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A Reference for Randomness Beacons

Format and Protocol Version 2

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National Institute of
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Reports on Computer Systems Technology

The Information Technology Laboratory (ITL) at the National Institute of Standards and Technology (NIST) promotes the U.S. economy and public welfare by providing technical leadership for the Nation's measurement and standards infrastructure. ITL develops tests, test methods, reference data, proof of concept implementations, and technical analyses to advance the development and productive use of information technology. ITL's responsibilities include the development of management, administrative, technical, and physical standards and guidelines for the cost-effective security and privacy of other than national security-related information in federal information systems.

Abstract

A randomness beacon produces timed outputs of fresh public randomness. Each output, called a pulse, also includes metadata and cryptographic elements to support several security and usability features. This document specifies a reference "version 2" of a format for pulses and of a protocol for beacon operations. The main goal of the description is to serve as a baseline for the deployment of numerous interoperable beacons, including the NIST Beacon. In the proposed reference, a Beacon periodically outputs a pulse containing 512 fresh random bits, time-stamped, signed and hash-chained. For example, each pulse also pre-commits to the randomness to be released in the next pulse. The latter enables users to securely combine randomness from different beacons. The Beacon protocol also specifies the interface for users to interact with the Beacon, in order to obtain information about past pulses.

Keywords: cryptography; public randomness; beacons; hash chaining; timestamping; auditability; unpredictability.

Acknowledgments

This reference document is an output of the NIST Beacon project, which started in 2011. Ron Rivest played an important early role in motivating the creation of the project, by pointing out to NIST that a public source of randomness could be valuable for auditing voting machines. Michael Fischer was a valuable early collaborator in thinking about a theoretical framework for public randomness. Andrew Regenscheid provided valuable administrative and technical support to the project. Overall, the NIST Beacon project has motivated several outputs, by the Information Technology Laboratory (ITL) and the Physics Measurement Laboratory (PML), involving collaboration from various NIST members, including Michael Bartock, Lawrence E. Bassham, Joshua Bienfang, Peter L. Bierhorst, Thomas Gerrits, Scott C. Glancy, Michaela Iorga, Emanuel H. Knill, Paulina Kuo, Alan Migdall, Carl A. Miller, Sae Woo Nam, Andrew Rukhin, Krister Shalm, and Michael Wayne. These outputs include the deployment of a prototype NIST randomness Beacon in 2013 (version 1), the experimental validation of Bell inequalities (a loophole-free Bell test experiment) in 2015, the development in 2017 of a random-number generator based on probabilities of quantum photon detection, the upgrade of the NIST randomness Beacon implementation in 2018 (version 2). The development of the present document benefited from the context of the NIST Beacon project. In turn, we expect this reference document to advance the development of technology related to the support of public randomness for privacy and auditability applications of societal benefit.

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Executive Summary

A "randomness beacon" is a timed source of public randomness. It pulsates fresh randomness at expected times, making it available to the public. This can for example consist of timely generating and storing random values, timestamped, signed and hash-chained, in a publicly readable database. Thereafter, any external user can freely retrieve, via database queries, any past pulse (and additional associated data). This document puts forward a *reference* (version 2) for randomness beacons, defining a *format* for pulses and a *protocol* for beacon operations. The goal is to promote the development of an ecosystem of interoperable beacons. This reference is labeled as "version 2" for distinction from the initial format (version 1) used by the NIST Randomness Beacon prototype deployed in 2013.

The development of trustworthy sources of public randomness will enable applications and services of societal benefit. Beacons offer the potential to improve fairness, auditability and efficiency in numerous societal applications that require randomness. Examples include selection of control groups for clinical trials, random assignment of court cases to judges and drawing the winning numbers in public lotteries. A notable benefit of using public randomness is in enabling after-the-fact verifiability, for the purpose of public transparency. If an unforgeable transcript of interactions is available, then parties not involved in a randomized procedure can still later check that the used randomness was fresh at the appropriate time. Another benefit is the reduction of interaction complexity in multi-party protocols.

As an example, suppose that a quality-control audit requires testing items randomly sampled from a set. If this procedure is in place to test potential falsification of products, then it is essential that the sample be unpredictable. Otherwise, a malicious producer that would be able to predict the sample would also be able to pass the test while falsifying in advance all non-sampled items. There would also be problems if a malicious auditor could undetectably control the sample outcome. Such auditor could then, while claiming having sampled uniformly at random, bias the process into either detecting too few or too many faulty items (if having help from an insider). In general, many processes involving random sampling can be made more robust, trustworthy and verifiable by using a public source of randomness.

The present reference proposes a randomness Beacon that outputs at predictable moments in time a pulse containing 512 unpredictable bits of fresh randomness. The usefulness of those pulses is enhanced by a number of auxiliary features. An important one is the hash-chaining structure that ensures that a sequence of pulses constitutes an immutable history. Specifically, a cryptographic hash of each pulse is bound to the next pulse by means of an unforgeable digital signature. This means that for each pulse there is a single sequence of previous pulses that the beacon database is able to reveal as consistent past history. Since the signature is based on public-key cryptography, even an off-line party can verify and prove the authenticity of a possessed pulse or sequence thereof.

A recurring guiding question in the development of the present reference has been: to which extent should external parties place trust on the beacon, and which properties can they verify? The designed pulse format and beacon protocol facilitates several features for

security and envisioned applications. For example, the new design facilitates the distribution of trust across beacons. The idea is to allow users to obtain trustworthy randomness by securely combining the randomness from several beacons. The user can get a *good* random value even if a single beacon is honest and all other beacons are malicious. For this purpose, the new format adds fields that enable a beacon to cryptographically commit, in each pulse, to a local random value that is only revealed in the subsequent pulse. If all beacons produce their pulses at the minute mark, then they have to choose their random value before seeing the respective random value of the others. This allows users to obtain a final random string with security assurances similar to what would be obtained through a secure *coin-tossing* protocol.

Another enhancement is the use of a *skiplist* structure, allowing a more efficient verification of linkage between two pulses with distant timestamps. In a simple hash chain, such verification required analyzing all intermediate pulses, e.g., more than two million pulses between 2013 and 2018. In the new structure (version 2) fewer than 200 pulses are sufficient to check the linkage between any two pulses originated with a time separation of 50 years.

The new format also provisions, by means of a uniform resource identifier (URI) field, the original source of pulses and the identification of the Beacon authority. This is aligned with another goal of this document — to promote that several beacons co-exist as separate administrative identities, including across different countries. An essential goal of this document is to promote interoperability across beacons. For example, the timestamp of pulses is now encoded (up to milliseconds precision) in Universal Time Coordinated (UTC) format, to facilitate comparison of timestamps independently of local timezones.

Applications of a public randomness require a number of security and cryptographic guarantees. For better trustworthiness, a main challenge is enhancing security against insider threats. For example, it is important to mitigate the possibility of pre-calculation of an unbounded number of pulses by a malicious beacon operator. Version 2 provides a new layer of prevention against this, by provisioning in the new pulse format the insertion of unpredictable external values. Scheduling such insertions technically prevents, before each external value is known, advance calculation of pulses with timestamps beyond the time of insertion.

Other security aspects are not externally verifiable but warrant appropriate care. For example, the internal clock must be well synchronized with global UTC time to ensure timely generation and release of calculated randomness. As another example, the pulse randomness must be obtained by a proper cryptographic combination and transformation of the output of more than one random number generator (RNG). This mitigates the otherwise adverse consequences that would arise from a single RNG being compromised. These operational protocol aspects that are not externally verifiable are sometimes called beacon *promises*.

The interoperability goal also includes allowing users to interact similarly with different beacons. For this purpose, this document also specifies a set of core interface rules defining how external users can query the beacon database. The beacon web frontend is assumed to have a interface that translates well-formed URIs into respective database queries, which then elicit replies. This allows users to obtain previously generated pulses, or sequences thereof, as well as system values not in pulses (e.g., public verification keys and certificates).

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1 Introduction

This document defines a *reference* for randomness beacons. At high level, a randomness beacon is a service that regularly outputs randomness, along with cryptographically associated metadata, including timestamps and cryptographic signatures. Each output of a beacon is called a *pulse*. A chronological sequence of pulses with certain semantic relations is called a *chain*. Within the context of a chain in a beacon, an individual pulse can be unequivocally identified by the value in some of its fields, e.g., by the timestamp (in `timeStamp`) or by the pulse index (in `pulseIndex`).

Defining a beacon involves describing the *format* for pulses and a corresponding *protocol* for beacon operations. NIST deployed in 2013 an initial beacon prototype (version 1). In comparison, this document describes a *reference*, called version 2, that uses a new *format* and *protocol* for randomness beacons. Interoperability advantages are expected to arise from having several administratively independent beacons adhere to this new reference.

The *format* defines the fields in pulses and their configuration. Knowledge of the format is needed by users to correctly interpret the information contained in pulses and to verify their correctness. External users can verify whether or not the beacon is following the format.

The *protocol* consists of operational guidelines. Some relate to the secure and timely *generation* of pulses by the beacon, to ensure good quality randomness output, e.g., fresh and unpredictable (with full entropy). Other guidelines relate to the *timely* release of generated pulses to a publicly readable database. The adherence by the beacon to some of these guidelines is not externally verifiable. Some of those unverifiable protocol guidelines can be called *promises*. There are also guidelines specifying the interface calls (a.k.a. queries) that enable external users to perform (e.g., web based) efficient *retrieval* of past pulses (and associated information).

1.1 Related work

Randomness beacons were proposed by Rabin in 1983 [Rab83], as a way to implement certain cryptographic applications. In a simple version, the beacon would periodically pulsate a timestamped and signed integer. Such integers could be used for contract signing between several parties. For more complex applications, such as "confidential disclosures", a beacon would pulsate a sequence of n random public keys and, at a latter time, would reveal only one of the respective private keys.

Public randomness can be useful in cryptography [HL93]. Over the years, public randomness beacons have been considered for various other cryptographic applications, e.g., traceable signatures [KTY04], voting protocols [MN10], currency mixes for anonymous payments in cryptocurrencies [BNM$^+$14].

It is often possible to replace the beacon by well-studied cryptographic primitives from the areas of zero-knowledge proofs and secure multiparty computation. However, a trusted randomness beacon remains useful as a facilitator of practical protocols with reduced interaction between many parties, as well as of public verifiability of randomized procedures.

Several works have looked at providing public randomness based on decentralized sources of entropy e.g., based on atmospheric noise [Haa18], financial data [CH10], crypto-currencies [BCG15], and lotteries [BDF+15].

A major concern with public sources of randomness is trust. How to know if a beacon is trustworthy? From a user perspective, a way to avoid trusting a single beacon is to use randomness determined by different beacons. This is conceptually similar to the idea of using randomness from two parties to ensure a secure coin-flipping [Blu81]. Recent works have demonstrated the ability to implement systems composed of a secure combination of randomness from many beacons, where some can be malicious (including aborting). Examples of these systems include RandHerd and RandHound [SJK+17], SCRAPE [CD17], and HydRand [SJSW18].

