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Security Assessment of the Transmission Control Protocol (TCP)
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Abstract

This document contains a security assessment of the specifications of the Transmission Control Protocol (TCP), and of a number of

mechanisms and policies in use by popular TCP implementations. Additionally, it contains best current practices for hardening a TCP implementation.

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1. Preface

1.1. Introduction

The TCP/IP protocol suite was conceived in an environment that was quite different from the hostile environment they currently operate in. However, the effectiveness of the protocols led to their early adoption in production environments, to the point that, to some extent, the current world's economy depends on them.

While many textbooks and articles have created the myth that the Internet protocols were designed for warfare environments, the top level goal for the DARPA Internet Program was the sharing of large service machines on the ARPANET [Clark, 1988]. As a result, many protocol specifications focus only on the operational aspects of the protocols they specify, and overlook their security implications.

While the Internet technology evolved since it early inception, the Internet's building blocks are basically the same core protocols adopted by the ARPANET more than two decades ago. During the last twenty years, many vulnerabilities have been identified in the TCP/IP stacks of a number of systems. Some of them were based on flaws in

some protocol implementations, affecting only a reduced number of systems, while others were based in flaws in the protocols themselves, affecting virtually every existing implementation [Bellovin, 1989]. Even in the last couple of years, researchers were still working on security problems in the core protocols [NISCC, 2004] [NISCC, 2005].

The discovery of vulnerabilities in the TCP/IP protocol suite usually led to reports being published by a number of CSIRTs (Computer Security Incident Response Teams) and vendors, which helped to raise awareness about the threats and the best mitigations known at the time the reports were published. Unfortunately, this also led to the documentation of the discovered protocol vulnerabilities being spread among a large number of documents, which are sometimes difficult to identify.

For some reason, much of the effort of the security community on the Internet protocols did not result in official documents (RFCs) being issued by the IETF (Internet Engineering Task Force). This basically led to a situation in which "known" security problems have not always been addressed by all vendors. In addition, in many cases vendors have implemented quick "fixes" to the identified vulnerabilities without a careful analysis of their effectiveness and their impact on interoperability [Silbersack, 2005].

Producing a secure TCP/IP implementation nowadays is a very difficult

task, in part because of the lack of a single document that serves as a security roadmap for the protocols. Implementers are faced with the hard task of identifying relevant documentation and differentiating between that which provides correct advice, and that which provides misleading advice based on inaccurate or wrong assumptions.

This document is the result of a security assessment of the IETF specifications of the Transmission Control Protocol (TCP), from a security point of view. Possible threats are identified and, where possible, countermeasures are proposed. Additionally, many implementation flaws that have led to security vulnerabilities have been referenced in the hope that future implementations will not incur the same problems.

This document is heavily based on the "Security Assessment of the Transmission Control Protocol (TCP)" released by the UK Centre for the Protection of National Infrastructure (CPNI), available at: http://www.cpni.gov.uk/Products/technicalnotes/Feb-09-security-assessment-TCP.aspx .

1.2. Scope of this document

While there are a number of protocols that may affect the way TCP operates, this document focuses only on the specifications of the Transmission Control Protocol (TCP) itself.

The following IETF RFCs were selected for assessment as part of this work:

- RFC 793, "Transmission Control Protocol. DARPA Internet Program. Protocol Specification" (91 pages)
- RFC 1122, "Requirements for Internet Hosts -- Communication Layers" (116 pages)
- RFC 1191, "Path MTU Discovery" (19 pages)
- RFC 1323, "TCP Extensions for High Performance" (37 pages)
- RFC 1948, "Defending Against Sequence Number Attacks" (6 pages)
- RFC 1981, "Path MTU Discovery for IP version 6" (15 pages)
- RFC 2018, "TCP Selective Acknowledgment Options" (12 pages)
- RFC 2385, "Protection of BGP Sessions via the TCP MD5 Signature Option" (6 pages)

- RFC 2581, "TCP Congestion Control" (14 pages)
- RFC 2675, "IPv6 Jumbograms" (9 pages)
- RFC 2883, "An Extension to the Selective Acknowledgement (SACK) Option for TCP" (17 pages)
- RFC 2884, "Performance Evaluation of Explicit Congestion

Notification (ECN) in IP Networks" (18 pages)

