments/seq number



(b) Connection uploading data, 10 pings/seq number, 1000 spoofed segments/seq number

Figure 4: When a sequence number of a spoofed segment is in-window, the smallest average RTT and loss rate are measured. The RTT and loss rate of other probes are large, increasing duration of the scan. Natural traffic spike could mask a minimum. Ping is considered lost if the response did not arrive within two RTTs of previous pings related to the same sequence number.

resources needed.

There is a trick that allows to further improve the search efficiency. Netfilter can be easily fooled to set the value of the 'largest sender window seen' to the maximum value allowed by a window scaling factor that was set during the connection establishment. To do it, 65075 ACKs need to be sent, covering the whole 2^{32} acknowledge number space with values that differ by 66000. All these ACKs need to have window size set to the maximum allowed value: $0xFFFF$. One of the ACKs should be accepted by Netfilter and sets maximum window seen so far to $0xFFFF \times 2^{\text{window scaling factor}}$ (note that this does not affect the real window size, the TCP end point rejects the ACK because it carries an incorrect sequence number). In the experimental setup, the sender set the window size to 114 with the scaling factor of 7, which resulted in a small window of $114 \times 2^7 = 14592$B. The sequence of spoofed ACKs fooled Netfilter that the window increased to $0xFFFF \times 2^7 = 8388480$B. Such a window allowed to cover the whole 2^{32} acknowledge number space with only 512 values. As it was the case when the host following RFC 793 was targeted, the attacker does not need to know the size of the victim's window and the scaling factor. Maximum allowed window of 1GB can be assumed, and divided by two until an acceptable acknowledge number is found.

See table 3 for summary of resources needed by the search.

Knowing an acceptable acknowledge number, binary search can be used to find the sequence number of the next octet to be sent by the victim. This requires $\log(\max(66000, \text{largest sender window seen}))$ queries.

If the victim's peer SND.NXT needs to be known, the attacker has several ways to reveal it:

- Segments with a single byte of data can be used. Netfilter validates sequence numbers of segments that carry data. If the number is in-window, the segment is passed to the TCP layer which generates ACK in response because data is out of order. If the sequence number is out of the window, Netfilter drops the segment. This technique carries the risk

Table 3: Acceptable acknowledge number search. The attacker fooled Netfilter that the sender window increased to 8.3MB, this allowed to cover the whole acknowledge number space with a small number of queries.

connection type	scan time[s]	queries	pings	max ack values per query	spoofed segments	reflected segments
idle	3.4	60	300 5/query 24kB total 21ms avg RTT	25	20520 30/ack value/query 1.6MB total	240 18kB
download	61	51	510 10/query 42kB total 866ms avg RTT	25	627000 1000/ack value/query 49MB total	4000 0.3MB
upload	59	56	560 10/query 45kB total 602ms avg RTT	25	728000 1000/ack value/query 57MB total	6000 0.5MB

of corrupting the session with the accepted byte.

- If the attacker is able to send spoofed traffic to both ends, and to reliably monitor traffic spikes of both ends, the other end of the connection can be targeted. If the other end follows the RFC 793, only 32 queries are needed to find the second SND.NXT. If it is protected by Netfilter, the steps described in this section can be used again.

- Resource intensive search for a sequence number that does not generate any response can be performed in a similar way it was done for a system following RFC 793 in the previous subsection. The only difference is that acceptable acknowledge number is already known, only in-window sequence number needs to be found.

5.3 Other variants

Different TCP stacks may implement different segment processing rules, possibly closing some leaks described in this paper, or opening new ones. For example, to prevent a blind RST injection attack described in [12], a new recommendation for RST processing was created [3]. According to RFC 793 any in-window RST should be accepted and should reset the connection. The stricter and safer rules require RST to have sequence number exactly equal to the next expected sequence number, otherwise, in-window RST segment should generate ACK in response without resetting the connection. The document advises to optionally throttle such ACKs. If such ACKs are not throttled, the attacker can query for a window using RST segments with little risk of accidentally resetting the connection.

6 Advanced scanning technique

TCP Fast Retransmit [13] can be exploited to trigger substantial traffic spikes with relatively small number of spoofed segments. Fast Retransmit is activated by 3 duplicated ACKs. TCP layer interprets such duplicates as a message that a segment was lost but 3 subsequent segments successfully arrived at the destination. Each following duplicated ACK is interpreted as an acknowledgement that another segment was successfully received, but the lost segment still didn't reach the destination. Because segments are successfully leaving the network, sender sends a new segment in response to each such duplicated ACK. A burst of ACKs can trick the sender to send a full window of data in a very short time as described in [9]. The amplification factor for a network with MTU 1500 is 37. This allows the attacker to trigger observable traffic spikes with much fewer spoofed segments.

The technique can also be used to detect ephemeral port number of a host that does not filter segments addressed to not existing connection but responds with RST to each such segment. A sequence of spoofed segments directed to an incorrect port, results in a sequence of RSTs that are silently dropped by the other end point with no side effect. A sequence of spoofed segments directed to the correct port, results in a sequence of ACKs that trigger the other side to abruptly send a full window of data. If the attacker can detect the spike in traffic caused by this window of data, the port can be determined.

The technique was not tested in practice.

7 Protection

To be fully protected against side channel information leakage described in this paper, the protocol would need to ensure that not authenticated segments are never answered. If it was the case, the only information that would leak to an off-path attacker, would be that the segment was not authenticated. Providing authentication mechanism is strong enough to make probability of generating acceptable request negligible, the attacker learns nothing through the side channel that couldn't be figured out without mounting the attack. The TCP Authentication Option [14] provides exactly such mechanism, but the option is not widely used.