Version 1 of the NIST Randomness Beacon was active as an online prototype starting September 05, 2013 [NIS18]. It outputted a string of 512 random bits per minute, along with metadata that included a time-stamp and signature. This is conceptually close to the first type of beacon described by Rabin, since it generates uniform numbers that are timestamped and signed. Version 2 of the NIST Randomness Beacon uses the new format that is described in this document. Pulses in the new format contain additional fields. For example, Version 2 pulses contain fields enabling secure coin-tossing based on randomness from various beacons. Other randomness beacon projects, external to NIST, will implement beacons that are interoperable with Version 2. These include projects in Chile [CLC18] and in Brazil [INM18].

1.2 Recommendations and requirements

This document provides some guidance promoting interoperable Beacon implementations. The guidance includes *recommendations* and *requirements* related to the reference for Randomness Beacons put forward. These are sometimes expressed using terms formatted in small caps and bold weight, with special meaning as follows:

- "**SHALL**" and "**SHALL NOT**" indicate requirements to be followed strictly in order to conform to the publication and from which no deviation is permitted;
- "**SHOULD**" and "**SHOULD NOT**" indicate that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others, or that a certain course of action is preferred but not necessarily required, or that (in the negative form) a certain possibility or course of action is discouraged but not prohibited.
- "**MAY**" and "**NEED NOT**" indicate a course of action permissible within the limits of the publication.

- "**CAN**" and "**CANNOT**" indicate a possibility and capability, whether material, physical or causal.

1.3 Version numbering

This document covers the version 2 of the Beacon reference. We specify as "2.0.0" the detailed version number of the current reference. Future non-major updates of this reference **SHOULD** update the version to "2.y.z" (where y and z are non-negative integers). Those potential future revisions **SHOULD** be defined within revisions of this NISTIR document or related official documentation.

Incrementing z (starting at 0 for each new y) **SHALL** correspond to simple patches that do not break any handling of previous pulses, and which do not require reinitializing any ongoing chain. For example, this **CAN** be from assigning a new cryptographic primitive to a previously non-assigned value in the `cipherSuite` field, by requiring support to new interface calls, or by defining for the `status` field the meaning of previously undefined bit-flags (without deprecating existing ones).

We say that a simple increment of z corresponds to a sub-version update, which does not require being reflected within the `version` field of a pulse, which only show the version up to the y level, i.e., "2.y" (e.g., "2.0"), omitting z.

Incrementing y (e.g., going from version "2.0.z" to "2.1.0") **SHALL** correspond to changes that require distinct handling across values y. This **CAN** be for example from adding a new field of required parsing by the signature algorithm, by changing the way an existing field is calculated, or changing the handling of some previously defined bit flag in the `statusCode` field.

1.4 Note to Reviewers

We seek constructive feedback from interested parties, including about the specification of pulse format, cryptographic primitives, interface calls, applications, recommendations and requirements, security analysis, terminology, and related-work references.

1.5 Document structure

The remainder of the document is organized as follows: Section 2 defines terminology and notation. Section 3 overviews the beacon protocol and the pulse fields. Section 4 specifies in detail all the fields of a pulse. Section 5 explains the hash-chaining of pulses and the corresponding skiplists. Section 6 describes the interface that allows users to obtain past pulses and associated data. Section 7 provides guidelines for using beacon randomness, including how to combine randomness from several beacons. Section 8 makes a security analysis. Section 9 mentions some aspects open to consideration with respect to additional functionality and changes in format.

2 Terminology and notation

This section defines terminology and notation that will be used throughout this document.

2.1 Terminology

The term *Beacon* denotes the service that provides timestamped, signed and hash-chained random numbers. Figure 1 illustrates, at a high level, the components of a beacon:

1. *(beacon) engine* — The internal parts of the beacon service where the actual pulses are formed. This is a computer with well-defined physical boundaries. It includes an internal clock, and internal RNG and the capabilities needed to run the "Beacon App" software. These parts are not accessible to the outside.

2. *(web) frontend* — The public-facing parts of the beacon, providing a web interface to answer requests of information stored in a database (DB). All past pulses, and certain associated data, are stored in the DB.

3. *hardware security module* (HSM) — A device independent from the beacon engine, safeguarding cryptographic keys and performing cryptographic operations.

4. *random number generator* (RNG) — A hardware-based generator of true random numbers. At least two RNGs **SHALL** be used in a randomness beacon, and at least one **SHOULD** be independent of the Beacon engine. Additional RNGs **MAY** be used.

The following terms relate directly to the generation of pulses:

- *pulse* — The periodic message output from a beacon, which contains a timestamp, a signature, and a random number, among other fields (described in Section 4).

- *chain* — A sequence of hash-chained pulses, produced consecutively, with a fixed chain index and increasing pulse index. All pulses in a chain follow the same format.

- *period* — The fixed time window between expected consecutive pulses in a chain. For the current NIST Beacon this is one minute (specified as 60,000 milliseconds).

- *gap* — A time interval during which one or more regularly-scheduled pulses were not produced by the beacon, presumably due to some kind of outage.

2.2 Notation for pulses and fields

A pulse from a beacon and within a chain. The symbol P is used to denote a pulse. In examples hereafter, the beacon authority and the scope of a chain are often left implicit.

Field names. A pulse is composed of several fields. The expression $P.\langle \textit{fieldname} \rangle$ represents the value in field $\langle \textit{fieldname} \rangle$ of pulse P. Text in monospaced font type (teletype) is

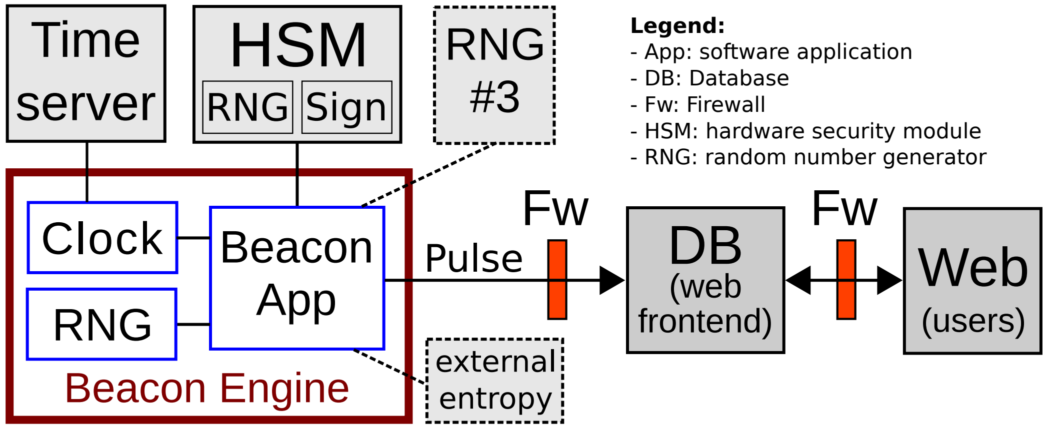


Figure 1. Beacon service components

used for concrete field names, e.g., `pulseIndex`, `timeStamp` and `localRandomValue`. For example, P.`pulseIndex` is the pulse index of pulse P.

Pulses identified by index. When the beacon authority (e.g., A) and the chain (e.g., j) are clear or implicit in the context, pulses **CAN** be identified via the pulse index i. For example, P_i is the i^{th} pulse in the chain. Pulse indices are consecutive positive integers, starting with 1, implying $P_i.\texttt{pulseIndex} = i$. There are never gaps of pulse indices within the same chain, so if a pulse P_i exists for some $i \geq 2$, then P_{i-1} also exists. Since `pulseIndex` is a unique identifier of a pulse (within a chain and within a beacon domain), we **CAN** use $\langle \textit{fieldname} \rangle_i$ (e.g., $\texttt{timeStamp}_i$) as an abbreviation to denote $P_i.\langle \textit{fieldname} \rangle$.

Pulses identified by timestamp. $P[T]$ denotes the pulse P with a timestamp T, i.e., satisfying $P.\texttt{timeStamp} = T$, indicating the time promised by the Beacon to not have yet released the pulse. T does not necessarily represent the exact release time (see Section 3.3). The abbreviation $\langle \textit{fieldname} \rangle [T]$ (e.g., $\texttt{outputValue}[T]$) denotes the value $P[T].\langle \textit{fieldname} \rangle$.

Timestamps are represented as byte strings, using the format described in RFC3339 [NK02]. For example, 2018-07-23T19:26:00.000Z represents the time-of-day equal to 19 hours, 26 minutes, 0 seconds and 0 milliseconds in the 23^{rd} day of July of the year 2018.

Different beacons and chains. The distinction of pulses from different beacons and/or different chains **CAN** be made via indices in the pulse symbol P. For example, $P_A[T]$ and $P_B[T]$ represent two pulses from beacons A and B, respectively, both associated with the same timestamp T. Several indices **CAN** be used concurrently, e.g., $P_{A,j,i}$ denotes the i^{th} pulse in the j^{th} chain of beacon A.

3 Protocol and pulse fields

There are many things a beacon operator needs to do in order to provide a useful Beacon. We partition the beacon-protocol guidelines into two main categories of operation:

1. *generation and release of pulses* — related to computation and release of pulses **by the Beacon engine**; this part of the protocol deals with verifiable properties of the format of pulses and relations between pulses (Section 3.1), as well as with externally-unverifiable *promises* (Section 3.3), and other *recommendations* (Section 3.5).
2. *retrieval* (interface) — related to user *interface* at the web-frontend (see Section 3.6).

Some aspects introduced in this section are further detailed in later sections, e.g., the pulse format (Section 4) and the retrieval interface (Sections 5 and 6). Certain aspects of implementation security outside the scope of this section are described as an operational baseline in Section 8.2.

3.1 Pulse fields

The NIST Beacon pulse format 2.0 includes the following 21 fields:

F_1. `uri` — a uniform resource identifier (URI) that uniquely identifies the pulse;

F_2. `version` — the version of the beacon format being used;

F_3. `cipherSuite` — the ciphersuite (set of cryptographic algorithms) being used;

F_4. `period` — the number (denoted by π) of milliseconds between the timestamps of this pulse and the expected subsequent pulse;

F_5. `certificateId` — the hash of the certificate that allows verifying the signature in the pulse; the full certificate must be available via the website of the beacon;

F_6. `chainIndex` — the chain index (integer identifier, starting at 1) of the chain to which the pulse belongs;

F_7. `pulseIndex` — the pulse index (integer identifier, starting at 1), conveying the order of generation of this pulse within its chain;

F_8. `timeStamp` — the time (UTC) of pulse release by the Beacon Engine (the actual release time **MAY** be slightly larger, but **SHALL NOT** be smaller);

F_9. `localRandomValue` — the `hash()` of two or more high-quality random bit sources; (For all practical purposes, it is expected to have full entropy; in rigor it **MAY** forfeit up to less than one bit of entropy, while indistinguishable from uniformly random.)

