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TCP Usage Guidance in the Internet of Things (IoT)
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Abstract

This document provides guidance on how to implement and use the Transmission Control Protocol (TCP) in Constrained-Node Networks (CNNs), which are a characterstic of the Internet of Things (IoT). Such environments require a lightweight TCP implementation and may not make use of optional functionality. This document explains a number of known and deployed techniques to simplify a TCP stack as well as corresponding tradeoffs. The objective is to help embedded developers with decisions on which TCP features to use.

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Table of Contents

1. Introduction 3
2. Conventions used in this document 4
3. Characteristics of CNNs relevant for TCP 4
3.1. Network and link properties 4
3.2. Usage scenarios 5
3.3. Communication and traffic patterns 6
4. TCP implementation and configuration in CNNs 6
4.1. Path properties 7
4.1.1. Maximum Segment Size (MSS) 7
4.1.2. Explicit Congestion Notification (ECN) 8
4.1.3. Explicit loss notifications 9
4.2. TCP guidance for single-MSS windows and buffers 9
4.2.1. Single-MSS stacks - benefits and issues 9
4.2.2. TCP options for single-MSS stacks 9
4.2.3. Delayed Acknowledgments for single-MSS stacks 10
4.2.4. RTO estimation for single-MSS stacks 11
4.3. General recommendations for TCP in CNNs 11
4.3.1. Loss recovery and congestion/flow control 11
4.3.1.1. Selective Acknowledgments (SACK) 12
4.3.2. Delayed Acknowledgments 12
5. TCP usage recommendations in CNNs 13
5.1. TCP connection initiation 13
5.2. Number of concurrent connections 13
5.3. TCP connection lifetime 13
6. Security Considerations 15
7. Acknowledgments 16
8. Annex. TCP implementations for constrained devices 16
8.1. uIP 17
8.2. lwIP 17
8.3. RIOT 17
8.4. TinyOS 18
8.5. FreeRTOS 18
8.6. uC/OS 18
8.7. Summary 19
9. Annex. Changes compared to previous versions 20
9.1. Changes between -00 and -01 20
9.2. Changes between -01 and -02 20
9.3. Changes between -02 and -03 20
9.4. Changes between -03 and -04 21

9.5. Changes between -04 and -05 21
9.6. Changes between -05 and -06 21
9.7. Changes between -06 and -07 21
10. References 21
10.1. Normative References 21
10.2. Informative References 23
Authors' Addresses 26

1. Introduction

The Internet Protocol suite is being used for connecting Constrained-Node Networks (CNNs) to the Internet, enabling the so-called Internet of Things (IoT) [RFC7228]. In order to meet the requirements that stem from CNNs, the IETF has produced a suite of new protocols specifically designed for such environments (see e.g. [RFC8352]). New IETF protocol stack components include the IPv6 over Low-power Wireless Personal Area Networks (6LoWPAN) adaptation layer, the IPv6 Routing Protocol for Low-power and lossy networks (RPL) routing protocol, and the Constrained Application Protocol (CoAP).

As of the writing, the main current transport layer protocols in IP-based IoT scenarios are UDP and TCP. However, TCP has been criticized (often, unfairly) as a protocol for the IoT. In fact, some TCP features are not optimal for IoT scenarios, such as relatively long header size, unsuitability for multicast, and always-confirmed data delivery. However, many typical claims on TCP unsuitability for IoT (e.g. a high complexity, connection-oriented approach incompatibility with radio duty-cycling, and spurious congestion control activation in wireless links) are not valid, can be solved, or are also found in well accepted IoT end-to-end reliability mechanisms (see [IntComp] for a detailed analysis).

At the application layer, CoAP was developed over UDP [RFC7252]. However, the integration of some CoAP deployments with existing infrastructure is being challenged by middleboxes such as firewalls, which may limit and even block UDP-based communications. This the main reason why a CoAP over TCP specification has been developed [RFC8323].

Other application layer protocols not specifically designed for CNNs are also being considered for the IoT space. Some examples include HTTP/2 and even HTTP/1.1, both of which run over TCP by default [RFC7230] [RFC7540], and the Extensible Messaging and Presence Protocol (XMPP) [RFC6120]. TCP is also used by non-IETF application-layer protocols in the IoT space such as the Message Queue Telemetry Transport (MQTT) and its lightweight variants.

TCP is a sophisticated transport protocol that includes optional functionality (e.g. TCP options) that may improve performance in some environments. However, many optional TCP extensions require complex logic inside the TCP stack and increase the codesize and the memory requirements. Many TCP extensions are not required for interoperability with other standard-compliant TCP endpoints. Given the limited resources on constrained devices, careful "tuning" of the TCP implementation can make an implementation more lightweight.