- RFC 2988, "Computing TCP's Retransmission Timer" (8 pages)
- RFC 3168, "The Addition of Explicit Congestion Notification (ECN) to IP" (63 pages)
- RFC 3465, "TCP Congestion Control with Appropriate Byte Counting (ABC)" (10 pages)
- RFC 3517, "A Conservative Selective Acknowledgment (SACK)-based Loss Recovery Algorithm for TCP" (13 pages)
- RFC 3540, "Robust Explicit Congestion Notification (ECN) Signaling with Nonces" (13 pages)
- RFC 3782, "The NewReno Modification to TCP's Fast Recovery Algorithm" (19 pages)

1.3. Organization of this document

This document is basically organized in two parts. The first part contains a discussion of each of the TCP header fields, identifies their security implications, and discusses the possible countermeasures. The second part contains an analysis of the security implications of the mechanisms and policies implemented by TCP, and of a number of implementation strategies in use by a number of popular TCP implementations.

2. The Transmission Control Protocol

The Transmission Control Protocol (TCP) is a connection-oriented transport protocol that provides a reliable byte-stream data transfer service.

Very few assumptions are made about the reliability of underlying data transfer services below the TCP layer. Basically, TCP assumes it can obtain a simple, potentially unreliable datagram service from the lower level protocols. Figure 1 illustrates where TCP fits in

the DARPA reference model.

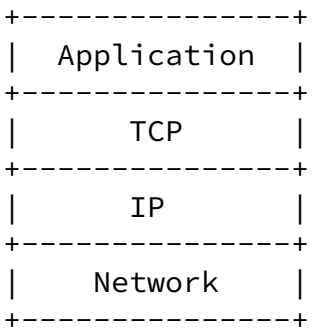


Figure 1: TCP in the DARPA reference model

TCP provides facilities in the following areas:

- Basic Data Transfer
- Reliability
- Flow Control
- Multiplexing
- Connections
- Precedence and Security
- Congestion Control

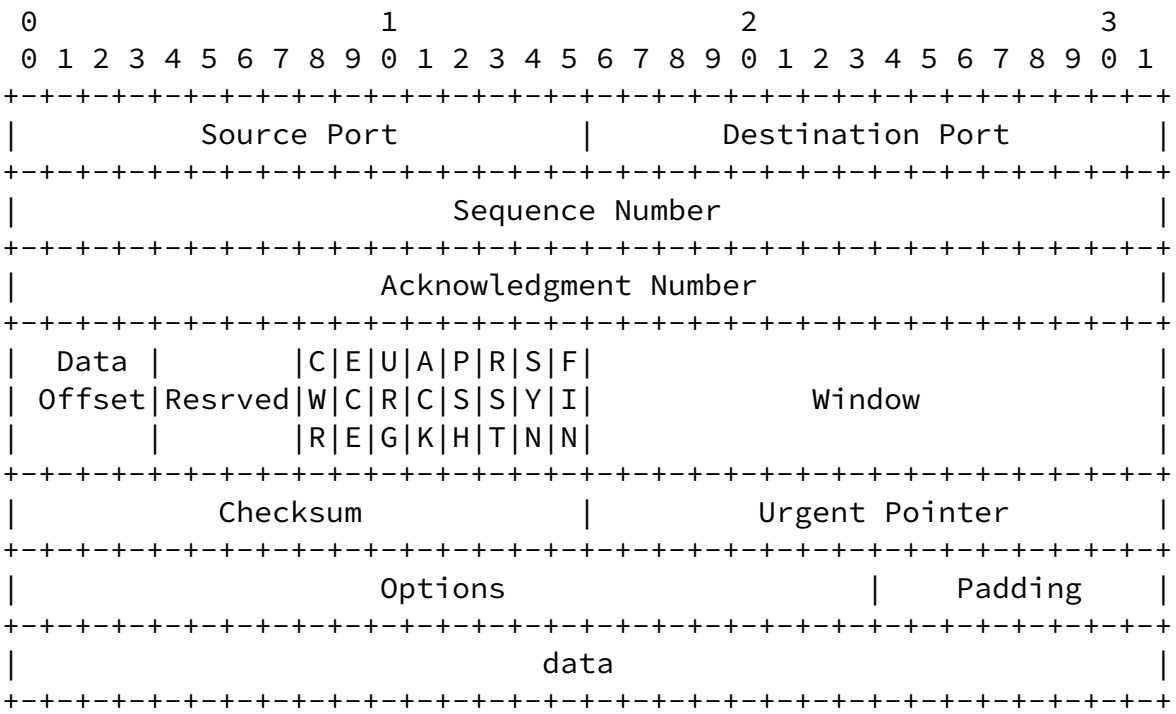
The core TCP specification, RFC 793 [Postel, 1981c], dates back to 1981 and standardizes the basic mechanisms and policies of TCP. RFC 1122 [Braden, 1989] provides clarifications and errata for the original specification. RFC 2581 [Allman et al, 1999] specifies TCP congestion control and avoidance mechanisms, not present in the original specification. Other documents specify extensions and improvements for TCP.