F_{10}. `external.sourceId` — the `hash()` of a text description of the source of the external value, or an all-zeros byte string (with exactly $hLB = \lceil |hash()|/8 \rceil$ bytes) if there is no external value;

F_{11}. `external.statusCode` — the status of the external value;

F_{12}. `external.value` — the `hash()` of an external value, drawn from a verifiable external source from time to time, or an all-zeros string if there is no external value;

F_{13}. `previous` — the `outputValue` of the **previous** pulse;

F_{14}. `hour` — the `outputValue` of the first pulse in the (UTC) **hour** of the previous pulse;

F_{15}. `day` — the `outputValue` of the first pulse in the (UTC) **day** of the previous pulse;

F_{16}. `month` — the `outputValue` of the first pulse in the (UTC) **month** of the previous pulse;

F_{17}. `year` — the `outputValue` of the first pulse in the (UTC) **year** of the previous pulse;

F_{18}. `precommitmentValue` — the `hash()` of the *next* pulse's `localRandomValue`;

F_{19}. `statusCode` — the status of the chain at this pulse;

F_{20}. `signatureValue` — a `signature` on all the above fields;

F_{21}. `outputValue` — the `hash()` of all the above fields.

Field names, types and aliases. Table 1 lists all field names and their types. Field names just serve a labeling purpose, not being used as input to computation (e.g., hash or signature) of any pulse field. The table also defines aliases used for conciseness in this document.

Table 1. Field names, aliases and types

#	Default name	Alias	Default type
F_1	`uri`		uriStr
F_2	`version`		verStr
F_3	`cipherSuite`	`cipher`	uint32
F_4	`period`		uint32
F_5	`certificateId`	`certId`	hashOut
F_6	`chainIndex`	`chainId`	uint64
F_7	`pulseIndex`	`pulseId`	uint64
F_8	`timeStamp`	`time`	dateStr
F_9	`localRandomValue`	`randLocal`	hashOut
F_{10}	`external.sourceId`	`ext.srcId`	hashOut
F_{11}	`external.statusCode`	`ext.status`	uint64
F_{12}	`external.value`	`ext.value`	hashOut
F_{13}	`previous`	`out.Prev`	hashOut
F_{14}	`hour`	`out.H`	hashOut
F_{15}	`day`	`out.D`	hashOut
F_{16}	`month`	`out.M`	hashOut
F_{17}	`year`	`out.Y`	hashOut
F_{18}	`precommitmentValue`	`preCom`	hashOut
F_{19}	`statusCode`	`status`	uint32
F_{20}	`signatureValue`	`sig`	sigOut
F_{21}	`outputValue`	`randOut`	hashOut

"uriStr", "verStr" and "dateStr" denote UTF8 character strings with respective structural restrictions to URI, version number and UTC date. "uint32" and "uint64" respectively denote 32-bit and 64-bit unsigned integers.

Data types. A *pulse* is a structure composed of 21 fields, of which: eleven (11) are hash outputs; one (1) is a signature output; three (3) are characters strings; three (3) are unsigned integers; three (3) are bit-flag sequences or value-sets also fitting within an unsigned integer.

Fields have further associated structure. For example, "dateStr" is a character-string type that must be specified within the UTC format and incorporates an implicit *linear order* ($\leq$) that allows chronological comparison of any two timestamps.

The indication of default data types in Table 1 serves an informative purpose, but the field values **CAN** be represented in various ways depending on the purpose. For example, when performing serialization, "hashOut" (for hash outputs) and "sigOut" (for signature output) **CAN** both be converted to byte string format (Byt) when used for hashing, or to hexadecimal format (hex) when output within a MIME type text/plain document.

Section 4.1 discusses in more detail the field types and data representations.

3.2 Relations of field values within each chain

The pulses within each chain must satisfy formatting and relational rules (further detailed along Section 4).

Constant or incremental fields. For example, the following short identities hold:

- $\text{pulseId}_{i+i} = \text{pulseId}_i + 1 = i + 1$ (each new pulse increments the pulse index by 1);
- $\texttt{out.Prev}_i = \texttt{randOut}_{i-1}$ (the `out.prev` of a pulse is the `randOut` of the previous pulse);
- `version`, `cipher`, `period` and `chainId` remain constant (and because of that do not require specification of the pulse index).
- $\text{time}_{i+1} = \text{time}_i + (1 + g_i) \times \texttt{period}$, where g_i is a non-negative integer (usually 0) representing the number of pulse gaps immediately before pulse i (the condition $g_i > 0$ also has an implication on $\texttt{statusCode}_i$).

Serialization. A rigorous description of the relation between the values of some fields requires specifying how field values are serialized when used as input to a hash function. We use an upper bar to denote byte serialization, i.e., $\overline{\langle \textit{fieldname} \rangle_i}$ denotes the byte-string serialization of $\langle \textit{fieldname} \rangle_i$. If the field is not of integer type (uint32 or uint64), then its serialization also includes as a prefix the field length encoded as a (serialized) 64-bit unsigned integer. Section 4.1.2 describes the details of serialization.

Relations involving a hash function. Let $\text{F}_{k,i}$ denote $P_i.\text{F}_k$, i.e., the value in the field F_k in the pulse with index i. Let $||$ denote concatenation. For succinctness, we **CAN** write:

- $F_{21,i} = \texttt{randOut}_i = \texttt{hash}\left(||_{k \in \{1,\ldots,20\}} \overline{\text{F}_{k,i}}\right)$, i.e., the output value ($\texttt{randOut}_i$) is the `hash()` output of the "serialized" concatenation of encodings of all other fields.
- $F_{20,i} = \texttt{sig}_i = \textit{Sign}\left(S_K, \texttt{hash}\left(||_{k \in \{1,\ldots,19\}} \overline{\text{F}_{k,i}}\right)\right)$, where *Sign* is the signature algorithm (corresponding to the `cipher` value), with its first argument S_K holding the secret signing key (for which there is a certificate(s) with hash equal to `certId`), and its second argument S_K being the hash to be signed.

Similarly, we **CAN** write relations using aliases, such as:

- $\texttt{randOut}_i = \texttt{hash}\left(\overline{\texttt{uri}_i}||\overline{\texttt{version}_i}||\overline{\text{cipher}_i}||\overline{\text{period}_i}||\overline{\texttt{certId}_i}||\overline{\text{chainId}_i}||\overline{\text{pulseId}_i}|| \overline{\text{time}_i}||\overline{\texttt{randLocal}_i}||\overline{\text{ext.srcId}_i}||\overline{\text{ext.status}_i}||\overline{\text{ext.value}_i}|| \left(||_{x\in\{\texttt{Prev,H,D,M,Y}\}}\overline{\texttt{out}.x_i}\right)||\overline{\texttt{preCom}_i}||\overline{\text{status}_i}||\overline{\text{sig}_i}\right)$
- $\texttt{preCom}_i = \texttt{hash}(\overline{\texttt{randLocal}_{i+1}})$

Assembling a pulse. Figure 2 illustrates the generation of a pulse P_i. It depicts how to combine several fields to compute $\texttt{sig}_i$ and $\texttt{randOut}_i$. For simplicity, the depiction omits details about the serialization of fields, including about the ordering and encoding of the inputs to various hashes.

In the Figure: $\rho_{i,j}$ is the "raw" random 512-bit string produced by the j^{th} RNG; M_i is the input (the needed serialization is left implicit) for the hash of the signature algorithm; S_i is the signature output; and P_i, produced by *Pulsify*, is the i^{th} pulse in some structure decodable by the database (DB). The DB **CAN** later provide pulses in various formats, e.g., *bare* or XML. For example, the bare format is $bare(P_i) = ||_{k\in\{1,\dots,21\}}\overline{F_{k,i}}$

The hash of M_i is represented with an asterisk (Hash*) because it is actually the hash specified by the signature protocol (e.g., RSA PKCSv1.5). The hashing is not repeated inside the illustrated Signing module. The reason for representing it outside of the HSM (where the Signing module is) is to convey that it is possible to even prevent the HSM from learning in advance the information needed to compute the "output value" (`randOut`) of the pulse. This is relevant for an adversarial setting where the HSM is semi-honest.

3.3 *Promises* generation and release

A beacon service **SHOULD**, via its frontend, make pulses available at a steady and predictable rate. This requires a proper functioning of the backend, where the Beacon engine makes certain *promises* on which unpredictability, freshness, timeliness and unambiguity hinge.

- **Promise 1: No advanced release.** The Beacon engine **SHALL NOT** release before time T a pulse with timestamp T.
- **Promise 2: Generate with entropy.** The Beacon engine **SHALL** compute `randLocal` in each pulse as the hash() of at least two outputs from independent random number generators, each expected to have as much entropy as the size of the `randLocal` field.
- **Promise 3: No advanced generation.** When internally computing $\texttt{randLocal}_{i+i}$ needed for the calculation of $\texttt{preCom}_i$, the Beacon engine **SHALL** sample the needed randomness ($\rho_{i,j}$, for $j = 1,2[,\dots]$) from the several local RNGs only after releasing the previous pulse (P_{i-1}) and after time $\texttt{timeStamp}_i - \pi$.
- **Promise 4: No delayed release.** If until time $T + \pi/4$ the Beacon engine has not released a pulse with timestamp T, then it **SHALL** avoid such release and enforce a time-gap in the chain.

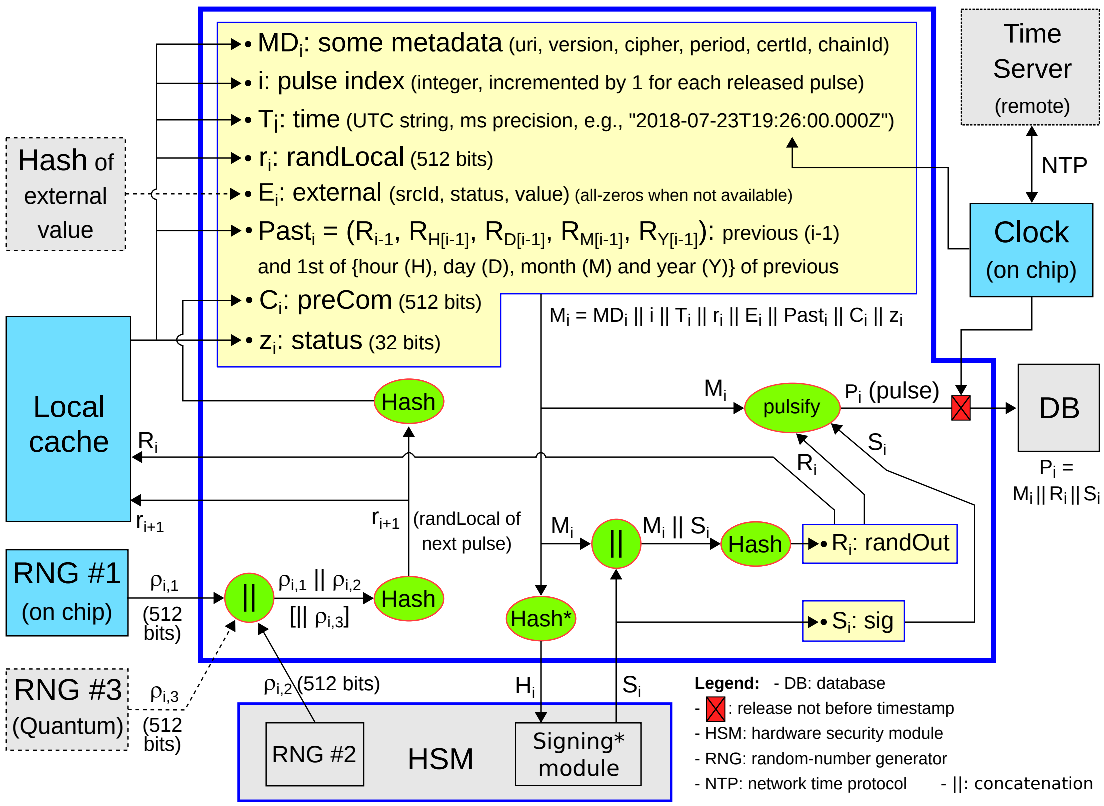


Figure 2. Illustration of the generation of the i^{th} pulse by a Beacon App (2.0)

