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Security and Privacy Implications of Numeric Identifiers Employed in
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Abstract

This document performs an analysis of the security and privacy implications of different types of "numeric identifiers" used in IETF protocols, and tries to categorize them based on their interoperability requirements and the associated failure severity when such requirements are not met. It describes a number of algorithms that have been employed in real implementations to meet such requirements and analyzes their security and privacy properties. Additionally, it provides advice on possible algorithms that could be employed to satisfy the interoperability requirements of each identifier type, while minimizing the security and privacy implications, thus providing guidance to protocol designers and protocol implementers. Finally, it provides recommendations for future protocol specifications regarding the specification of the aforementioned numeric identifiers.

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Predictable Numeric IDs

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1. Introduction

Network protocols employ a variety of numeric identifiers for different protocol entities, ranging from DNS Transaction IDs (TxIDs) to transport protocol numbers (e.g. TCP ports) or IPv6 Interface Identifiers (IIDs). These identifiers usually have specific properties that must be satisfied such that they do not result in negative interoperability implications (e.g. uniqueness during a specified period of time), and associated failure severities when such properties are not met, ranging from soft to hard failures.

For more than 30 years, a large number of implementations of the TCP/IP protocol suite have been subject to a variety of attacks, with effects ranging from Denial of Service (DoS) or data injection, to information leakage that could be exploited for pervasive monitoring [[RFC7528](#)]. The root of these issues has been, in many cases, the poor selection of identifiers in such protocols, usually as a result of an insufficient or misleading specification. While it is generally trivial to identify an algorithm that can satisfy the interoperability requirements for a given identifier, there exists practical evidence that doing so without negatively affecting the security and/or privacy properties of the aforementioned protocols is prone to error.

For example, implementations have been subject to security and/or privacy issues resulting from:

- o Predictable TCP sequence numbers
- o Predictable transport protocol numbers
- o Predictable IPv4 or IPv6 Fragment Identifiers
- o Predictable IPv6 IIDs
- o Predictable DNS TxIDs

Recent history indicates that when new protocols are standardized or new protocol implementations are produced, the security and privacy properties of the associated identifiers tend to be overlooked and inappropriate algorithms to generate identifier values are either suggested in the specification or selected by implementors. As a result, we believe that advice in this area is warranted.

This document contains a non-exhaustive survey of identifiers employed in various IETF protocols, and aims to categorize such identifiers based on their interoperability requirements, and the associated failure severity when such requirements are not met. Subsequently, it analyzes several algorithms that have been employed in real implementation to meet such requirements and analyzes their security and privacy properties, and provides advice on possible algorithms that could be employed to satisfy the interoperability requirements of each category, while minimizing the associated security and privacy implications. Finally, it provides recommendations for future protocol specifications regarding the specification of the aforementioned numeric identifiers.

[2.](#) Terminology

Identifier:

A data object in a protocol specification that can be used to definitely distinguish a protocol object (a datagram, network interface, transport protocol endpoint, session, etc) from all other objects of the same type, in a given context. Identifiers are usually defined as a series of bits and represented using integer values. We note that different identifiers may have

additional requirements or properties depending on their specific use in a protocol. We use the term "identifier" as a generic term to refer to any data object in a protocol specification that satisfies the identification property stated above.

Failure Severity:

The consequences of a failure to comply with the interoperability requirements of a given identifier. Severity considers the worst potential consequence of a failure, determined by the system damage and/or time lost to repair the failure. In this document we define two types of failure severity: "soft" and "hard".

Hard Failure:

A hard failure is a non-recoverable condition in which a protocol does not operate in the prescribed manner or it operates with excessive degradation of service. For example, an established TCP connection that is aborted due to an error condition constitutes, from the point of view of the transport protocol, a hard failure,

since it enters a state from which normal operation cannot be recovered.

Soft Failure:

A soft failure is a recoverable condition in which a protocol does not operate in the prescribed manner but normal operation can be resumed automatically in a short period of time. For example, a simple packet-loss event that is subsequently recovered with a retransmission can be considered a soft failure.

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 [RFC 2119](#) [[RFC2119](#)].

[3.](#) Threat Model

Throughout this document, we assume an attacker does not have physical or logical device to the device(s) being attacked. We assume the attacker can simply send any traffic to the target devices, to e.g. sample identifiers employed by such devices.