This document provides guidance on how to implement and use TCP in CNNs. The overarching goal is to offer simple measures to allow for lightweight TCP implementation and suitable operation in such environments. A TCP implementation following the guidance in this document is intended to be compatible with a TCP endpoint that is compliant to the TCP standards, albeit possibly with a lower performance. This implies that such a TCP client would always be able to connect with a standard-compliant TCP server, and a corresponding TCP server would always be able to connect with a standard-compliant TCP client.

This document assumes that the reader is familiar with TCP. A comprehensive survey of the TCP standards can be found in [RFC7414]. Similar guidance regarding the use of TCP in special environments has been published before, e.g., for cellular wireless networks [RFC3481].

2. Conventions used in this document

The key words "MUST", "MUST NOT", "REQUIRED", "SHALL","SHALL NOT", "SHOULD", "SHOULD NOT", "RECOMMENDED", "MAY", and "OPTIONAL" in this document are to be interpreted as described in [RFC2119].

3. Characteristics of CNNs relevant for TCP

3.1. Network and link properties

CNNs are defined in [RFC7228] as networks whose characteristics are influenced by being composed of a significant portion of constrained nodes. The latter are characterized by significant limitations on processing, memory, and energy resources, among others [RFC7228]. The first two dimensions pose constraints on the complexity and on the memory footprint of the protocols that constrained nodes can support. The latter requires techniques to save energy, such as radio duty-cycling in wireless devices [RFC8352], as well as minimization of the number of messages transmitted/received (and their size).

[RFC7228] lists typical network constraints in CNN, including low achievable bitrate/throughput, high packet loss and high variability of packet loss, highly asymmetric link characteristics, severe penalties for using larger packets, limits on reachability over time, etc. CNN may use wireless or wired technologies (e.g., Power Line Communication), and the transmission rates are typically low (e.g. below 1 Mbps).

For use of TCP, one challenge is that not all technologies in CNN may be aligned with typical Internet subnetwork design principles [RFC3819]. For instance, constrained nodes often use physical/link layer technologies that have been characterized as 'lossy', i.e., exhibit a relatively high bit error rate. Dealing with corruption loss is one of the open issues in the Internet [RFC6077].

3.2. Usage scenarios

There are different deployment and usage scenarios for CNNs. Some CNNs follow the star topology, whereby one or several hosts are linked to a central device that acts as a router connecting the CNN to the Internet. CNNs may also follow the multihop topology [RFC6606]. One key use case for the use of TCP is a model where constrained devices connect to unconstrained servers in the Internet. But it is also possible that both TCP endpoints run on constrained devices.

In constrained environments, there can be different types of devices [RFC7228]. For example, there can be devices with single combined send/receive buffer, devices with a separate send and receive buffer, or devices with a pool of multiple send/receive buffers. In the latter case, it is possible that buffers also be shared for other protocols.

When a CNN comprising one or more constrained devices and an unconstrained device communicate over the Internet using TCP, the communication possibly has to traverse a middlebox (e.g. a firewall, NAT, etc.). Figure 1 illustrates such scenario. Note that the scenario is asymmetric, as the unconstrained device will typically not suffer the severe constraints of the constrained device. The unconstrained device is expected to be mains-powered, to have high amount of memory and processing power, and to be connected to a resource-rich network.

Assuming that a majority of constrained devices will correspond to sensor nodes, the amount of data traffic sent by constrained devices (e.g. sensor node measurements) is expected to be higher than the amount of data traffic in the opposite direction. Nevertheless, constrained devices may receive requests (to which they may respond),

commands (for configuration purposes and for constrained devices including actuators) and relatively infrequent firmware/software updates.

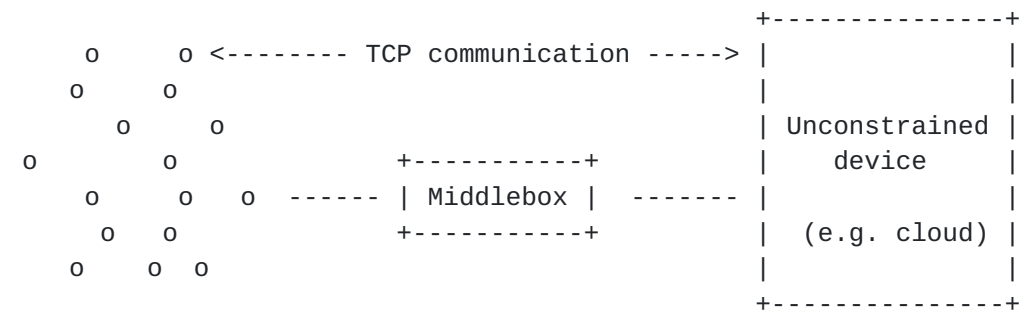


Figure 1: TCP communication between a constrained device and an unconstrained device, traversing a middlebox.