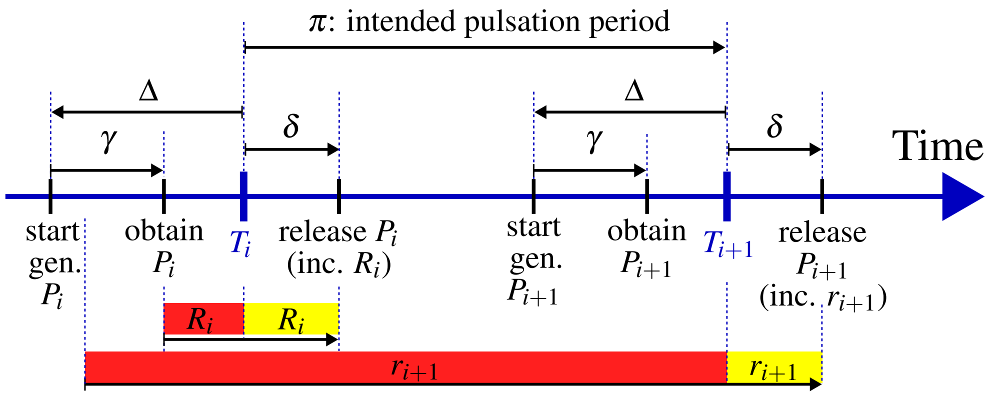
- **Promise 5: Unambiguous indexation.** A beacon **SHALL**, within each chain, increment by 1 the pulse index of each newly released pulse, and **SHALL NOT** release two pulses with timestamps separated by less than one period (π).

In the above *promises* the words "time" and "release" are defined from the perspective of the Beacon engine. Therefore, it is essential to ensure that the local clock of the Beacon engine is adequately synchronized with UTC.

The above requirements are called "promises" because compliance with them, even though essential for security, **CANNOT** in general be verified by outsiders. The trust that users place on the Beacon service should thus depend on the trust they can place on the upholding of these promises by the Beacon engine. The promises are subject to being broken by a crooked beacon operator, or by an outside attacker compromising the beacon engine, or by some kind of programming error or equipment failure.

In a non-compromised beacon engine, the promises imply the following properties:

- Promises 1 and 2 $\Rightarrow$ **unpredictability** of "rands": $\texttt{randOut}_i$ and $\texttt{randLocal}_{i-1}$ remain unpredictable to outsiders at least until the time instant $\texttt{timeStamp}_i$.
- Promise 3 $\Rightarrow$ **freshness**: $\texttt{randOut}_i$ and $\texttt{preCom}_i$ depend on randomness sampled



Legend:
gen. (generating); inc. (including);
γ: time taken to generate a pulse;
Δ: anticipation of generation start;

T_i: scheduled allowed time for P_i release;
δ: release delay, after allowed release time;
R_i: P_i.`randOut`; r_{i+1}: P_{i+1}.`randLocal`.

(Section 8.3.1 describes a solution that significantly reduces the window of predictability of `randLocal`)

Figure 3. Timeline of pulse generation and release

within less than one pulsation period from $\texttt{timeStamp}_i$; whenever $\texttt{statusCode}_i = 0$, which implies $i > 1$ and P_i not following immediately after a time-gap, $\texttt{randLocal}_i$ depends on randomness sampled within less than two pulsation periods from $\texttt{timeStamp}_i$.

- Promise 4 $\Rightarrow$ **timeliness**: except in cases of time-gaps and/or of delays or failures outside the Beacon engine (e.g., in the external database and frontend), each released pulse will be available to users shortly after the time indicated in its timestamp.
- Promise 5 $\Rightarrow$ **unambiguity**: within a chain, an index uniquely identifies a pulse and a timestamp uniquely identifies either a gap in the chain or a pulse.

3.4 Time variables

Figure 3 shows a timeline for pulse generation and release. It depicts: the anticipated-generation-start offset Δ, before the allowed release time; the duration γ needed for pulse generation; the pulse-release offset δ, after the allowed release time. The promises require:

$$\Delta < \pi \qquad \text{(avoid too-early generation-start)} \qquad (1)$$

$$0 \leq \delta \qquad \text{(avoid too-early release)} \qquad (2)$$

$$\max(\delta, \gamma - \Delta) < \pi/4 \qquad \text{(avoid too-late release)} \qquad (3)$$

The red bars indicate the time-intervals during which a semi-honest beacon App (i.e., passively corrupted), capable of exfiltrating internal state but otherwise following the protocol, could break the *unpredictability* property with respect to `randOut` (R_i) and `randLocal`

(r_i). Conversely, an honest Beacon must take all reasonable precautions to avoid early disclosure of components from calculated pulses.

3.5 Additional recommendations

The defined promises still leave some timeline flexibility. Yet, there is envisioned utility in having a Beacon engine with predictable rate. Thus, besides the defined promises, we *recommend* that a Beacon engine **SHOULD** perform the pulse release at time 0^+, and start the pulse generation (including the sampling of raw randomness from the RNGs) as late as possible while obtaining the pulse by time 0^-. The symbols 0^- and 0^+ mean values as close as possible to 0, respectively from below or above.

The time restrictions **SHOULD** be adjusted according to the possibility of local-clock skew (σ), to still meet the promises and the above-mentioned recommendations even in the presence of clock drift between consecutive synchronizations. Appendix A.1 specifies recommendations to promote better timing expectations and interoperable implementations:

- *hard recommendations* request that the maximum skew ahead (σ^+) and behind (σ^-) of UTC be estimated and enforced below one tenth of the period, and that on the basis of such estimation the other parameters (Δ, δ, γ) be set in such a way that the promises 1, 3 and 4 are met even when taking the skew into account.
- *soft recommendations* ask for a fine-tuning of the time parameters such that the generation start and end, and the release time, are all as close as possible to the `timeStamp`.

The appendix also defines the concepts of tuning slack (η) and time accuracy (α), to help quantify a kind of "distance" to an ideal implementation. Tables 13 and 14 therein exemplify acceptable and unacceptable parameter sets, in terms of hard time-recommendations.

3.6 Retrieval interface

The beacon interface determines the ability of external users to obtain released pulses and associated data. Section 6 provides further details on the retrieval interface. Some requests are of mandatory support, whereas others are simply recommended but left as optional in this specification. For example, the beacon frontend must:

- Make all previous pulses available for retrieval (see Section 6.2).
- Provide *skiplists* upon request (see Section 6.3). (Skiplists allow efficient verification of consistency between two distant pulses, as discussed in section 5.)
- Provide associated data which is referenced but not included in pulses; Such associated data includes public-key certificates (§6.4) and external source descriptions §6.5.

It is recommended, though optional, that a randomness Beacon enables retrieval of any other associated data that may improve usability of the beacon. This **MAY** include, for example, pre-images of past external values (see Section 6.5).

4 The Pulse Format

Version 2.0 of the pulse format has become more complex, compared to the version (1) used in the initial NIST beacon prototype. Some of the new complexity intends to make operating a beacon easier. Other parts intend to improve the security against a misbehaving beacon. Still others intend to make it easier to securely combine outputs from different beacons.

This section starts by describing used data formats (§4.1), for representation of fields and compositions thereof, including serialization procedures. It then describes the meaning and calculation procedures for each field of a pulse. The description follows the fields ordering already defined in Section 3.1, but also organizing fields by topics: administrative (§4.2), indexation (§4.3), the local random value (§4.4), the external source (§4.5), past outputs (§4.6), precommitment (§4.7), signature related (§4.8), and the output value (§4.9).

4.1 Data formatting and representation

4.1.1 Basic data formats for fields

The handling of pulses and associated data involves parsing diverse elements with various syntaxes and representations. For different purposes, the same data, often contextualized within a field, **CAN** be expressed with different representations.

We refer to the following basic data formats:

- **B64:** A base 64 encoding, allowing characters A–Z, a–z, 0–9, + and /. For example, it is used to encode a PEM file (whose `hash()` is `certId`) containing the public certificate(s) corresponding to the secret signature key.
- **bin:** A UTF8 string of zeros (0) and ones (1) expressing a sequence of bits. This is useful for example to describe a sequence of bit flags. The prefix “0b” (without the quotes) **MAY** be used to denote that what follows is a value written in binary format. When the length of the variable is implicit, the representation **MAY** omit left zeros.
- **Byt:** A string of bytes (bit octets), where any byte value (0 through 255) is allowed. It is used for example for encoding inputs for hashing, and is not used for textual printing. Two specialized formats are uint32 and uint64, correspondingly consisting of 4 and 8 bytes representing unsigned integers (in big-endian order).
- **dec:** A UTF8 string expressing an integer in decimal format, without padding left zeros; the only allowed characters are 0, 1, ..., 9.
- **hex:** A UTF8 string of hexadecimal characters (0, 1, ..., 9, A, B, ..., F), with the letters in upper-case. The prefix “0x” (without the quotes) **MAY** be used to denote that what follows is a value written in hexadecimal. When the length is implicit, the representation **MAY** omit left zeros.

- **str:** A UTF8 character string [Yer03].

Examples of varying representations.

- `randOut` is a byte string when used as a hash input, but is expressed in hexadecimal when part of an XML output.
- `pulseId` is an octet of bytes when used as a hash input, but is expressed as a decimal string when used as a component of the `uri` field.
- `status` is a quartet of bytes when used as a hash input, but **CAN** also be interpreted as a sequence of 32 bit-flags when describing its meaning, and **CAN** be expressed in hexadecimal within some pulse representations.

It is thus useful to have notation to disambiguate the representation required of a field.

Encoding into a basic format. Sometimes it is necessary to ensure that a variable is converted/encoded into a particular format. Function `encode` is used for that purpose:

- $\texttt{encode}(var, form)$ denotes a value *var* represented in format *form*, using the minimal number of base elements of format *form*.
- $\texttt{encode}(var, form : len)$ is the same but conditioned to an exact length *len* (the number of base elements of format *form*), e.g., if-need-be adding leading zeros.

The actual transformation **MAY** depend on the format of the input, but we leave that implicit. For example: when converting from hex to Byt, each pair of hexadecimal characters is converted into one byte; when converting from bin to Byt, then each octet of bits is converted into one byte.

Endianness. All encodings are in big-endian order. For example:

- $\texttt{encode}(x, \texttt{uint32}) = \texttt{encode}(x, Byt, 4)$, receiving as input an unsigned integer x between 0 and $2^{32} - 1$, encodes it as a 32-bit string in big-endian, using 4 bytes.
- $\texttt{encode}(x, \texttt{uint64}) = \texttt{encode}(x, Byt, 8)$, receiving as input an unsigned integer x between 0 and $2^{64} - 1$, encodes it as a 64-bit string in big-endian, using 8 bytes.