[4.](#) Issues with the Specification of Identifiers

While assessing protocol specifications regarding the use of identifiers, we found that most of the issues discussed in this document arise as a result of one of the following:

- o Protocol specifications which under-specify the requirements for their identifiers
- o Protocol specifications that over-specify their identifiers
- o Protocol implementations that simply fail to comply with the specified requirements

A number of protocol implementations (too many of them) simply overlook the security and privacy implications of identifiers. Examples of them are the specification of TCP port numbers in [[RFC0793](#)], the specification of TCP sequence numbers in [[RFC0793](#)], or the specification of the DNS TxID in [[RFC1035](#)].

On the other hand, there are a number of protocol specifications that over-specify some of their associated protocol identifiers. For example, [[RFC4291](#)] essentially results in link-layer addresses being embedded in the IPv6 Interface Identifiers (IIDs) when the interoperability requirement of uniqueness could be achieved in other ways that do not result in negative security and privacy implications [[RFC7721](#)]. Similarly, [[RFC2460](#)] suggests the use of a global counter

for the generation of Fragment Identification values, when the interoperability properties of uniqueness per {Src IP, Dst IP} could be achieved with other algorithms that do not result in negative security and privacy implications.

Finally, there are protocol implementations that simply fail to comply with existing protocol specifications. For example, some popular operating systems (notably Microsoft Windows) still fail to implement randomization of transport protocol ephemeral ports, as specified in [[RFC6056](#)].

[5.](#) Timeline of Vulnerability Disclosures Related to Some Sample Identifiers

This section contains a non-exhaustive timeline of vulnerability

disclosures related to some sample identifiers and other work that has led to advances in this area. The goal of this timeline is to illustrate:

- o That vulnerabilities related to how the values for some identifiers are generated and assigned have affected implementations for an extremely long period of time.
- o That such vulnerabilities, even when addressed for a given protocol version, were later reintroduced in new versions or new implementations of the same protocol.
- o That standardization efforts that discuss and provide advice in this area can have a positive effect on protocol specifications and protocol implementations.

5.1. IPv4/IPv6 Identification

December 1998:

[[Sanfilippo1998a](#)] finds that predictable IPv4 Identification values can be leveraged to count the number of packets sent by a target node. [[Sanfilippo1998b](#)] explains how to leverage the same vulnerability to implement a port-scanning technique known as dumb/idle scan. A tool that implements this attack is publicly released.

November 1999:

[[Sanfilippo1999](#)] discusses how to leverage predictable IPv4 Identification to uncover the rules of a number of firewalls.

November 1999:

[[Bellovin2002](#)] explains how the IPv4 Identification field can be exploited to count the number of systems behind a NAT.

December 2003:

[[Zalewski2003](#)] explains a technique to perform TCP data injection attack based on predictable IPv4 identification values which requires less effort than TCP injection attacks performed with bare TCP packets.

November 2005:

[[Silbersack2005](#)] discusses shortcoming in a number of techniques

to mitigate predictable IPv4 Identification values.

October 2007:

[[Klein2007](#)] describes a weakness in the pseudo random number generator (PRNG) in use for the generation of the IP Identification by a number of operating systems.

June 2011:

[[Gont2011](#)] describes how to perform idle scan attacks in IPv6.

November 2011:

Linux mitigates predictable IPv6 Identification values
[[RedHat2011](#)] [[SUSE2011](#)] [[Ubuntu2011](#)].

December 2011:

[[I-D.ietf-6man-predictable-fragment-id-08](#)] describes the security implications of predictable IPv6 Identification values, and possible mitigations.

May 2012:

[[Gont2012](#)] notes that some major IPv6 implementations still employ predictable IPv6 Identification values.

June 2015:

[[I-D.ietf-6man-predictable-fragment-id-08](#)] notes that some popular host and router implementations still employ predictable IPv6 Identification values.

[5.2](#). TCP Initial Sequence Numbers (ISNs)

September 1981:

[[RFC0793](#)], suggests the use of a global 32-bit ISN generator, whose lower bit is incremented roughly every 4 microseconds. However, such an ISN generator makes it trivial to predict the ISN that a TCP will use for new connections, thus allowing a variety of attacks against TCP.

February 1985:

[[Morris1985](#)] was the first to describe how to exploit predictable

TCP ISNs for forging TCP connections that could then be leveraged for trust relationship exploitation.