3.3. Communication and traffic patterns

IoT applications are characterized by a number of different communication patterns. The following non-comprehensive list explains some typical examples:

- Unidirectional transfers: An IoT device (e.g. a sensor) can send (repeatedly) updates to the other endpoint. Not in every case there is a need for an application response back to the IoT device.

- Request-response patterns: An IoT device receiving a request from the other endpoint, which triggers a response from the IoT device.

- Bulk data transfers: A typical example for a long file transfer would be an IoT device firmware update.

A typical communication pattern is that a constrained device communicates with an unconstrained device (cf. Figure 1). But it is also possible that constrained devices communicate amongst themselves.

4. TCP implementation and configuration in CNNs

This section explains how a TCP stack can deal with typical constraints in CNN. The guidance in this section relates to the TCP implementation and its configuration.

4.1. Path properties

4.1.1. Maximum Segment Size (MSS)

Assuming that IPv6 is used, and for the sake of lightweight implementation and operation, unless applications require handling large data units (i.e. leading to an IPv6 datagram size greater than 1280 bytes), it may be desirable to limit the MTU to 1280 bytes in order to avoid the need to support Path MTU Discovery [RFC8201].

An IPv6 datagram size exceeding 1280 bytes can be avoided by setting the TCP MSS not larger than 1220 bytes. This assumes that the remote sender will use no TCP options, aside from possibly the MSS option, which is only used in the initial TCP SYN packet. In order to accommodate unrequested TCP options that may be used by some TCP implementations, a constrained device may advertise an MSS not larger than 1200 bytes.

Note that setting the MTU to 1280 bytes is possible for link layer technologies in the CNN space, even if some of them are characterized by a short data unit payload size, e.g. up to a few tens or hundreds of bytes. For example, the maximum frame size in IEEE 802.15.4 is 127 bytes. 6LoWPAN defined an adaptation layer to support IPv6 over IEEE 802.15.4 networks. The adaptation layer includes a fragmentation mechanism, since IPv6 requires the layer below to support an MTU of 1280 bytes [RFC2460], while IEEE 802.15.4 lacked fragmentation mechanisms. 6LoWPAN defines an IEEE 802.15.4 link MTU of 1280 bytes [RFC4944]. Other technologies, such as Bluetooth LE [RFC7668], ITU-T G.9959 [RFC7428] or DECT-ULE [RFC8105], also use 6LoWPAN-based adaptation layers in order to enable IPv6 support. These technologies do support link layer fragmentation. By exploiting this functionality, the adaptation layers that enable IPv6 over such technologies also define an MTU of 1280 bytes.

On the other hand, there exist technologies also used in the CNN space, such as Master Slave / Token Passing (TP) [RFC8163], Narrowband IoT (NB-IoT) [RFC8376] or IEEE 802.11ah [I-D.delcarpio-6lo-wlanah], that do not suffer the same degree of frame size limitations as the technologies mentioned above. The MTU for MS/TP is recommended to be 1500 bytes [RFC8163], the MTU in NB-IoT is 1600 bytes, and the maximum frame payload size for IEEE 802.11ah is 7991 bytes.

While IPv6 is the main IP version used in IP-based IoT environments, some IoT scenarios use IPv4. In IPv4, the MTU is 576 bytes. In order to avoid exceeding the IPv4 MTU, the MSS needs to be set to a value not larger than 536 bytes. Similarly to the recommendations given above for IPv6, a constrained device using IPv4 may advertise

an MSS not larger than 516 bytes in order to accommodate unrequested TCP options.

Finally, note that using larger MSS (to a suitable extent) may be beneficial, especially when transferring large payloads, as it reduces the number of packets (and packet headers) required for a given payload.

4.1.2. Explicit Congestion Notification (ECN)

Explicit Congestion Notification (ECN) [RFC3168] ECN allows a router to signal in the IP header of a packet that congestion is arising, for example when a queue size reaches a certain threshold. An ECN-enabled TCP receiver will echo back the congestion signal to the TCP sender by setting a flag in its next TCP ACK. The sender triggers congestion control measures as if a packet loss had happened.

The document [RFC8087] outlines the principal gains in terms of increased throughput, reduced delay, and other benefits when ECN is used over a network path that includes equipment that supports Congestion Experienced (CE) marking. In the context of CNNs, a remarkable feature of ECN is that congestion can be signalled without incurring packet drops (which will lead to retransmissions and consumption of limited resources such as energy and bandwitdh).