Examples.

- $\texttt{encode}(S, Byt)$ converts the input S into a sequence of bytes;
- $\texttt{encode}(H, Byt : BLenHash)$ converts H into a sequence of exactly $BLenHash$ bytes;
- $\texttt{ZeroH} = \texttt{encode}(0, Byt : BLenHash)$ is a constant sequence of $BLenHash$ bytes, all with value 0, where $BLenHash$ is the number of bytes in a hash output.

- `encode`(S, hex) converts the input S into a sequence of hexadecimal characters (e.g., useful when representing hash outputs in a Txt pulse format for human readability).

Alternative notation. It is sometimes useful to define variable strings with resort to variable components/fields. The `uri` field is one such case, where some of its components vary across pulses. In that setting, when expressing a variable supposed to be instantiated with a particular format, we use the following notation:

- $\langle$*field*:form$\rangle$ denotes a field "field" to be replaced with a value with format "form"
- $\langle$*field*:form:len$\rangle$ denotes the same but conditioned to using exactly len base elements of format "form".

4.1.2 Byte serialization of fields

For unambiguous transmission or processing it is sometimes useful to encode a sequence of fields into a single data packet that enables proper parsing. For example, hash functions and signature algorithms process inputs received as strings of bytes. Thus, when preparing the input needed to compute the hashes and signature needed within a pulse, we construct the corresponding byte-string input from the needed fields.

The process of producing a single byte-sequence from a sequence of fields is denoted byte serialization (or simply *serialization*). The procedure processes each field at a time, in one or two steps. If the field is of uint32 or uint64 type, then the field serialization is simply the (big endian) byte encoding into 4 or 8 bytes, respectively. For other types (non-integer), the field serialization produces a concatenation of two components: the second component is the byte-string encoding of the field value (sometimes with a fixed length); the first component is the byte-string encoding of the length (number of bytes) of the second component. Table 2 shows the length after byte serialization of each default data type previously identified in Table 1.

Table 2. Length after byte serialization, per default field type

Default field type	**Length prepended?** (8 bytes)	**Number of bytes** (not counting the prepended length encoding)	
		General	Example
`uriStr`	Yes	variable (> 33)	50 if `domain=beacon.nist.gov`, `pulseId`:`dec`=1 and `chainId`:`dec`=1
`verStr`	Yes	≥ 3	3 if `version`:`dec`="2.0"
`dateStr`	Yes	24	
`hashOut`	Yes	*BLenHash*	64 if `cipher`=0
`sigOut`	Yes	*BLenSig*	512 if `cipher`=0 and the RSA modulus has 4096 bits
`uint32`	No	4	
`uint64`	No	8	

Auxiliary BytLen function. Let BytLen(S) return the uint64 (8-bytes) encoding of the length (len), in number of bytes, of the byte encoding of the input S, i.e.:

$$\texttt{BytLen}(S) = \texttt{encode}(len(\texttt{encode}(S, Byt)), \texttt{uint64}). \tag{4}$$

Byte serialization of single fields. We define three byte-serialization functions for individual fields. Despite some redundancy, their distinction enable us to make more evident what is the default type of each input field, and corresponding restrictions (e.g., hashes have an expected fixed length).

- Byt_serialize_string(S), receiving as input a UTF8 string, outputs a byte string, resulting from the concatenation of two components: the 2^nd^ is the byte encoding of the UTF8 string S; the 1^st^ is the BytLen of the second component. The result is:

  $$\texttt{BytLen}(S) \parallel \texttt{encode}(S, Byt) \tag{5}$$

  Remark. For the UTF8-string fields `version` and `time`, The number of bytes in the UTF8-string fields `version` and `time` is equal to the corresponding number of UTF8 characters, since the characters must be within the ASCII (American Standard Code for Information Interchange) collection of 128 characters. Conversely, the UTF8-string field `uri` is allowed to include non-ASCII characters, which require more than one byte. Prefixing (an encoding of) the number of bytes, rather than the number of characters, eases the process of parsing a sequence of serialized fields, since the jump across fields does not requiring parsing the UTF8 characters.

- Byt_serialize_hash(H), receiving as input a hash value, calculates its byte encoding and then prefixes its BytLen, which must correspond to $BLenHash$. The output is:

  $$\texttt{encode}(BLenHash, \texttt{uint64}) || \texttt{encode}(H, Byt : BLenHash). \tag{6}$$

  The integer $BLenHash$ is a global variable denoting the number of bytes (e.g., 64 bytes if the hash function is SHA512) of the hash in use within a chain. We leave implicit the verification that the length of the byte encoding of the input is not larger than $BLenHash$. (Otherwise the case is considered as an error.)

  When a field of type hashOut is set to "zero" to represent an absent hash() value, the serialization produces an all-zeros string of the same length ($BLenHash$ bytes) as a normal hash() output. We denote such constant byte string as `ZeroH`.

- Byt_serialize_sig(S), receiving as input a signature value, calculates its byte encoding and then prefixes the corresponding BytLen, which must be the encoding of

BLenSig. The output is:

$$\texttt{encode}(BLenSig, \texttt{uint64}) || \texttt{encode}(H, Byt : BLenSig). \tag{7}$$

The integer *BLenSig* is a global variable within a chain, e.g., with value 512 if the signature algorithm uses RSA with a 4096-bit modulus.

Byte serialization of a sequence of fields. The serialization of sequences of fields is required in several cases related to pulse handling, such as for encoding:

- the input of the hash that is signed to produce `sig`;
- the hash pre-image of `randOut`;
- a pulse in the bare pulse format;
- the hash pre-image of `ext.value`.

Algorithm 1 describes function `Byt_serialize_fields`, which serializes a sequence (vector) of fields. The algorithm sequentially processes each field, taking into account the each field type. The output is a sequence of bytes.

Algorithm 1 Serialize field sequence to a byte string.

function BYT_SERIALIZE_FIELDS($vector$)
    $\langle field_1, \ldots, field_n \rangle \overset{\text{parse}}{\longleftarrow} vector$
    $Z \leftarrow$ “” (*empty string*)
    for $i = 1, ..., n$ **do**
        $x \leftarrow value(field_i)$ $t \leftarrow type(field_i)$
        if $t = \text{uint32}$ **then** $Z \leftarrow Z \,\|\, \texttt{encode\_uint32}(x)$
        else if $t = \text{uint64}$ **then** $Z \leftarrow Z \,\|\, \texttt{encode\_uint64}(x)$
        else if $t \in \{\text{uriStr}, \text{verStr}, \text{dateStr}\}$ **then** $Z \leftarrow Z \,\|\, \texttt{Byt\_serialize\_string}(x)$
        else if $t = \text{hashOut}$ **then** $Z \leftarrow Z \,\|\, \texttt{Byt\_serialize\_hash}(x)$
        else if $t = \text{sigOut}$ **then** $Z \leftarrow Z \,\|\, \texttt{Byt\_serialize\_sig}(x)$
        else abort
    return (Z)

Example (input for hashing needed before signing). The procedure for producing the cryptographic signature (`sig`) that is part of a pulse requires hashing the sequence of preceding fields. Recalling the notation introduced in Sections 3.1 and 3.2, the input of such hash is equal to $||_{k\in\{1,...,19\}}\overline{\mathrm{F}_{k,i}}$. This is the same as

$$\texttt{Byt\_serialize\_fields}\,(vector)\,, \tag{8}$$

where $vector = \langle F_{k,i} : k = 1,...,19 \rangle$, or, more precisely, $vector = \langle$ `uri`, `version`, `cipher`, `period`, `certId`, `chainId`, `pulseId`, `time`, `randLocal`, `ext.srcId`, `ext.status`,`ext.value`, `out.Prev`, `out.H`, `out.D`, `out.M`, `out.Y`, `preCom`, `status` $\rangle$.

As a concrete example, Algorithm 2 shows the unrolled serialization operation.

Algorithm 2 Serialize the hash input of the `sig` field of a pulse

```
Z ← Byt_serialize_string(uri)
Z ← Z || Byt_serialize_string(version)
Z ← Z || encode(cipherSuite, uint32)
Z ← Z || encode(period, uint32)
Z ← Z || Byt_serialize_hash(certificateId)
Z ← Z || encode(chainIndex, uint64)
Z ← Z || encode(pulseIndex, uint64)
Z ← Z || Byt_serialize_string(timeStamp)
Z ← Z || Byt_serialize_hash(localRandomValue)
Z ← Z || Byt_serialize_hash(external.sourceId)
Z ← Z || encode(external.statusCode, uint64)
Z ← Z || Byt_serialize_hash(external.value)
Z ← Z || Byt_serialize_hash(previous)
Z ← Z || Byt_serialize_hash(hour)
Z ← Z || Byt_serialize_hash(day)
Z ← Z || Byt_serialize_hash(month)
Z ← Z || Byt_serialize_hash(year)
Z ← Z || Byt_serialize_hash(precommitmentValue)
Z ← Z || encode(statusCode, uint32)
return (Z)
```

4.1.3 The Bare Pulse Format

The *bare* pulse format if a byte-string pulse representation (Byt format) that concatenates all byte-serialized fields of a pulse, including corresponding prefixes of the field lengths for the non-integer field types. This forms an unambiguous sequence of bytes. Recalling the notation introduced in Sections 3.1 and 3.2, the bare pulse is equal to:

$$bare_i = ||_{k \in \{1,...,21\}} \overline{\mathrm{F}_{k,i}} \tag{9}$$

Algorithm 3 (construct_bare_pulse()) shows a corresponding pseudo-code for generation of a *bare* pulse, based on the 2 example.

Algorithm 3 Unambiguously encode an entire pulse as a byte string.

function CONSTRUCT_BARE_PULSE(`uri`, `version`, `period`, ..., `outputValue`)
  $Z \leftarrow$ `Byt_serialize_fields`(`uri`, `version`, `period`, ..., `statusCode`)
  $Z \leftarrow Z \,\|\,$ `Byt_serialize_sig`(`signatureValue`)
  $Z \leftarrow Z \,\|\,$ `Byt_serialize_hash`(`outputValue`)
  return (Z)

4.1.4 The Txt pulse format

The Txt format for pulses intends a balance between conciseness and human-readability and is aimed for inclusion in MIME type text/plain documents. It has a simple logic:

- It starts and ends with delimiter lines of the description of a pulse;
- Within the delimited description, each new line identifies a field name (abbreviated), the format that follows, and the respective field value, followed by a line break.

This design also enables a straightforward concatenation of multiple Txt pulses.

Figure 4 shows a concrete example. Algorithm 4 shows concise pseudo-code for function `Txt_Serialize`, to produce a Txt serialization of a pulse. The Txt serialization of a pulse **CAN** be expressed as Txt_Serialize(vector), where $vector = \langle (A_i, R_i, F_i) : i = 1, ..., 21 \rangle$, with the field alias A_i and the representation format R_i corresponding to field F_i being determined from Table 3.