April 1989:

[[Bellovin1989](#)] discussed the security implications of predictable ISNs (along with a range of other protocol-based vulnerabilities).

February 1995:

[[Shimomura1995](#)] reported a real-world exploitation of the attack described in 1985 (ten years before) in [[Morris1985](#)].

May 1996:

[[RFC1948](#)] was the first IETF effort, authored by Steven Bellovin, to address predictable TCP ISNs. The same concept specified in this document for TCP ISNs was later proposed for TCP ephemeral ports [[RFC6056](#)], TCP Timestamps, and eventually even IPv6 Interface Identifiers [[RFC7217](#)].

March 2001:

[[Zalewski2001](#)] provides a detailed analysis of statistical weaknesses in some ISN generators, and includes a survey of the algorithms in use by popular TCP implementations.

May 2001:

Vulnerability advisories [[CERT2001](#)] [[USCERT2001](#)] are released regarding statistical weaknesses in some ISN generators, affecting popular TCP/IP implementations.

March 2002:

[[Zalewski2002](#)] updates and complements [[Zalewski2001](#)]. It concludes that "while some vendors [...] reacted promptly and tested their solutions properly, many still either ignored the issue and never evaluated their implementations, or implemented a flawed solution that apparently was not tested using a known approach". [[Zalewski2002](#)].

February 2012:

[[RFC6528](#)], after 27 years of Morris' original work [[Morris1985](#)], formally updates [[RFC0793](#)] to mitigate predictable TCP ISNs.

August 2014:

[[I-D.eddy-rfc793bis-04](#)], the upcoming revision of the core TCP protocol specification, incorporates the algorithm specified in [[RFC6528](#)] as the recommended algorithm for TCP ISN generation.

6. Protocol Failure Severity

[Section 2](#) defines the concept of "Failure Severity" and two types of failures that we employ throughout this document: soft and hard.

Our analysis of the severity of a failure is performed from the point of view of the protocol in question. However, the corresponding severity on the upper application or protocol may not be the same as that of the protocol in question. For example, a TCP connection that is aborted may or may not result in a hard failure of the upper application: if the upper application can establish a new TCP connection without any impact on the application, a hard failure at the TCP protocol may have no severity at the application level. On the other hand, if a hard failure of a TCP connection results in excessive degradation of service at the application layer, it will also result in a hard failure at the application.

7. Categorizing Identifiers

This section includes a non-exhaustive survey of identifiers, and proposes a number of categories that can accommodate these identifiers based on their interoperability requirements and their failure modes (soft or hard)

| Identifier | Interoperability Requirements | Failure Severity |
|---------------|--|------------------|
| IPv6 Frag ID | Uniqueness (for IP address pair) | Soft/Hard (1) |
| IPv6 IID | Uniqueness (and constant within IPv6 prefix) (2) | Soft (3) |
| TCP SEQ | Monotonically-increasing | Hard (4) |
| TCP eph. port | Uniqueness (for connection ID) | Hard |
| IPv6 Flow L. | Uniqueness | None (5) |
| DNS TxID | Uniqueness | None (6) |

Table 1: Survey of Identifiers

(1)

While a single collision of Fragment ID values would simply lead to a single packet drop (and hence a "soft" failure), repeated collisions at high data rates might trash the Fragment ID space, leading to a hard failure [[RFC4963](#)].

(2)

While the interoperability requirements are simply that the Interface ID results in a unique IPv6 address, for operational reasons it is typically desirable that the resulting IPv6 address (and hence the corresponding Interface ID) be constant within each network [[I-D.ietf-6man-default-iids](#)] [[RFC7217](#)].

(3)

While IPv6 Interface IDs must result in unique IPv6 addresses, IPv6 Duplicate Address Detection (DAD) [[RFC4862](#)] allows for the detection of duplicate Interface IDs/addresses, and hence such Interface ID collisions can be recovered.

(4)

In theory there are no interoperability requirements for TCP sequence numbers, since the TIME-WAIT state and TCP's "quiet time" take care of old segments from previous incarnations of the connection. However, a widespread optimization allows for a new incarnation of a previous connection to be created if the Initial Sequence Number (ISN) of the incoming SYN is larger than the last sequence number seen in that direction for the previous incarnation of the connection. Thus, monotonically-increasing TCP sequence numbers allow for such optimization to work as expected [[RFC6528](#)].