ECN can further reduce packet losses since congestion control measures can be applied earlier [RFC2884]. Less lost packets implies that the number of retransmitted segments decreases, which is particularly beneficial in CNNs, where energy and bandwidth resources are typically limited. Also, it makes sense to try to avoid packet drops for transactional workloads with small data sizes, which are typical for CNNs. In such traffic patterns, it is more difficult to detect packet loss without retransmission timeouts (e.g., as there may be no three duplicate ACKs). Any retransmission timeout slows down the data transfer significantly. In addition, if the constrained device uses power saving techniques, a retransmission timeout will incur a wake-up action, in contrast to ACK clock-triggered sending. When the congestion window of a TCP sender has a size of one segment, the TCP sender resets the retransmit timer, and the sender will only be able to send a new packet when the retransmit timer expires [RFC3168]. Effectively, the TCP sender reduces at that moment its sending rate from 1 segment per Round Trip Time (RTT) to 1 segment per RTO, which can result in a very low throughput. In addition to better throughput, ECN can also help reducing latency and jitter.

ECN can be incrementally deployed in the Internet. Guidance on configuration and usage of ECN is provided in [RFC7567]. Given the

benefits, more and more TCP stacks in the Internet support ECN, and it specifically makes sense to leverage ECN in controlled environments such as CNNs. Note, however, that supporting ECN increases implementation complexity.

4.1.3. Explicit loss notifications

There has been a significant body of research on solutions capable of explicitly indicating whether a TCP segment loss is due to corruption, in order to avoid activation of congestion control mechanisms [ETEN] [RFC2757]. While such solutions may provide significant improvement, they have not been widely deployed and remain as experimental work. In fact, as of today, the IETF has not standardized any such solution.

4.2. TCP guidance for single-MSS windows and buffers

This section discusses TCP stacks that focus on transferring a single MSS. More general guidance is provided in Section 4.3.

4.2.1. Single-MSS stacks - benefits and issues

A TCP stack can reduce the memory requirements by advertising a TCP window size of one MSS, and also transmit at most one MSS of unacknowledged data. In that case, both congestion and flow control implementation is quite simple. Such a small receive and send window may be sufficient for simple message exchanges in the CNN space. However, only using a window of one MSS can significantly affect performance. A stop-and-wait operation results in low throughput for transfers that exceed the length of one MSS, e.g., a firmware download. Furthermore, a single-MSS solution relies solely on timer-based loss recovery, therefore missing the performance gain of Fast Retransmit and Fast Recovery (which require a larger window size, see Subsection 4.3.1).

If CoAP is used over TCP with the default setting for NSTART in [RFC7252], a CoAP endpoint is not allowed to send a new message to a destination until a response for the previous message sent to that destination has been received. This is equivalent to an application-layer window size of 1. For this use of CoAP, a maximum TCP window of one MSS will be sufficient.

4.2.2. TCP options for single-MSS stacks

A TCP implementation needs to support, at a minimum, TCP options 2, 1 and 0. These are, respectively, the Maximum Segment Size (MSS) option, the No-Operation option, and the End Of Option List marker [RFC0793]. None of these are a substantial burden to support. These

options are sufficient for interoperability with a standard-compliant TCP endpoint, albeit many TCP stacks support additional options and can negotiate their use. A TCP implementation is permitted to silently ignore all other TCP options.

A TCP implementation for a constrained device that uses a single-MSS TCP receive or transmit window size may not benefit from supporting the following TCP options: Window scale [RFC7323], TCP Timestamps [RFC7323], Selective Acknowledgments (SACK) and SACK-Permitted [RFC2018]. Also other TCP options may not be required on a constrained device with a very lightweight implementation. With regard to the Window scale option, note that it is only useful if a window size greater than 64 kB is needed.

One potentially relevant TCP option in the context of CNNs is TCP Fast Open (TFO) [RFC7413]. As described in Section 5.3, TFO can be used to address the problem of traversing middleboxes that perform early filter state record deletion.

4.2.3. Delayed Acknowledgments for single-MSS stacks

TCP Delayed Acknowledgments are meant to reduce the number of ACKs sent within a TCP connection, thus reducing network overhead, but they may increase the time until a sender may receive an ACK. In general, usefulness of Delayed ACKs depends heavily on the usage scenario. There can be interactions with stacks that use single-MSS windows.

A device that advertises a single-MSS receive window should avoid use of Delayed ACKs in order to avoid contributing unnecessary delay (of up to 500 ms) to the RTT [RFC5681], which limits the throughput and can increase the data delivery time.

A device that can send at most one MSS of data is significantly affected if the receiver uses Delayed ACKs, e.g., if a TCP server or receiver is outside the CNN. One known workaround is to split the data to be sent into two segments of smaller size. A standard compliant TCP receiver will acknowledge the second MSS of data, which can improve throughput. This "split hack" works if the TCP receiver uses Delayed ACKs, but the downside is the overhead of sending two IP packets instead of one.

Similar issues happen when the sender uses the Nagle algorithm. Disabling the algorithm will not have impact if the sender can only handle stop-and-wait operation.