Algorithm 4 Txt serialization of a pulse

Require: Input *vector* has 21 elements
Require: Elements A_i and R_i are from Table 3

function TXT_SERIALIZE(*vector*)
  print `"-----BEGIN BEACON-PULSE FORMAT TXT-----\n"`
  for $i = 1, ..., 21$ **do**
    $x \leftarrow vector_i$
    print A_i + `":"` + R_i + `"=\""` + `encode`(x, R_i) + `"\"\n"`
  print `"-----END BEACON-PULSE FORMAT TXT-----\n"`

The sequence “`\n`” represents a line break; the sequence “`\"`” represents the double quote character `"`.

Hexadecimal serialization. When producing certain output documents, e.g., MIME type text/plain, fields **CANNOT** use the full spectrum of bytes. A useful alternative serialization is based on hexadecimal characters (0...9, A...F). Each byte (value between 0 and 255) is represented in hex format, as a pair of hexadecimal characters. For example, a 512-bit `hash()` output is then represented with 128 hexadecimal characters. The serialization **MAY** omit prefixing the length if the beginning and end of the hexadecimal string is otherwise

```
-----BEGIN BEACON-PULSE FORMAT TXT-----
uri:str="https://beacon.nist.gov/beacon/2.0/chain/1/pulse/220394"
version:str="Version 2.0"
cipher:hex="00000000"
period:dec="60000"
certId:hex="5501e3d72bc42f3b96e16de4dcadcb16768e109662bd16d667d5fd9aee585af31bbdc5dd4f53592276
064b53dddd76c8f3604b2a41db6e09f78f82bb5d6569e7"
chainId:dec="1"
pulseId:dec="220394"
time:str="2018-12-26T16:07:00.000Z"
randLocal:hex="5FF1E44E70C019C42C77FA72D5228A2E663416D0778BFAC826F6B4757B634B076C50ED2D5A3975C
BAF237C211A027EDAFF3E241A885D69EAA7237E2744E6C1E2"
ext.srcId:hex="0000000000000000000000000000000000000000000000000000000000000000000000000000000
0000000000000000000000000000000000000000000000000"
ext.status:hex="0000000000000000"
ext.value:hex="0000000000000000000000000000000000000000000000000000000000000000000000000000000
0000000000000000000000000000000000000000000000000"
previous:hex="BA646CC4E7AE195D2C85E9D3AE9C9722B974F2134699D2493FA9E296C34995E8E471B329CB5F6323
5982CEE3395A749C618E61466847951D543ADC2FBAD23ECB"
out.H:hex="E75A5877169CC15220BCB11C8DA18159F14B880D85C5F3E9E462D010DC49BFCFE36D116D72C1D32A95A
E8FFD9F0B6CE20DC073ED881BA36D5EF4687DC5B12328"
out.D:hex="CDD24473B4427C3D3C856C66DF669444CE79D1262F94F4CC745E037AB781245A560E722514A62BEFF9A
BE3B72EAFDF5EAE5A43EA806F5571B05EA04B8E7B02B7"
out.M:hex="A9EDA202336C7DB1F05DE3BB24AAC1B54E98C9BD46CDF3D193FAE2BF4E0CD696AD6A743DFDF4DC48E59
85BE329652E0A74816C7B69BBAF644FF0ACA352207FFB"
out.Y:hex="7665F054F21B50DF62CD3E50AF8EB783E30D271B091DE051212D301E0E3D17FFCF0367DB41CFFD3C51E
88BDE0B0621F49EB03435BC373D5D49480941A8B3547E"
preCom:hex="269908B840E79BE71991FFE62CEC4EBAEB3C050E93D71248CBB3E4358445FF0858D1D2CCF899A19B86
1C0C11CECCF16A0859AFD68E58481D4ADB1BE61F30E419"
status:hex="00000000"
sig:hex="17943D886DA8C7C24B9244BE5BD5DF281983D28CFFC8928846BC26529309C9724F6849F039591361DAF6B
8DDAB6BC275CF86F448AF1800996889508D08D8AAAD19586E7A4B04FC4C97F1DA6D619EFAE2332150328C79C23BB9F
E6A03E8FABDFF1AD66C5A8789D28AED4D25FF0FC5E88BE366280D7516A504EFD63706641828DDBF3C7082524F36E77
EE9E07A9801D0C3BAD0646AA89DDDD8E2B4C0D7F8ED67664864B598E59ABF20CA8D761BB7B32B9A32698A22935D2C7
127952625BB5580B2847FBBC8DFEF9039C4F5ACF12877E11121D031AED58217286F8DCF291C6E315773B42FF470B1A
B587F787D44381F6E655DB903F1601B65AAC86BC2B7083AEEA9B3A27A5A208674056EFBB3C44629F333C810ADAD00E
4FCFCE48E54F8FB7FC700598EA3E6497821736D24E5DA801A8B9DEC28A2B68E50FE13752270EB9CA7912B21EB6C104
E78D105D0C0A635686B9A8CA26F87A1E63F0E411FD228F21B08BCD24660B305A4A42A9229154DE364FAB4DFF257A59
DEA814034BF65C38A4C7AAEE79FEE5CC69010B1FE9759E23F192E218A19D9B8E95F6DD37D5D2F672E6CF0A0D457D9C
619B1808274C2B0B2D3A3A7A8D8B1BB423FDDC56110784F2E0B7A23F065B56EC6E40234786DAB8C840E47811950331
CBCFADEAD2EEE901D1C0A3A7E18D18A93089FC4E1CEFBA7571D2E47F10893D24BAD967FCA9DAEA67AD6B7F390AFC0"
randOut:hex="0A8863E03E200F694CBA50F0F9A009B078555FE637B07CA2C0A0E4D564080173787B26376C4762377
A139D1BCAA916A10419504850EB7CF91552A17FDCAA0463"
-----END BEACON-PULSE FORMAT TXT-----
```

Note: the value "`Version 2.0`" was indeed used in the `version` field of the exemplified pulse, but a correct implementation **SHALL** use "`2.0`" instead. The NIST beacon will correct this for pulses with `chainId` ≥ 2.

Figure 4. Pulse example in format Txt

patent. This is the case whenever the representation is delimited by non-hexadecimal characters, e.g., double quotes as in "`08A0`". The prefix 0x **MAY** also be used to make more explicit the start of an hexadecimal string, e.g., as in "`0x08A0`".

As another example, a pulse **MAY** be represented in text format, representing the se-

Table 3. Field names, formats and values for Txt Serialization

# (i)	Alias (A_i)	Format (R_i)	Value (F_i)
1	`uri`	str	F_1
2	`version`	str	F_2
3	`cipher`	hex:8	F_3
4	`period`	hex:8	F_4
5	`certId`	hex:HL	F_5
6	`chainId`	dec	F_6
7	`pulseId`	dec	F_7
8	`time`	str	F_8
9	`randLocal`	hex:HL	F_9
10	`ext.srcId`	hex:HL	F_{10}
11	`ext.status`	hex:16	F_{11}
12	`ext.value`	hex:HL	F_{12}
13	`out.Prev`	hex:HL	F_{13}
14	`out.H`	hex:HL	F_{14}
15	`out.D`	hex:HL	F_{15}
16	`out.M`	hex:HL	F_{16}
17	`out.Y`	hex:HL	F_{17}
18	`preCom`	hex:HL	F_{18}
19	`status`	hex:8	F_{19}
20	`sig`	hex:SL	F_{20}
21	`randOut`	hex:HL	F_{21}

HL and *SL* are used as abbreviations of *BLenHash* and *BLenSig*, respectively.

quence of all fields in a sequence that favors human readability, including some fields represented in hexadecimal format, others in decimal, and others in UTF8 format.

4.1.5 Other structured pulse formats

The *bare* and the *txt* formats are not the only ways in which a pulse can be represented. As mentioned with further detail in Section 6.1.2, other generic standardized formats, such as HTML, JSON, XML, etc., are possible. The detailed definition of some of these formats is left outside this report, being deferred to auxiliary documents. Nonetheless, for the purpose of interoperability, it is currently defined that a Beacon **SHALL** be able to support at least the JSON format.

Besides the mandatory values in a pulse, the additional structured formats **MAY** (optionally) include auxiliary information (not part of the hash-chain), such as:

- the order (1...21) of each mandatory field, as defined in Section 3.1;
- timestamps (`time`) and pulse indices (`pulseId`) of the included past output values (`out.Prev`, `out.H`, `out.D`, `out.M`, `out.Y`);
- the public key used for signature verification;
- the timings (Δ, γ and δ) of pulse generation and release (in milliseconds).

4.2 Administrative fields

These fields tell the user how to interpret the rest of the pulse, and give general information about what to expect from the beacon.

4.2.1 URI

Field name: `uri`

Default type: uriStr (a type of byte-string)

Relations: contains components derivable from `version`, `chainId` and `pulseId`.

Example. The `uri` value in the first pulse of the first chain of the NIST Randomness Beacon version 2.0 is the following string:

`https://beacon.nist.gov/beacon/2.0/chain/1/pulse/1` (10)

Description: It is a URI [BLFM05], specifying a valid URL from which the beacon pulse is expectedly available upon release. It is a variable length string structured as ⟨*webPrefix*:str⟩`/beacon/`⟨*version*:str⟩`/chain/`⟨*cid*:dec⟩`/pulse/`⟨*pid*:dec⟩, where:

- ⟨*webPrefix*:str⟩ is a string ⟨*scheme*:str⟩`://`⟨*domain*:str⟩/⟨*optContext/*:str⟩, where:
  - ⟨*scheme*:str⟩ is the *scheme* component of a URI. In the current Beacon reference, the only allowed scheme is `https` (Hyper Text Transfer Protocol Secure). Future beacon references **MAY** allow other (secure) schemes.
  - ⟨*domain*:str⟩ is the expected beacon web domain; typically this will be a parent of the domain certified in the public certificate(s) of the beacon signature key. The current NIST beacon implementation uses `beacon.nist.gov` as its domain, whereas the domain of the signature certificate is `engine.beacon.nist.gov`.
  - ⟨*optContext/*:str⟩ is a possibly empty string denoting an optional context. If not empty it **CAN** be anything that is legal to appear in the *hier-part* (hierarchical partitioning component) of a URL, but restricted to terminating with a front slash character "/" and not containing the substring "`chain/`" nor the characters "?" (used for queries) and "#" (used for fragments) — see Section 6 for details.
- ⟨*version*:str⟩ is the version number (as a UTF8 string), e.g., "2.0" or "`2.0-beta1`".
- ⟨*cid*:dec⟩ is the decimal representation of the integer value that appears in the `chainId` field of the pulse.
- ⟨*pid*:dec⟩ is the decimal representation of the `pulseId` field of the pulse.

Recommendation: when generating experimental (a.k.a. *beta*) pulses with the real signature key, the ⟨*optContext/*⟩ sub-field **SHOULD** indicate the *beta* quality, possibly redundantly with the "`beta`" that appears in the `version` value.

4.2.2 Version

Field name: `version`

Default type: verStr (a type of byte-string)

Relations: its value must remain constant within each chain.

Description. It is a variable-length string that indicates how to interpret the fields of the pulse. The value presented in this field is of the form 2.y, which is "2.0" in the version considered at the time of this writing.