(5)

The IPv6 Flow Label is typically employed for load sharing [[RFC7098](#)], along with the Source and Destination IPv6 addresses. Reuse of a Flow Label value for the same set {Source Address, Destination Address} would typically cause both flows to be multiplexed into the same link. However, as long as this does not occur deterministically, it will not result in any negative implications.

(6)

DNS TxIDs are employed, together with the Source Address, Destination Address, Source Port, and Destination Port, to match DNS requests and responses. However, since an implementation knows which DNS requests were sent for that set of {Source Address, Destination Address, Source Port, and Destination Port, DNS TxID}, a collision of TxID would result, if anything, in a small performance penalty (the response would be discarded when it

is found that it does not answer the query sent in the corresponding DNS query).

Based on the survey above, we can categorize identifiers as follows:

| Cat # | Category | Sample Proto IDs |
|-------|--|----------------------------------|
| 1 | Uniqueness (soft failure) | IPv6 Flow L., DNS TxIDs |
| 2 | Uniqueness (hard failure) | IPv6 Frag ID, TCP ephemeral port |
| 3 | Uniqueness, constant within context (soft failure) | IPv6 IIDs |
| 4 | Uniqueness, monotonically increasing within context (hard failure) | TCP ISN |

Table 2: Identifier Categories

We note that Category #4 could be considered a generalized case of category #3, in which a monotonically increasing element is added to a constant (within context) element, such that the resulting identifiers are monotonically increasing within a specified context. That is, the same algorithm could be employed for both #3 and #4, given appropriate parameters.

8. Common Algorithms for Identifier Generation

The following subsections describe common algorithms found for Protocol ID generation for each of the categories above.

[8.1.](#) Category #1: Uniqueness (soft failure)

[8.1.1.](#) Simple Randomization Algorithm

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```
/* Ephemeral port selection function */
id_range = max_id - min_id + 1;
next_id = min_id + (random() % id_range);
count = next_id;

do {
    if(check_suitable_id(next_id))
        return next_id;

    if (next_id == max_id) {
        next_id = min_id;
    } else {
        next_id++;
    }

    count--;
} while (count > 0);

return ERROR;
```

Note:

random() is a function that returns a pseudo-random unsigned integer number of appropriate size. Note that the output needs to be unpredictable, and typical implementations of POSIX random()

function do not necessarily meet this requirement. See [[RFC4086](#)] for randomness requirements for security.

The function `check_suitable_id()` can check, when possible, whether this identifier is e.g. already in use. When already used, this algorithm selects the next available protocol ID.

All the variables (in this and all the algorithms discussed in this document) are unsigned integers.

[8.1.2.](#) Another Simple Randomization Algorithm

The following pseudo-code illustrates another algorithm for selecting a random identifier in which, in the event the identifier is found to be not suitable (e.g., already in use), another identifier is selected randomly:

```
id_range = max_id - min_id + 1;
next_id = min_id + (random() % id_range);
count = id_range;

do {
    if(check_suitable_id(next_id))
        return next_id;

    next_id = min_id + (random() % id_range);
    count--;
} while (count > 0);

return ERROR;
```

This algorithm might be unable to select an identifier (i.e., return "ERROR") even if there are suitable identifiers available, when there are a large number of identifiers "in use".

[8.2.](#) Category #2: Uniqueness (hard failure)

One of the most trivial approaches for achieving uniqueness for an identifier (with a hard failure mode) is to implement a linear function. As a result, all of the algorithms described in [Section 8.4](#) are of use for complying the requirements of this identifier category.

[8.3.](#) Category #3: Uniqueness, constant within context (soft-failure)

The goal of this algorithm is to produce identifiers that are constant for a given context, but that change when the aforementioned context changes.

Keeping one value for each possible "context" may in many cases be considered too onerous in terms of memory requirements. As a workaround, the following algorithm employs a calculated technique (as opposed to keeping state in memory) to maintain the constant identifier for each given context.

In the following algorithm, the function `F()` provides (statelessly) a constant identifier for each given context.