In case of sequence numbers based authentication, it can be difficult to ensure in a backward compatible way that the protocol never responds to rejected segments. Sequence numbers have double purpose. They were intended primary for detecting duplicates, lost and out of order segments. The use of sequence numbers as a protection mechanism against an adversary was emergent, not even mentioned in the original specification. If Netfilter filtered SYN-ACK segments addressed to an established connection and dropped ACK segments with invalid sequence numbers, the attack against a system protected by Netfilter would be probably impossible. But such stricter filtering rules require very careful analysis to prevent hanged connections in corner cases.

Throttling responses to rejected segments should be sufficient to make the information leakage non-exploitable in practice. Throttling mechanism for ACKs generated in response to in-window RSTs and in-window SYN-ACKs was proposed in [3]. To be effective, the mechanism would need to throttle also ACKs generated in response to other rejected segments.

The attack is the easiest if the attacker shares an edge router with the victim. The first few hops are also the best place to reliably filter spoofed IP packets. Network that is configured to drop such traffic is protected at least against a local attacker.

Queueing policy that better isolates traffic coming from different users could make the attack more difficult to execute. A privacy protecting scheduling policy was studied in [15]. The authors were able to significantly reduce the correlation between traffic patterns of users sharing a routing queue without introducing prohibitive performance degradation. The designed policy reduced the leakage of information regarding the traffic pattern of a user, but the traffic load of a user was still leaking through the increased packet processing time. To execute the attack described in this paper, it is enough to detect increased traffic load, knowing the exact traffic pattern is not necessary. Further research is needed to asses the effect of different queuing policies on the attack applicability.

8 Summary

The paper demonstrated how changes in processing time of packets that traverse a shared queue can reveal if a host responded to spoofed traffic. It was shown that in case of the TCP protocol, being able to determine if a system responded to spoofed segments is sufficient to compromise the session, direct interception of the TCP traffic is not required. Two different TCP implementations with different processing rules were examined. Both implementations responded to partially incorrect TCP segments, allowing the attacker to determine values of secret fields in separate steps. Substantial part of the work was dedicated to experiments to determine if the attack is practical in real-life scenario and to provide estimates of resources needed. The paper concluded with the discussion of possible attack prevention mechanisms.

The work did not try to determine the practical limits of the technique. There is a lot of room for further experiments in scenarios more adverse for the attacker (lower bandwidth between the attacker and the victim, busy bottleneck shared between many users, different queuing policies). Provided proof of concept can be used as a starting point for such experiments. The paper also did not attempt to provide a detailed survey of applicability of the technique against popular TCP implementations. Finally, the paper concentrated on compromising TCP session, but the presented technique can be applicable in other scenarios.

9 Acknowledgments

The author would like to pass a non-spoofed ACK to Wojtek Matyjewicz for reviewing first drafts of the paper, valuable comments and discussions.

References

[1] J. Postel, Transmission control protocol, RFC 793, Internet Engineering Task Force, 1981, `http://tools.ietf.org/html/rfc793`

[2] G. Van Rooij, Real Stateful TCP Packet Filtering in IP Filter, 2001, `www.usenix.org/events/sec01/invitedtalks/rooij.pdf`

[3] A. Ramaiah, R. Stewart, M. Dalal, Improving TCP's Robustness to Blind In-Window Attacks, RFC 5961, 2011, `http://tools.ietf.org/html/rfc5961`

[4] M. Larsen, F. Gont, Transport Protocol Port Randomization Recommendations, RFC 6056, 2011, `http://tools.ietf.org/html/rfc6056`

[5] F. Gont, Security Assessment of the Transmission Control Protocol, 2011 http://tools.ietf.org/html/draft-ietf-tcpm-tcp-security-0

[6] S. Kadloor, Xun Gong, N. Kiyavash, T. Tezcan, N. Borisov. 2010, Low-Cost Side Channel Remote Traffic Analysis Attack in Packets Networks, IC-CIEEE, 2010

[7] Antirez, New tcp scan method, 1998, http://seclists.org/bugtraq/1998/Dec/79

[8] klm, Blind TCP/IP hijacking is still alive, 2007, http://www.phrack.org/issues.php?issue=64&id=15

[9] S. Savage, N. Cardwell, D. Wetherall, T. Anderson, TCP Congestion Control with a Misbehaving Receiver, ACM Computer Communication Review, 29(5), October 1999

[10] A. Kumar, D. Sisalem, TCP based denial-of-service attacks to edge network: Analysis and detection, 2004, iptel.org/~dor/papers/Kumar1204_TCP.pdf

[11] Fyodor, Remote OS Detection, Nmap Network Scanning. http://nmap.org/book/osdetect.html

[12] P. Watson, Slipping in the Window: TCP Reset Attacks, CanSecWest 2004 Conference

[13] M. Allman, V. Paxson, W. Stevens, TCP Congestion Control, RFC 2581, 1999, http://tools.ietf.org/html/rfc2581

[14] J. Touch, A. Mankin, R. Bonica, The TCP Authentication Option, RFC 5925, 2010, http://tools.ietf.org/html/rfc5925

[15] S. Kadloor, Xun Gong, N. Kiyavash, P. Venkitasubramaniam, Designing Privacy Preserving Router Scheduling Policies, Information Sciences and Systems (CISS), 2011

[16] Reflection Scan Proof of Concept https://github.com/wrr/reflection_scan (to be published)