4.2.4. RTO estimation for single-MSS stacks

The Retransmission Timeout (RTO) estimation is one of the fundamental TCP algorithms. There is a fundamental trade-off: A short, aggressive RTO behavior reduces wait time before retransmissions, but it also increases the probability of spurious timeouts. The latter lead to unnecessary waste of potentially scarce resources in CNNs such as energy and bandwidth. In contrast, a conservative timeout can result in long error recovery times and thus needlessly delay data delivery.

[RFC6298] describes the standard TCP RTO algorithm. If a TCP sender uses very small window size, and it cannot use Fast Retransmit/Fast Recovery or SACK, the Retransmission Timeout (RTO) algorithm has a larger impact on performance than for a more powerful TCP stack. In that case, RTO algorithm tuning may be considered, although careful assessment of possible drawbacks is recommended [I-D.ietf-tcpm-rto-consider].

As an example, an adaptive RTO algorithm for CoAP over UDP has been defined [I-D.ietf-core-cocoa] that has been found to perform well in CNN scenarios [Commag].

4.3. General recommendations for TCP in CNNs

This section summarizes some widely used techniques to improve TCP, with a focus on their use in CNNs. The TCP extensions discussed here are useful in a wide range of network scenarios, including CNNs. This section is not comprehensive. A comprehensive survey of TCP extensions is published in [RFC7414].

4.3.1. Loss recovery and congestion/flow control

Devices that have enough memory to allow a larger (i.e. more than 3 MSS of data) TCP window size can leverage a more efficient loss recovery than the timer-based approach used for smaller TCP window size (see Subsection 3.2.1) by using Fast Retransmit and Fast Recovery [RFC5681], at the expense of slightly greater complexity and TCB size. Assuming that Delayed ACKs are used by the receiver, the mentioned algorithms work efficiently for window sizes of at least 5 MSS: If in a given TCP transmission of segments 1, 2, 3, 4, 5, and 6 the segment 2 gets lost, the sender should get an ACK for segment 1 when 3 arrives and duplicate acknowledgements when 4, 5, and 6 arrive. It will retransmit segment 2 when the third duplicate ACK arrives. In order to have segment 2, 3, 4, 5, and 6 sent, the window has to be at least 5 MSS. With an MSS of 1220 byte, a buffer of the size of 5 MSS would require 6100 bytes.

For bulk data transfers further TCP improvements may also be useful, such as limited transmit [RFC3042].

4.3.1.1. Selective Acknowledgments (SACK)

If a device with less severe memory and processing constraints can afford advertising a TCP window size of several MSS, it makes sense to support the SACK option to improve performance. SACK allows a data receiver to inform the data sender of non-contiguous data blocks received, thus a sender (having previously sent the SACK-Permitted option) can avoid performing unnecessary retransmissions, saving energy and bandwidth, as well as reducing latency. SACK is particularly useful for bulk data transfers. The receiver supporting SACK will need to manage the reception of possible out-of-order received segments, requiring sufficient buffer space. SACK adds 8*n+2 bytes to the TCP header, where n denotes the number of data blocks received, up to 4 blocks. For a low number of out-of-order segments, the header overhead penalty of SACK is compensated by avoiding unnecessary retransmissions.

4.3.2. Delayed Acknowledgments

For certain traffic patterns, Delayed ACKs may have a detrimental effect, as already noted in Section 4.2.3. Advanced TCP stacks may use heuristics to determine the maximum delay for an ACK. For CNNs, the recommendation depends on the expected communication patterns.

When traffic over a CNN is expected to mostly be unidirectional messages with a size typically up to one MSS, and the time between two consecutive message transmissions is greater than the delayed ACK timeout, it may make sense to use a small timeout or disable delayed ACKs at the receiver. This avoids incurring additional delay, as well as the energy consumption of the sender (which might e.g. keep its radio interface in receive mode) during that time. Note that disabling delayed ACKs may only be possible if the peer device is administered by the same entity managing the constrained device. For request-response traffic, enabling delayed ACKs is recommended, in order to allow combining a response with the ACK into a single segment, thus increasing efficiency.

In contrast, Delayed ACKs allow to reduce the number of ACKs in bulk transfer type of traffic, e.g. for firmware/software updates or for transferring larger data units containing a batch of sensor readings.

Note that, in many scenarios, the peer that a constrained device communicates with will be a general purpose system that communicates with both constrained and unconstrained devices. Since delayed ACKs are often configured through system-wide parameters, delayed ACKs

behavior at the peer will be the same regardless of the nature of the endpoints it talks to. Such a peer will typically have delayed ACKs enabled.

5. TCP usage recommendations in CNNs

This section discusses how a TCP stack can be used by applications that are developed for CNN scenarios. These remarks are by and large independent of how TCP is exactly implemented.