```
/* Protocol ID selection function */
id_range = max_id - min_id + 1;

counter = 0;

do {
    offset = F(CONTEXT, counter, secret_key);
    next_id = min_id + (offset % id_range);

    if(check_suitable_id(next_id))
        return next_id;
```

```
        counter++;

    } while (counter <= MAX_RETRIES);

    return ERROR;
```

The function `F()` provides a "per-CONTEXT" constant identifier for a given context. 'offset' may take any value within the storage type range since we are restricting the resulting identifier to be in the range `[min_id, max_id]` in a similar way as in the algorithm described in [Section 8.1.1](#). Collisions can be recovered by incrementing the 'counter' variable and recomputing `F()`.

The function `F()` should be a cryptographic hash function like SHA-256 [[FIPS-SHS](#)]. Note: MD5 [[RFC1321](#)] is considered unacceptable for `F()` [[RFC6151](#)]. CONTEXT is the concatenation of all the elements that define a given context. For example, if this algorithm is expected to produce identifiers that are unique per network interface card (NIC) and SLAAC autoconfiguration prefix, the CONTEXT should be the concatenation of e.g. the interface index and the SLAAC autoconfiguration prefix (please see [[RFC7217](#)] for an implementation of this algorithm for the generation of IPv6 IIDs).

The secret should be chosen to be as random as possible (see [[RFC4086](#)] for recommendations on choosing secrets).

[8.4](#). Category #4: Uniqueness, monotonically increasing within context (hard failure)

[8.4.1](#). Predictable Linear Identifiers Algorithm

One of the most trivial ways to achieve uniqueness with a low identifier reuse frequency is to produce a linear sequence. This obviously assumes that each identifier will be used for a similar period of time.

For example, the following algorithm has been employed in a number of operating systems for selecting IP fragment IDs, TCP ephemeral ports, etc.


```

/* Initialization at system boot time. Could be random */
next_id = min_id;
id_inc= 1;

/* Identifier selection function */
count = max_id - min_id + 1;

do {
    if (next_id == max_id) {
        next_id = min_id;
    }
    else {
        next_id = next_id + id_inc;
    }

    if (check_suitable_id(next_id))
        return next_id;

    count--;
} while (count > 0);

return ERROR;

```

Note:

check_suitable_id() is a function that checks whether the resulting identifier is acceptable (e.g., whether its in use, etc.).

For obvious reasons, this algorithm results in predictable sequences. If a global counter is used (such as "next_id" in the example above), a node that learns one protocol identifier can also learn or guess values employed by past and future protocol instances. On the other hand, when the value of increments is known (such as "1" in this case), an attacker can sample two values, and learn the number of identifiers that were generated in-between.

Where identifier reuse would lead to a hard failure, one typical approach to generate unique identifiers (while minimizing the security and privacy implications of predictable identifiers) is to obfuscate the resulting protocol IDs by either:

- o Replace the global counter with multiple counters (initialized to a random value)

- o Randomizing the "increments"

Avoiding global counters essentially means that learning one identifier for a given context (e.g., one TCP ephemeral port for a given {src IP, Dst IP, Dst Port}) is of no use for learning or guessing identifiers for a different context (e.g., TCP ephemeral ports that involve other peers). However, this may imply keeping one additional variable/counter per context, which may be prohibitive in some environments. The choice of `id_inc` has implications on both the security and privacy properties of the resulting identifiers, but also on the corresponding interoperability properties. On one hand, minimizing the increments (as in "`id_inc = 1`" in our case) generally minimizes the identifier reuse frequency, albeit at increased predictability. On the other hand, if the increments are randomized predictability of the resulting identifiers is reduced, and the information leakage produced by global constant increments is mitigated.

[8.4.2.](#) Per-context Counter Algorithm

One possible way to achieve similar (or even lower) identifier reuse frequency while still avoiding predictable sequences would be to employ a per-context counter, as opposed to a global counter. Such an algorithm could be described as follows:

```
/* Initialization at system boot time. Could be random */
id_inc= 1;

/* Identifier selection function */
count = max_id - min_id + 1;

if(lookup_counter(CONTEXT) == ERROR){
    create_counter(CONTEXT);
}

next_id= lookup_counter(CONTEXT);

do {
    if (next_id == max_id) {
        next_id = min_id;
    }
    else {
        next_id = next_id + id_inc;
    }

    if (check_suitable_id(next_id)){
        store_counter(CONTEXT, next_id);
        return next_id;
    }

    count--;
} while (count > 0);