Version updates requiring change of value. Incrementing the value y **SHALL** happen when the pulse format is updated in a way that requires a pulse handling incompatible with the previous version, e.g., if adding or changing the order of fields used as input to the `hash()` used in the calculation of the pulse signature `signatureValue` or the output value `randOut`.

Identifying beta versions. The ⟨`version`⟩ value **SHOULD** contain the string "beta" whenever producing experimental pulses with a signature that uses the same key as used to to be used with non-beta pulses. For example, "2.0-beta" or "2.0-beta1" and/or "2.0-beta2" would denote `version` values used for beta testing. This allows repetition of values of chain—pulse indices while doing tests (which **MAY** involve creating real signatures). The "beta" expression signals users that such pulses **MAY** contain errors due to experimental procedures, including not obeying promises relating to timing or index-uniqueness.

Sub-versioning updates. As previously mentioned, some minor updates of the beacon reference **MAY** refer to a sub-version that is not reflected in the `version` or `uri` fields. These updates, which refer to component z within 2.y.z, do not interfere with the interpretation of any previous pulses. This includes adding a specification for interpreting a new (previously undefined) value of the `statusCode` or `cipherSuite` fields. Those sub-version upgrades **MAY** require updating software for better parsing of new values, but must not imply any loss or invalidation of the relations between previous pulses within the same `version` value 2.y.

Consider that some version 2.0.z defines how to interpret the first n bit-flags of field `statusCode`, and that the $n+1^{\text{th}}$ through the m bit-flags are open for definition in future versions. Then, a software built for version 2.0.z **CAN** simply ignore those flags, or output a warning if/when detecting that they are filled with non-default values in a pulse with `version`=2.0.

Consider that a new `cipher` value is defined in a sub-version update. Since `cipher` **CANNOT** change within a chain, the update does not interfere with the parsing of any pulses continuing from a pre-existing chain. If a software for version 2.0.w encounters an unknown `cipher` value, then it **SHOULD** output a corresponding informative warning/error to the user.

Remark (`version` in the NIST beacon). In the initial NIST Beacon implementation of version 2.0, the pulses of chain 1 used value "Version 2.0" in the `version` field. The prefix “Version ” is to be discontinued; the second chain of the NIST Beacon corrected the `version` value to simply “2.0”.

4.2.3 Cipher Suite

Field name: `cipherSuite` or (abbreviated) `cipher`

Default type: uint32

Relations: its value must remain constant within each chain.

Description. It is a 32-bit integer used to indicate which cryptographic standards are used for the hash function and signature. Table 4 describes the existing attributions for defined `cipherSuite` values. At present, only value 0 is defined.

Table 4. Attributions defined for `cipherSuite`

`cipherSuite` **value**	**Hash function**		**Signature standard**	
	Name	Byte length (*BLenHash*)	Name	Byte length (*BLenSig*)
0	SHA512 [NIS15]	64	RSA with PKCS 1.5 padding [NIS13a] (but allowing more keys sizes	$256+i$, for some $i \in \mathbb{N}_0$

The outputs of both hash function and signature algorithms are represented as big-endian integers and are serialized as byte strings. The hash function is defined for all uses of `hash()`, including in the signature. For each signature key, the signature length *BLenSig* is fixed as the length of the RSA modulus. Note that using only 2048 bits (=256 bytes) for RSA is not considered enough to provide 128 bits of security.

The hash function is represented as `hash()`, such that `hash`(x) is the hash of some byte-string serialized input x. The signature function is represented as `SIGN`(,), such that `SIGN`(SK,H) uses the signing key SK to produce the signature of a message whose hash (using `hash()`) is H.

4.2.4 Period

Field name: `period`

Default type: uint32

Description. Is is a 32-bit unsigned integer that specifies the number of milliseconds of increment between the `timeStamp` values of two consecutive pulses when there are no gaps. The pulsating period of a chain is sometimes represented with symbol π.

Relations: its value must remain constant within each chain; for example, if the *period* of a chain is one minute, then all pulses of that chain will have $\pi = 60,000$ (sixty thousand).

4.3 Indexation fields

The indexation fields allow identifying a pulse with respect to its order and position with the sequence(s) of generated pulses.

4.3.1 Chain Index

Field name: `chainIndex` or (abbreviated) `chainId`

Default type: uint64

Description. It is the positive integer index of the *chain* to which this pulse belongs. It has value 1 for the initial chain of each Beacon administrative domain implementing the Beacon reference version 2. The chain index is incremented by 1 for each new chain.

Relations. The values in the fields `version`, `cipherSuite` and `period` **SHALL** be invariant within each chain. This implies in particular that any new value in any of these fields must happen in the first pulse of a new chain.

Also, a chain **SHALL NOT** continue if the Beacon, e.g., due to some malfunctioning, loses the ability to ensure certain needed relation across the sequence of pulses. For example, a Beacon **SHALL NOT** continue a chain if it **CANNOT** produce a new pulse that satisfies the defined hash-chaining properties related to past output values within the chain.

4.3.2 Pulse Index

Field name: `pulseIndex` or (abbreviated) `pulseId`

Default type: uint64

Description. It is the positive integer index of this pulse within its chain. The first pulse of each chain has index 1, and each new pulse in each chain increments `pulseId` by 1.

4.3.3 Timestamp

Field name: `timeStamp` or (abbreviated) `time`

Default type: dateStr (a type of byte string)

Description. It contains a timestamp, representing a time instant, in the Universal Time Coordinated (UTC) standard, rather than in local time.

As mentioned in Section 3.3, the `timeStamp` in a pulse does not represent the exact release time, but rather the promised time before which the Beacon engine does not release the pulse (see Promise 1), and the reference for other time limits on release (see Promise 4) and generation start (see Promise 3).

Format. The value in the `timeStamp` field is represented as a string with 24 single-byte characters, following the format in RFC3339 [NK02]:

$$\langle \mathit{year}\rangle\texttt{-}\langle \mathit{month}\rangle\texttt{-}\langle \mathit{day}\rangle\texttt{T}\langle \mathit{hour}\rangle\texttt{:}\langle \text{minute}\rangle\texttt{:}\langle \text{second}\rangle\texttt{.}\langle \text{millisecond}\rangle\texttt{Z} \tag{11}$$

The string is composed by a *date*, followed by an identifier character "T" (denoting that a time of day will follow), then by the *time of day*, and finally by a character "Z" (denoting "Zulu", meaning the zero hours zone, which identifies the UTC format).

The date is a 10-byte string, composed of three numeric components — a 4-digit *year*, a 2-digit *month* and a 2-digit *day* — separated by a dash "-". The time of day is a 13-byte string composed of four numeric components — a 2-digit *hour*, a 2-digit *minute*, a 2-digit *second* and a 3-digit *millisecond* components — the first three separated by a colon ":" and the last one separated by a dot ".". For example:

- the timestamp 1945-06-26T16:59:11.000Z identifies the date of signing the United Nations Charter, on June 06, 1945, at the UTC time 16 hours, 59 minutes and 11 seconds.
- the timestamp 2019-01-01T00:00:00.000Z identifies the starting instant of the year 2019, in UTC time, up to millisecond precision.

The beacon format requires pulses to always use this format in the `timeStamp` field, including the "T" and "Z" characters, and the seconds and milliseconds components.

When serializing fields, an integer is also used to describe the number of bytes (24) of characters used to express the `timeStamp` string.

Abbreviation. For improved readability, in the remainder of this document we often use an abbreviated format for timestamps. This is specially useful since we adopt as default examples cases where timestamps have the second and millisecond components equal to 0. In such cases, we use a space (" ") instead of "T", and omits the seconds, milliseconds, and "Z". For example, for a beacon that pulsates with a period of 1 minute, and whose *promises* establish the minute mark as the allowed release time for pulses, we **CAN** say in this document, but not in the actual pulses, that the timestamps

2020-01-01 00:00

2020-01-01 01:01

2020-01-01 02:02

are expected to be the first ones to appear in the year 2020. However, the actual timestamps in the corresponding pulses **SHALL** be written as

2020-01-01T00:00:00.000Z
2020-01-01T01:01:00.000Z
2020-01-01T02:02:00.000Z.

Relations. If T is the timestamp in a pulse, then $T - \pi$ and $T + \pi$ are the previous and the next timestamps, if there are no time-gaps.

4.3.4 Status

Field name: `statusCode` or (abbreviated) `status`

Default type: uint32

Description. It is a sequence of 32 bits (a.k.a. *bit flags*), indicating the current status of the chain. Each flag indicates some aspect of the status, as defined in Table 5. The ordering (1$^{\text{st}}$, 2$^{\text{nd}}$,..., 32$^{\text{th}}$) of flags is from right to left, to match the ordering of least significant bits (LSBs) of the 32-bit unsigned integer corresponding to the (big-endian) serialization of the bit-vector.

Detailed explanation. In the current Beacon reference version (2.0.0), only the four right-most flags are defined with a fixed meaning. All other flags are by default set to 0, unless if/when possibly defining a new meaning for them. The 5$^{\text{th}}$ through the 16$^{\text{th}}$ rightmost flags are reserved for future sub-versions (including 2.0.z) or versions (2.y.z) of the beacon format. The 17$^{\text{th}}$ through the 32$^{\text{nd}}$ rightmost flags are reserved for individual beacon operators to define. The definition of the latter require that a description be available for users — see corresponding interface call (5k) in Section 6.6

Example values. Let `0bX...X` be a sequence of bits X...X, where the i^{th} X, counting from right to left, represents the i^{th} LSB of (i.e., with additive weight 2^{i-1} in the) integer value `status`. Compared with an enumeration of all possible `status` integer values, the specification using bit-flags is specially useful considering that the number of possible combinations grow exponentially with the number of flags. We enumerate several special examples:

- `status` = `0b0` = 0: Indicates a normal transition since the previous pulse in the chain: without a time gap; without a change of `certId`; with `randLocal` being well related to the `preCom` in the previous pulse; with more pulses being expected for this chain.
- `status` = `0b1` = 1: The `randLocal` value does not correspond to a previous `preCom` in the chain. In an ideal functioning, this status occurs only if this pulse is the first

Table 5. Bit-flags of the `status` field

LSB	Variable name	What?	if set (1)	if unset (0)	Possible values in the 1st pulse of a chain
1st	`FLS_rndloc`	`randLocal` without corresponding `preCom` in chain?	yes	no	1
2nd	`FLS_gap`	Gap in chain?	yes	no	0
3rd	`FLS_certid`	`certId` changed in chain?	yes	no	0
4th	`FLS_end`	End of chain?	yes	no	0
5th–16th	—	Reserved for definition in future versions	—	—	—
17th–32th	—	Reserved for local definition (per beacon)	—	—	—

LSB = least significant bit. The FLS prefix indicates a flag of the `status` field.

in a chain. However, an abnormal functioning of a Beacon **CAN** lead to a non-first pulse with this status code, if the sequence of pulses would not have gaps and at the same time the field `randOut` was not populated (i.e., was filled with all zeros). Such abnormal case **SHOULD** warrant an external application to invalidate the pulse for the purpose of combining beacons (see Section 7.4).