5.1. TCP connection initiation

In the constrained device to unconstrained device scenario illustrated above, a TCP connection is typically initiated by the constrained device, in order for this device to support possible sleep periods to save energy.

5.2. Number of concurrent connections

TCP endpoints with a small amount of memory may only support a small number of connections. Each TCP connection requires storing a number of variables in the Transmission Control Block (TCB). Depending on the internal TCP implementation, each connection may result in further memory overhead, and connections may compete for scarce resources (e.g. further memory overhead for send and receive buffers, etc).

A careful application design may try to keep the number of concurrent connections as small as possible. A client can for instance limit the number of simultaneous open connections that it maintains to a given server. Multiple connections could for instance be used to avoid the "head-of-line blocking" problem in an application transfer. However, in addition to comsuming resources, using multiple connections can also cause undesirable side effects in congested networks. For example, the HTTP/1.1 specification encourages clients to be conservative when opening multiple connections [RFC7230]. Furthermore, each new connection will start with a 3-way handshake, therefore increasing message overhead.

Being conservative when opening multiple TCP connections is of particular importance in Constrained-Node Networks.

5.3. TCP connection lifetime

In order to minimize message overhead, it makes sense to keep a TCP connection open as long as the two TCP endpoints have more data to send. If applications exchange data rather infrequently, i.e., if TCP connections would stay idle for a long time, the idle time can

result in problems. For instance, certain middleboxes such as firewalls or NAT devices are known to delete state records after an inactivity interval. RFC 5382 specifies a minimum value for such interval of 124 minutes. A mean TCP NAT binding timeout of 386 minutes has been reported, while in some cases, inactivity timeouts are in the order of a few minutes [HomeGateway]. The timeout duration used by a middlebox implementation may not be known to the TCP endpoints.

In CNNs, such middleboxes may e.g. be present at the boundary between the CNN and other networks. If the middlebox can be optimized for CNN use cases, it makes sense to increase the initial value for filter state inactivity timers to avoid problems with idle connections. Apart from that, this problem can be dealt with by different connection handling strategies, each having pros and cons.

One approach for infrequent data transfer is to use short-lived TCP connections. Instead of trying to maintain a TCP connection for long time, possibly short-lived connections can be opened between two endpoints, which are closed if no more data needs to be exchanged. For use cases that can cope with the additional messages and the latency resulting from starting new connections, it is recommended to use a sequence of short-lived connections, instead of maintaining a single long-lived connection.

The message and latency overhead that stems from using a sequence of short-lived connections could be reduced by TCP Fast Open (TFO) [RFC7413], which is an experimental TCP extension, at the expense of increased implementation complexity and increased TCP Control Block (TCB) size. TFO allows data to be carried in SYN (and SYN-ACK) segments, and to be consumed immediately by the receiving endpoint. This reduces the message and latency overhead compared to the traditional three-way handshake to establish a TCP connection. For security reasons, the connection initiator has to request a TFO cookie from the other endpoint. The cookie, with a size of 4 or 16 bytes, is then included in SYN packets of subsequent connections. The cookie needs to be refreshed (and obtained by the client) after a certain amount of time. Nevertheless, TFO is more efficient than frequently opening new TCP connections with the traditional three-way handshake, as long as the cookie can be reused in subsequent connections. However, as stated in RFC 7413, TFO deviates from the standard TCP semantics, since the data in the SYN could be replayed to an application in some rare circumstances. Applications should not use TFO unless they can tolerate this issue, e.g., by using Transport Layer Security (TLS) [RFC7413]. A comprehensive discussion on TFO can be found at RFC 7413.

Another approach is to use long-lived TCP connections with application-layer heartbeat messages. Various application protocols support such heartbeat messages (e.g. CoAP over TCP [RFC8323]). Periodic application-layer heartbeats can prevent early filter state record deletion in middleboxes. If the TCP binding timeout for a middlebox to be traversed by a given connection is known, middlebox filter state deletion will be avoided if the heartbeat period is lower than the middlebox TCP binding timeout. Otherwise, the implementer needs to take into account that middlebox TCP binding timeouts fall in a wide range of possible values [HomeGateway]. One specific advantage of Heartbeat messages is that they also allow aliveness checks at the application level. In general, it makes sense to realize aliveness checks at the highest protocol layer possible that is meaningful to the application, in order to maximize the depth of the aliveness check. In addition, timely detection of a dead peer may allow savings in terms of TCB memory use. However, the transmission of heartbeat messages consumes resources. This aspect needs to be assessed carefully, considering the characteristics of each specific CNN.

A TCP implementation may also be able to send "keep-alive" segments to test a TCP connection. According to [RFC1122], "keep-alives" are an optional TCP mechanism that is turned off by default, i.e., an application must explicitly enable it for a TCP connection. The interval between "keep-alive" messages must be configurable and it must default to no less than two hours. With this large timeout, TCP keep-alive messages might not always be useful to avoid deletion of filter state records in some middleboxes. However, sending TCP keep-alive probes more frequently risks draining power on energy-constrained devices.