store_counter(CONTEXT, next_id);
return ERROR;
```

NOTE:

lookup_counter() returns the current counter for a given context, or an error condition if such a counter does not exist.

create_counter() creates a counter for a given context, and initializes such counter to a random value.

store_counter() saves (updates) the current counter for a given

context.

`check_suitable_id()` is a function that checks whether the resulting identifier is acceptable (e.g., whether its in use, etc.).

Essentially, whenever a new identifier is to be selected, the algorithm checks whether there is a counter for the

corresponding context. If there is, such counter is incremented to obtain the new identifier, and the new identifier updates the corresponding counter. If there is no counter for such context, a new counter is created and initialized to a random value, and used as the new identifier.

This algorithm produces a per-context counter, which results in one linear function for each context. Since the origin of each "line" is a random value, the resulting values are unknown to an off-path attacker.

This algorithm has the following drawbacks:

- o If, as a result of resource management, the counter for a given context must be removed, the last identifier value used for that context will be lost. Thus, if subsequently an identifier needs to be generated for such context, that counter will need to be recreated and reinitialized to random value, thus possibly leading to reuse/collision of identifiers.
- o If the identifiers are predictable by the destination system (e.g., the destination host represents the context), a vulnerable host might possibly leak to third parties the identifiers used by other hosts to send traffic to it (i.e., a vulnerable Host B could leak to Host C the identifier values that Host A is using to send packets to Host B). [Appendix A of \[RFC7739\]](#) describes one possible scenario for such leakage in detail.

[8.4.3.](#) Simple Hash-Based Algorithm

The goal of this algorithm is to produce monotonically-increasing sequences, with a randomized initial value, for each given context. For example, if the identifiers being generated must be unique for

each {src IP, dst IP} set, then each possible combination of {src IP, dst IP} should have a corresponding "next_id" value.

Keeping one value for each possible "context" may in many cases be considered too onerous in terms of memory requirements. As a workaround, the following algorithm employs a calculated technique (as opposed to keeping state in memory) to maintain the random offset for each possible context.

In the following algorithm, the function F() provides (statelessly) a random offset for each given context.

```
/* Initialization at system boot time. Could be random. */
counter = 0;

/* Protocol ID selection function */
id_range = max_id - min_id + 1;
offset = F(CONTEXT, secret_key);
count = id_range;

do {
    next_id = min_id +
              (counter + offset) % id_range;

    counter++;

    if(check_suitable_id(next_id))
        return next_id;

    count--;
} while (count > 0);

return ERROR;
```

The function F() provides a "per-CONTEXT" fixed offset within the identifier space. Both the 'offset' and 'counter' variables may take

any value within the storage type range since we are restricting the resulting identifier to be in the range [min_id, max_id] in a similar way as in the algorithm described in [Section 8.1.1](#). This allows us to simply increment the 'counter' variable and rely on the unsigned integer to wrap around.

The function F() should be a cryptographic hash function like SHA-256 [[FIPS-SHS](#)]. Note: MD5 [[RFC1321](#)] is considered unacceptable for F() [[RFC6151](#)]. CONTEXT is the concatenation of all the elements that define a given context. For example, if this algorithm is expected to produce identifiers that are monotonically-increasing for each set (Source IP Address, Destination IP Address), the CONTEXT should be the concatenation of these two values.

The secret should be chosen to be as random as possible (see [[RFC4086](#)] for recommendations on choosing secrets).

It should be noted that, since this algorithm uses a global counter ("counter") for selecting identifiers, if an attacker could, e.g., force a client to periodically establish a new TCP connection to an attacker-controlled machine (or through an attacker-observable routing path), the attacker could substract consecutive source port

values to obtain the number of outgoing TCP connections established globally by the target host within that time period (up to wrap-around issues and five-tuple collisions, of course).

[8.4.4](#). Double-Hash Algorithm

A trade-off between maintaining a single global 'counter' variable and maintaining $2*N$ 'counter' variables (where N is the width of the result of F()) could be achieved as follows. The system would keep an array of TABLE_LENGTH integers, which would provide a separation of the increment of the 'counter' variable. This improvement could be incorporated into the algorithm from [Section 8.4.3](#) as follows:

```
/* Initialization at system boot time */
for(i = 0; i < TABLE_LENGTH; i++)
    table[i] = random();

id_inc = 1;
```

```

/* Protocol ID selection function */
id_range = max_id - min_id + 1;
offset = F(CONTEXT, secret_key1);
index = G(CONTEXT, secret_key2);
count = id_range;

do {
    next_id = min_id + (offset + table[index]) % id_range;
    table[index] = table[index] + id_inc;

    if(check_suitable_id(next_id))
        return next_id;

    count--;