The large amount of documents that specify extensions, improvements, or modifications to existing TCP mechanisms has led the IETF to publish a roadmap for TCP, RFC 4614 [Duke et al, 2006], that clarifies the relevance of each of those documents.

3. TCP header fields

RFC 793 [Postel, 1981c] defines the syntax of a TCP segment, along with the semantics of each of the header fields. Figure 2

illustrates the syntax of a TCP segment.



Note that one tick mark represents one bit position

Figure 2: Transmission Control Protocol header format

The minimum TCP header size is 20 bytes, and corresponds to a TCP segment with no options and no data. However, a TCP module might be handed an (illegitimate) "TCP segment" of less than 20 bytes. Therefore, before doing any processing of the TCP header fields, the following check should be performed by TCP on the segments handed by the internet layer:

Segment.Size >= 20

If a segment does not pass this check, it should be dropped.

The following subsections contain further sanity checks that should be performed on TCP segments.

3.1. Source Port

This field contains a 16-bit number that identifies the TCP end-point that originated this TCP segment. Being a 16-bit field, it can contain any value in the range 0-65535.

The Internet Assigned Numbers Authority (IANA) has traditionally

reserved the following use of the 16-bit port range of TCP [IANA, 2008]:

- The Well Known Ports, 0 through 1023
- The Registered Ports, 1024 through 49151
- The Dynamic and/or Private Ports, 49152 through 65535

The range of assigned ports managed by the IANA is 0-1023, with the remainder being registered by IANA but not assigned [IANA, 2008]. It is also worth noting that, while some systems restrict use of the port numbers in the range 0-1024 to privileged users, no trust should be granted based on the port numbers used for a TCP connection.

Servers usually bind specific ports on which specific services are usually provided, while clients usually make use of the so-called "ephemeral ports" for the source port of their outgoing connections with the only requirement that the resulting four-tuple must be unique (not currently in use by any other transport protocol instance).

While the only requirement for a selected ephemeral port is that the resulting four-tuple (connection-id) is unique, in practice it may be necessary to not allow the allocation of port numbers that are in use by a TCP that is in the LISTEN or CLOSED states for use as ephemeral ports, as this might allow an attacker to "steal" incoming connections from a local server application. Section 10.2 of this document provides a detailed discussion of this issue.

It should also be noted that some clients, such as DNS resolvers, are known to use port numbers from the "Well Known Ports" range. Therefore, middle-boxes such as packet filters should not assume that clients use port number from only the Dynamic or Registered port ranges.

While port 0 is a legitimate port number, it has a special meaning in the UNIX Sockets API. For example, when a TCP port number of 0 is passed as an argument to the bind() function, rather than binding

port 0, an ephemeral port is selected for the corresponding TCP end-point. As a result, the TCP port number 0 is never actually used in TCP segments.

Different implementations have been found to respond differently to TCP segments that have a port number of 0 as the Source Port and/or the Destination Port. As a result, TCP segments with a port number of 0 are usually employed for remote OS detection via TCP/IP stack fingerprinting [Jones, 2003].

Since in practice TCP port 0 is not used by any legitimate application and is only used for fingerprinting purposes, a number of host implementations already reject TCP segments that use 0 as the Source Port and/or the Destination Port. Also, a number firewalls filter (by default) any TCP segments that contain a port number of zero for the Source Port and/or the Destination Port.

We therefore recommend that TCP implementations respond to incoming TCP segments that have a Source Port of 0 with an RST (provided these incoming segments do not have the RST bit set).