6. Security Considerations

Best current practise for securing TCP and TCP-based communication also applies to CNN. As example, use of Transport Layer Security (TLS) is strongly recommended if it is applicable.

There are also TCP options which can improve TCP security. One example is the TCP Authentication Option (TCP-AO) [RFC5925]. However, this option adds overhead and complexity. TCP-AO typically has a size of 16-20 bytes.

For the mechanisms discussed in this document, the corresponding considerations apply. For instance, if TFO is used, the security considerations of [RFC7413] apply.

Constrained devices are expected to support smaller TCP window sizes than less limited devices. In such conditions, segment

retransmission triggered by RTO expiration is expected to be relatively frequent, due to lack of (enough) duplicate ACKs, especially when a constrained device uses a single-MSS window size. For this reason, constrained devices running TCP may appear as particularly appealing victims of the so-called "shrew" Denial of Service (DoS) attack [shrew], whereby one or more sources generate a packet spike targetted to coincide with consecutive RTO-expiration-triggered retry attempts of a victim node. Note that the attack may be performed by Internet-connected devices, including constrained devices in the same CNN as the victim, as well as remote ones. Mitigation techniques include RTO randomization and attack blocking by routers able to detect shrew attacks based on their traffic pattern.

7. Acknowledgments

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8. Annex. TCP implementations for constrained devices

This section overviews the main features of TCP implementations for constrained devices. The survey is limited to open source stacks with small footprint. It is not meant to be all-encompassing. For more powerful embedded systems (e.g., with 32-bit processors), there are further stacks that comprehensively implement TCP. On the other hand, please be aware that this Annex is based on information available as of the writing.

8.1. uIP

uIP is a TCP/IP stack, targetted for 8 and 16-bit microcontrollers, which pioneered TCP/IP implementations for constrained devices. uIP has been deployed with Contiki and the Arduino Ethernet shield. A code size of ~5 kB (which comprises checksumming, IP, ICMP and TCP) has been reported for uIP [Dunk].

uIP uses the same global buffer for both incoming and outgoing traffic, which has a size of a single packet. In case of a retransmission, an application must be able to reproduce the same user data that had been transmitted. Multiple connections are supported, but need to share the global buffer.

The MSS is announced via the MSS option on connection establishment and the receive window size (of one MSS) is not modified during a connection. Stop-and-wait operation is used for sending data. Among other optimizations, this allows to avoid sliding window operations, which use 32-bit arithmetic extensively and are expensive on 8-bit CPUs.

Contiki uses the "split hack" technique (see Section 4.2.3) to avoid Delayed ACKs for senders using a single segment.

The code size of the TCP implementation in Contiki-NG has been measured to be of 3.2 kB on CC2538DK, cross-compiling on Linux.

8.2. lwIP

lwIP is a TCP/IP stack, targetted for 8- and 16-bit microcontrollers. lwIP has a total code size of ~14 kB to ~22 kB (which comprises memory management, checksumming, network interfaces, IP, ICMP and TCP), and a TCP code size of ~9 kB to ~14 kB [Dunk].

In contrast with uIP, lwIP decouples applications from the network stack. lwIP supports a TCP transmission window greater than a single segment, as well as buffering of incoming and outcoming data. Other implemented mechanisms comprise slow start, congestion avoidance, fast retransmit and fast recovery. SACK and Window Scale support has been recently added to lwIP.

8.3. RIOT

The RIOT TCP implementation (called GNRC TCP) has been designed for Class 1 devices [RFC 7228]. The main target platforms are 8- and 16-bit microcontrollers, with 32-bit platforms also supported. GNRC TCP offers a similar function set as uIP, but it provides and maintains an independent receive buffer for each connection. In

contrast to uIP, retransmission is also handled by GNRC TCP. GNRC TCP uses a single-MSS window size, which simplifies the implementation. The application programmer does not need to know anything about the TCP internals, therefore GNRC TCP can be seen as a user-friendly uIP TCP implementation.

The MSS is set on connections establishment and cannot be changed during connection lifetime. GNRC TCP allows multiple connections in parallel, but each TCB must be allocated somewhere in the system. By default there is only enough memory allocated for a single TCP connection, but it can be increased at compile time if the user needs multiple parallel connections.

The RIOT TCP implementation offers an optional POSIX socket wrapper that enables POSIX compliance, if needed.

Further details on RIOT and GNRC can be found in the literature [RIOT], [GNRC].