} while (count > 0);

return ERROR;

```

'table[]' could be initialized with random values, as indicated by the initialization code in pseudo-code above. The function G() should be a cryptographic hash function. It should use the same CONTEXT as F(), and a secret key value to compute a value between 0 and (TABLE_LENGTH-1). Alternatively, G() could take an "offset" as input, and perform the exclusive-or (XOR) operation between all the bytes in 'offset'.

The array 'table[]' assures that successive identifiers for a given context will be monotonically-increasing. However, the increments space is separated into TABLE_LENGTH different spaces, and thus identifier reuse frequency will be (probabilistically) lower than that of the algorithm in [Section 8.4.3](#). That is, the generation of identifier for one given context will not necessarily result in increments in the identifiers for other contexts.

It is interesting to note that the size of 'table[]' does not limit the number of different identifier sequences, but rather separates the *increments* into TABLE_LENGTH different spaces. The identifier sequence will result from adding the corresponding entry of 'table[]'

to the variable 'offset', which selects the actual identifier sequence (as in the algorithm from [Section 8.4.3](#)).

An attacker can perform traffic analysis for any "increment space" into which the attacker has "visibility" -- namely, the attacker can force a node to generate identifiers where $G(\text{offset})$ identifies the target "increment space". However, the attacker's ability to perform traffic analysis is very reduced when compared to the predictable linear identifiers (described in [Section 8.4.1](#)) and the hash-based identifiers (described in [Section 8.4.3](#)). Additionally, an implementation can further limit the attacker's ability to perform traffic analysis by further separating the increment space (that is, using a larger value for `TABLE_LENGTH`) and/or by randomizing the increments.

[8.4.5](#). Random-Increments Algorithm

This algorithm offers a middle ground between the algorithms that select ephemeral ports randomly (such as those described in [Section 8.1.1](#) and [Section 8.1.2](#)), and those that offer obfuscation but no randomization (such as those described in [Section 8.4.3](#) and [Section 8.4.4](#)).

```
/* Initialization code at system boot time. */
next_id = random();          /* Initialization value */
id_inc = 500;                /* Determines the trade-off */

/* Identifier selection function */
```



```

id_range = max_id - min_id + 1;

count = id_range;

do {
    /* Random increment */
    next_id = next_id + (random() % id_inc) + 1;

    /* Keep the identifier within acceptable range */
    next_id = min_id + (next_id % id_range);

    if(check_suitable_id(next_id))
        return next_id;

    count--;
} while (count > 0);

return ERROR;

```

This algorithm aims at producing a monotonically increasing sequence of identifiers, while avoiding the use of fixed increments, which would lead to trivially predictable sequences. The value "id_inc" allows for direct control of the trade-off between the level of obfuscation and the ID reuse frequency. The smaller the value of "id_inc", the more similar this algorithm is to a predictable, global monotonically-increasing ID generation algorithm. The larger the value of "id_inc", the more similar this algorithm is to the algorithm described in [Section 8.1.1](#) of this document.

When the identifiers wrap, there is the risk of collisions of identifiers (i.e., identifier reuse). Therefore, "id_inc" should be selected according to the following criteria:

- o It should maximize the wrapping time of the identifier space.
- o It should minimize identifier reuse frequency.
- o It should maximize obfuscation.

Clearly, these are competing goals, and the decision of which value of "id_inc" to use is a trade-off. Therefore, the value of "id_inc"

should be configurable so that system administrators can make the trade-off for themselves.

[9.](#) Common Vulnerabilities Associated with Identifiers

This section analyzes common vulnerabilities associated with the generation of identifiers for each of the categories identified in [Section 7](#).

[9.1.](#) Category #1: Uniqueness (soft failure)

Possible vulnerabilities associated with identifiers of this category are:

- o Use of trivial algorithms (e.g. global counters) that generate predictable identifiers
- o Use of flawed PRNGs.

Since the only interoperability requirement for these identifiers is uniqueness, the obvious approach to generate them is to employ a PRNG. An implementer should consult [\[RFC4086\]](#) regarding randomness requirements for security, and consult relevant documentation when employing a PRNG provided by the underlying system.

Use algorithms other than PRNGs for generating identifiers of this category is discouraged.

[9.2.](#) Category #2: Uniqueness (hard failure)

As noted in [Section 8.2](#) this category typically employs the same algorithms as Category #4, since a monotonically-increasing sequence tends to minimize the identifier reuse frequency. Therefore, the vulnerability analysis of [Section 9.4](#) applies to this case.

[9.3.](#) Category #3: Uniqueness, constant within context (soft failure)

There are two main vulnerabilities that may be associated with identifiers of this category:

1. Use algorithms or sources that result in predictable identifiers
2. Employing the same identifier across contexts in which constantcy is not required

At times, an implementation or specification may be tempted to employ a source for the identifier which is known to provide unique values. However, while unique, the associated identifiers may have other

properties such as being predictable or leaking information about the node in question. For example, as noted in [\[RFC7721\]](#), embedding link-layer addresses for generating IPv6 IIDs not only results in predictable values, but also leaks information about the manufacturer of the network interface card.

On the other hand, using an identifier across contexts where constantcy is not required can be leveraged for correlation of activities. One of the most trivial examples of this is the use of IPv6 IIDs that are constant across networks (such as IIDs that embed the underlying link-layer address).

[9.4.](#) Category #4: Uniqueness, monotonically increasing within context (hard failure)

A simple way to generalize algorithms employed for generating identifiers of Category #4 would be as follows:

```
/* Identifier selection function */
count = max_id - min_id + 1;

do {
    linear(CONTEXT)= linear(CONTEXT) + increment();
    next_id= offset(CONTEXT) + linear(CONTEXT);

    if(check_suitable_id(next_id))
        return next_id;

    count--;
} while (count > 0);

return ERROR;
```

Essentially, an identifier (`next_id`) is generated by adding a linear function (`linear()`) to an offset value, which is unknown to the attacker, and constant for given context.

The following aspects of the algorithm should be considered:

- o For the most part, it is the `offset()` function that results in identifiers that are unpredictable by an off-path attacker. While

the resulting sequence will be monotonically-increasing, the use of an offset value that is unknown to the attacker makes the resulting values unknown to the attacker.

- o The most straightforward "stateless" implementation of offset would be that in which offset() is the result of a

cryptographically-secure hash-function that takes the values that identify the context and a "secret" (not shown in the figure above) as arguments.

- o Another possible (but stateful) approach would be to simply generate a random offset and store it in memory, and then look-up the corresponding context when a new identifier is to be selected. The algorithm in [Section 8.4.2](#) is essentially an implementation of this type.
- o The linear function is incremented according to increment(). In the most trivial case increment() could always return the constant "1". But it could also possibly return small integers such the increments are randomized.

Considering the generic algorithm illustrated above we can identify the following possible vulnerabilities:

- o If the offset value spans more than the necessary context, identifiers could be unnecessarily predictable by other parties, since the offset value would be unnecessarily leaked to them. For example, an implementation that means to produce a per-destination counter but replaces offset() with a constant number (i.e., employs a global counter), will unnecessarily result in predictable identifiers.
- o The function linear() could be seen as representing the number of identifiers that have so far been generated for a given context. If linear() spans more than the necessary context, the "increments" could be leaked to other parties, thus disclosing information about the number of identifiers that have so far been generated. For example, an implementation in which linear() is implemented as a single global counter will unnecessarily leak information the number of identifiers that have been produced.

- o `increment()` determines how the `linear()` is incremented for each identifier that is selected. In the most trivial case, `increment()` will return the integer "1". However, an implementation may have `increment()` return a "small" integer value such that even if the current value employed by the generator is guessed (see [Appendix A of \[RFC7739\]](#)), the exact next identifier to be selected will be slightly harder to identify.

[10.](#) Security and Privacy Requirements for Identifiers

Protocol specifications that specify identifiers should:

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1. Clearly specify the interoperability requirements for selecting the aforementioned identifiers.
2. Provide a security and privacy analysis of the aforementioned identifiers.
3. Recommend an algorithm for generating the aforementioned identifiers that mitigates security and privacy issues, such as those discussed in [Section 9](#).

[11.](#) IANA Considerations

There are no IANA registries within this document. The RFC-Editor can remove this section before publication of this document as an RFC.

[12.](#) Security Considerations

The entire document is about the security and privacy implications of identifiers.

[13.](#) Acknowledgements

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