Responding with an RST segment to incoming segments that have the RST bit would open the door to RST-war attacks.

As discussed in Section 3.2, we also recommend TCP implementations to respond with an RST to incoming packets that have a Destination Port of 0 (provided these incoming segments do not have the RST bit set).

3.1.1. Problems that may arise as a result of collisions of connection-id's

A number of implementations will not allow the creation of a new connection if there exists a previous incarnation of the same connection in any state other than the fictional state CLOSED. This can be problematic in scenarios in which a client establishes connections with a specific service at a particular server at a high rate: even if the connections are also closed at a high rate, one of the systems (the one performing the active close) will keep each of the closed connections in the TIME-WAIT state for 2*MSL.

MSL (Maximum Segment Lifetime) is the maximum amount of time that a TCP segment can exist in an internet. It is defined to be 2 minutes

by RFC 793 [Postel, 1981c].

If the connection rate is high enough, at some point all the ephemeral ports at the client will be in use by some connection in the TIME-WAIT state, thus preventing the establishment of new connections. In order to overcome this problem, a number of TCP implementations include some heuristics to allow the creation of a new incarnation of a connection that is in the TIME-WAIT state. In such implementations a new incarnation of a previous connection is allowed if:

- The incoming SYN segment contains a timestamp option, and the timestamp is greater than the last timestamp seen in the previous incarnation of the connection (for that direction of the data transfer), or,

- The incoming SYN segment does not contain a timestamp option, but its Initial Sequence Number (ISN) is greater than the last sequence number seen in the previous incarnation of the connection (for that direction of the data transfer)

Unfortunately, these heuristics are optional, and thus cannot be relied upon. Additionally, as indicated by [Silbersack, 2005], if the Timestamp or the ISN are trivially randomized, these heuristics might fail.

Section 3.3.1 and Section 4.7.1 of this document recommend algorithms for the generation of TCP Initial Sequence Numbers and TCP timestamps, respectively, that provide randomization, while still allowing the aforementioned heuristics to work.

Therefore, the only strategy that can be relied upon to avoid this interoperability problem is to minimize the rate of collisions of connection-id's. A good algorithm to minimize rate of collisions of connection-id's would consider the time a given four-tuple {Source Address, Source Port, Destination Address, Destination Port} was last used, and would try avoid reusing it for 2*MSL. However, an efficient implementation approach for this algorithm has not yet been devised. A simple approach to minimize the rate collisions of connection-id's in most scenarios is to maximize the port reuse cycle, such that a port number is not reused before all the other

port numbers in the ephemeral port range have been used for outgoing connections. This is the traditional ephemeral port selection algorithm in 4.4BSD implementations.

However, if a single global variable is used to keep track of the last ephemeral port selected, ephemeral port numbers become trivially predictable.

Section 3.1.2 of this document analyzes a number of approaches for obfuscating the TCP ephemeral ports, such that the chances of an attacker of guessing the ephemeral ports used for future connections are reduced, while still reducing the probability of collisions of connection-id's. Finally, Section 3.1.3 makes recommendations about the port range that should be used for the ephemeral ports.

16.3. Broadcast and multicast IP addresses

17. Security Considerations

18. Acknowledgements

This document is based on the document "Security Assessment of the Transmission Control Protocol (TCP)" [CPNI, 2009] written by Fernando Gont on behalf of CPNI (Centre for the Protection of National Infrastructure).

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Appendix A. Changes from previous versions of the draft (to be removed by the RFC Editor before publishing this document as an RFC)

A.1. Changes from draft-gont-tcp-security-00

- Draft resubmitted as draft-ietf (boilerplate updated as required).

Appendix B. Advice and guidance to vendors

Vendors are urged to contact CSIRTUK (csirt@cpni.gsi.gov.uk) if they think they may be affected by the issues described in this document. As the lead coordination center for these issues, CPNI is well placed to give advice and guidance as required.

CPNI works extensively with government departments and agencies, commercial organizations and the academic community to research vulnerabilities and potential threats to IT systems especially where they may have an impact on Critical National Infrastructure's (CNI).

Other ways to contact CPNI, plus CPNI's PGP public key, are available at http://www.cpni.gov.uk/ .

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