8.4. TinyOS

TinyOS was important as platform for early constrained devices. TinyOS has an experimental TCP stack that uses a simple nonblocking library-based implementation of TCP, which provides a subset of the socket interface primitives. The application is responsible for buffering. The TCP library does not do any receive-side buffering. Instead, it will immediately dispatch new, in-order data to the application and otherwise drop the segment. A send buffer is provided by the application. Multiple TCP connections are possible. Recently there has been little further work on the stack.

8.5. FreeRTOS

FreeRTOS is a real-time operating system kernel for embedded devices that is supported by 16- and 32-bit microprocessors. Its TCP implementation is based on multiple-segment window size, although a 'Tiny-TCP' option, which is a single-MSS variant, can be enabled. Delayed ACKs are supported, with a 20-ms Delayed ACK timer as a technique intended 'to gain performance'.

8.6. uC/OS

uC/OS is a real-time operating system kernel for embedded devices, which is maintained by Micrium. uC/OS is intended for 8-, 16- and 32-bit microprocessors. The uC/OS TCP implementation supports a multiple-segment window size.

8.7. Summary

		uIP	lwIP orig	lwIP 2.1	RIOT	TinyOS	FreeRTOS	uC/OS
Memory	Code size(kB)	<5 (a)	~9 to ~14 (T1)	38 (T4)	<7 (T3)	N/A	<9.2 (T2)	N/A
TCP features	Single-Segm.	Yes	No	No	Yes	No	No	No
	Slow start	No	Yes	Yes	No	Yes	No	Yes
	Fast rec/retx	No	Yes	Yes	No	Yes	No	Yes
	Keep-alive	No	No	Yes	No	No	Yes	Yes
	Win. Scale	No	No	Yes	No	No	Yes	No
	TCP timest.	No	No	Yes	No	No	Yes	No
	SACK	No	No	Yes	No	No	Yes	No
	Del. ACKs	No	Yes	Yes	No	No	Yes	Yes
	Socket	No	No	Optional (I)		Subset	Yes	Yes
	Concur. Conn.	Yes	Yes	Yes	Yes	Yes	Yes	Yes
TLS supported		No	No	Yes	Yes	Yes	Yes	Yes

(T1) = TCP-only, on x86 and AVR platforms
(T2) = TCP-only, on ARM Cortex-M platform
(T3) = TCP-only, on ARM Cortex-M0+ platform (NOTE: RAM usage for the same platform is ~2.5 kB for one TCP connection plus ~1.2 kB for each additional connection)
(T4) = TCP-only, on CC2538DK, cross-compiling on Linux
(a) = includes IP, ICMP and TCP on x86 and AVR platforms. The Contiki-NG TCP implementation has a code size of 3.2 kB on CC2538DK, cross-compiling on Linux
(I) = optional POSIX socket wrapper which enables POSIX compliance if needed
Mult. = Multiple
N/A = Not Available

Figure 2: Summary of TCP features for differrent lightweight TCP

implementations. None of the implementations considered in this Annex support ECN or TFO.

9. **Annex.** Changes compared to previous versions

RFC Editor: To be removed prior to publication

9.1. **Changes between -00 and -01**

- Changed title and abstract
- Clarification that communcation with standard-compliant TCP endpoints is required, based on feedback from Joe Touch
- Additional discussion on communication patters
- Numerous changes to address a comprehensive review from Hannes Tschofenig
- Reworded security considerations
- Additional references and better distinction between normative and informative entries
- Feedback from Rahul Jadhav on the uIP TCP implementation
- Basic data for the TinyOS TCP implementation added, based on source code analysis

9.2. **Changes between -01 and -02**

- Added text to the Introduction section, and a reference, on traditional bad perception of TCP for IoT
- Added sections on FreeRTOS and uC/OS
- Updated TinyOS section
- Updated summary table
- Reorganized Section 4 (single-MSS vs multiple-MSS window size), some content now also in new Section 5

9.3. **Changes between -02 and -03**

- Rewording to better explain the benefit of ECN
- Additional context information on the surveyed implementations
- Added details, but removed "Data size" raw, in the summary table

- Added discussion on shrew attacks

9.4. Changes between -03 and -04

- Addressing the remaining TODOs
- Alignment of the wording on TCP "keep-alives" with related discussions in the IETF transport area
- Added further discussion on delayed ACKs
- Removed OpenWSN subsection from the Annex

9.5. Changes between -04 and -05

- Addressing comments by Yoshifumi Nishida
- Removed mentioning MD5 as an example (comment by David Black)
- Added memory footprint details of TCP implementations (Contiki-NG and lwIP 2.1.2) provided by Rahul Jadhav in the Annex
- Addressed comments by Ilpo Jarvinen throughout the whole document
- Improved the RIOT section in the Annex, based on feedback from Emmanuel Baccelli

9.6. Changes between -05 and -06

- Incorporated suggestions by Stuart Cheshire

9.7. Changes between -06 and -07

- Addressed comments by Gorry Fairhurst

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