- `status` = `0b10` = 2: The pulse follows after a gap without loss of randLocal — whenever the previous pulse has a `timeStamp` value more than one period (π) away in the past, and `randLocal` is still related as expected with the `preCom` of the previous pulse in the chain.
- `status` = `0b11` = 3: The pulse follows after gap with loss of randLocal — whenever the previous pulse has a `timeStamp` value more than one period (π) away in the past and the hash pre-images of the previous `preCom` as been lost. In this case the field `randLocal` is filled with an all-zeros string.
- `status` = `0b100` = 4: The value `certId` in a non-staring pulse (i.e., with `pulseId` > 1) has changed since the previous pulse in the chain.
- `status` = `0b1000` = 8: The pulse is, by purposed planning, the last in the chain.
- `status` = `0b1010` = 10: The pulse follows after a gap and is marked as the last in the chain.

Notes.

- There is no flag identifying the beginning of a chain; that property **CAN** already be determined from checking `pulseId` $\stackrel{?}{=} 1$.

- Even though `FL_rndloc` is equal to 1 in the first pulse of a chain, the field `randLocal` in a new chain **MAY** still be filled with the pre-image of `preCom` of the (last) pulse of another chain.
- The requirement that the first pulse of a chain has `FL_end` = 0 intends to enforce that chains are composed of more than one pulse.

Flags for local definitions. The definition of local flags must preserve the syntax of all remaining aspects of pulses. For example, a Beacon **MAY** specify (one or more) flags to:

- represent some information about the use of RNGs, e.g., whether or not more than two RNGs have been sampled;
- indicate information about the generation-start timing, e.g., using 8 bits to encode the number of seconds in advance at which the local randomness was sampled;
- indicate whether the certificate in use has expired;
- indicate whether the signing key has changed in comparison with the previous pulse.

Use-case. The `status` field is specially useful to indicate when there is something irregular or unusual about the chain between the previous and current pulse. For certain applications, the `statusCode` field may be useful to signal to users whether the pulse is acceptable for use or not. For example, when combining pulses from different beacons, it may be necessary to require that there were no previous gaps and that the `randLocal` is correct. This **CAN** be easily filtered by checking that the 1st and 2nd LSBs are 0, without prejudice of then performing other necessary verifications.

4.4 The local random value

Field name: `localRandomValue` or (abbreviated) `randLocal`

Default type: hashOut

Relations. It is the `hash()` preimage of the `preCom` value output in the previous pulse. In the first pulse of a chain it is filled with an all-zeros string.

Description. It is a 512-bit value with 512 bits* of entropy, generated by the Beacon engine during the process of generation of the previous pulse, but kept secret from the outside until its release. (* Actually, since the value is the output of a cryptographic-hash function, the actual entropy **MAY** forfeit up to less than one bit of entropy, while remaining indistinguishable from uniformly random.)

The `randLocal` must be entirely unpredictable to any attacker outside the beacon engine. By convention, it is the result of hashing with `hash()` the concatenation of two or more 512-bit random values from independent sources. For example, if the beacon has three independent random bit generators providing random numbers ρ_1, ρ_2, ρ_3, then

$$\texttt{randLocal} = \texttt{hash}(\rho_1 \parallel \rho_2 \parallel \rho_3). \tag{12}$$

The combination of randomness from several RNGs brings an important security advantage. Even if all but one RNGs fail or are malicious, the resulting `randLocal` is still a high-quality random number. For example, any RNG providing good randomness prevents any malicious RNG from exfiltrating information via the `randLocal` field. However, there is no way for a user of the Beacon to determine whether `randLocal` has been calculated from a correct combination of randomness sampled from several RNGs.

Remark (On the timing of learning `randLocal`). For the purpose of the timing of pulse generation, the beginning of generation of each pulse corresponds to the starting moment of sampling of the RNGs. In the current design, the `randLocal` value is then obtained by the Beacon App, still before the actual pulse output (`randOut`) is calculated. Section 8.3.1 mentions a conceivable alternative (for future versions), where the `randLocal` value would be calculated in a different way, satisfying a different relation with `preCom`, such that it could only be obtained after the end of the pulse generation, and such that it could not be fully decided even by a malicious Beacon operator.

Guidance (gaps with loss of local random value). Very rarely, the Beacon engine **MAY** suffer a memory failure such that the pre-generated `randLocal` value is lost. In this case, if the chain continues then the next pulse will fill `randLocal` with all-zeros and the 2$^{\text{nd}}$ bit flag of the `status` field will be set to 1 (see Table 5).

It is not expected that pre-generated `randLocal` value is lost without the occurrence of a gap. Such conceivable event would represent, for a non-starting pulse, an abnormal condition marked with a status value 1.

4.5 External value fields

The format 2.0 for pulses specifies three fields — `ext.srcId`, `ext.status`, `ext.value` — that support the inclusion of a verifiable external source of entropy. Using an external source enables providing strong assurance, to the outside world, that even a malicious beacon could have not computed far ahead in the past the output values (`randOut`) of pulses.

Informal summary. The field `ext.value` **MAY** sometimes, optionally, be filled with the hash of a value generated by an external source. The hashing **CAN** be computed locally (e.g., the hash of the results of public lotteries) or externally (e.g., if directly using the `randOut` value of another beacon, which is already a hash). The value **SHOULD** be obtained according to a description whose hash() is recorded in the field ext.srcId. Certain aspects of the use of the external source are indicated by corresponding elements of the ext.status field.

The purpose of the ext.value field is to introduce some value that is outside the control of the beacon operator, is hard to predict before a certain moment in time, and is relatively easy for anyone to verify after the fact. For example, a given beacon might use the hash of the closing prices of some stock market, the hash of the winning lottery numbers from diverse state lotteries, or the hash of every thousandth block of some popular public blockchain. For proper usability and security, there must be no ambiguity, given the text hashed by ext.srcId, about the correct value of ext.value.

While the use of external sources is optional, the three fields are always present. When, upon starting a new chain, an external value has not been previously used, the fields ext.value and ext.srcId are filed with all zeros, i.e., with ZeroH. Once an external value is used for the first time, the same value **CAN** be repeated in subsequent pulses until a new external value is used. The repetition is useful since it continues giving to those standalone pulses an element that enables proving that the pulse generation did not happen before the existence of the external value, i.e., without need to show relations to a previous pulse.

It can be useful to identify whether the external value in a pulse appeared for the first time in that pulse or in a previous one. It is in the first use that such value is most relevant with respect to mitigating a pre-computation attack by a malicious beacon. For that reason the ext.status field contains one flag used to indicate when the ext.value has changed. As a complementary relational feature, the pulse **MAY** also show, optionally, in part of its ext.status field, the pulseId of the first pulse which used the same value of ext.value.

4.5.1 External source identifier

Field name: external.sourceId or (abbreviated) ext.srcId

Field type: hashOut

Relations: ext.value = hash(ext.TextSrcDesc)

(Notice that ext.TextSrcDesc is not a pulse field.)

Description. It is filled with the hash() of a MIME type text/plain document, encoded as a UTF8 string (ext.TextSrcDesc), describing the external source of entropy, including instructions for updating ext.value. When an external source is not used in a pulse, the field is set to ZeroH.

To allow complete verification of all pulses, the text description of any source identifier ever used by the Beacon **SHALL** be available to users. Section 6.5 defines an interface call (4m) that specifies how users **CAN** obtain the text description ext.TextSrcDesc corresponding to a ext.srcId value.

Requirement.

- **Encoding of text description.** The description text (ext.TextSrcId) **SHALL** be specified as a UTF8 string. Is is used directly as the input of `hash`(), used to compute `ext.srcId`, being interpreted directly as a byte-string (each UTF8 character **MAY** be between 1 and 4 bytes long). Notice that here we do not apply `Byt_serialize_string`, which would otherwise prefix the byte length of the text description.

Recommendations. A definition of an external source **SHOULD** specify several attributes:

1. **External source (text description):** a short description of the type of value.
2. **Intended update frequency:** the expected frequency with which the `ext.value` field will be updated with respect to this source.
3. **Intended update moment:** the first timestamp intended for each new `ext.value`.
4. **Repeat until new available value (yes/no):** a "yes" or "no" answer to whether the value `ext.value` **SHOULD** continue repeating, in opposition to reverting to an all-zeros string, until a new external value is available for update.
5. **Local hashing (yes/no):** whether the Beacon needs to hash the value obtained from the external source. By default, we assume that external values **SHOULD** be hashed. However, this **CAN** be avoided if the value is already described as a suitable hash output of an externally obtainable pre-image. For example, this is the case if the external source value is the `randOut` value of some other compliant beacon. In that case, not doing local hashing has the benefits of allowing an easier external search for any used `ext.value`, and allowing an easier verification by the user (e.g., side-by-side comparison of the `randOut` in one beacon vs. the `external.value` in another beacon).
6. **Default URL for access (uriStr):** the expected URL from which users **CAN** obtain information about the value and authenticity of the pre-image of the used `ext.value`.
7. **Recommended sampling trials (string):** when to retry sampling, if initial trials fail.
8. **Fall back options:** what to do if the external source is unavailable beyond a reasonable time window.

A sketch example of a source identifier — Output values from an external beacon. "External source: from the Chilean Beacon (https://beacon.clcert.cl/), the output value (`randOut`) of the pulse with largest `timeStamp` value with ⟨hour⟩ component not larger than 12. Intended update frequency: daily. Intended update moment: for every "15:00:00.000" UTC time mark, update the external value in the first (local) pulse with `timeStamp` with ⟨hour⟩ component not smaller than 15. Repeat until new available value: yes. Local hashing: no. Default URL for access: https://beacon.clcert.cl/beacon/2.0/time/previous/⟨date⟩-12:00:00.001Z" where ⟨date⟩ is the current day if sampled after 15:00:00.000. Recommended sampling trials: starting at 12:05, sample the external source once every 5 minutes until obtaining `randOut` of a pulse with `timeStamp` not inferior to 12:00. Fall back options: None. (Always use the latest `randOut` value of the external beacon obtained from the recommended trials.)

The definition of an external source **SHOULD** be precise and careful. We currently defer those definitions to a future addendum or separate document, and simply enumerate here, in high-level, a few other examples of conceivable sources:

- *stock markets* — the closing index of some stock market, from the current trading day, e.g., updated at 23:00 local time on trading days (not on holidays).
- *time synchronization information* — the recorded offsets between national official clocks across many countries, with respect to a universally accepted global clock, possibly updated once an hour.
- *independently run lotteries* — results from national lotteries occurring at predictable days, across several states or countries.
- *seismic or weather data sources* — using structured data from a reliable publisher that allows search of corresponding historical data.

Additional aspects. A more detailed set of recommendations and examples is deferred to a future separate document.

4.5.2 External Status

Field name: `external.statusCode` or (abbreviated) `ext.status`

Default type. uint64

Description. It is a sequence of 64 bits, informing aspects of the status of the use of an external source. It provides useful information on how to interpret the use of fields `ext.srcId` and `ext.value`.

Serialization. When part of a hash input, it is serialized as a 64-bit unsigned integer. However, for ease of reference it **CAN** be described as a pair of 32-bit unsigned integers: the first, of optional filling, represents the index of the first pulse that used the same `ext.value` — if not filled it is set to `ZeroH`. the second represents a sequence of 32 bit-flags denoting aspects of the status of the use of an external source. In the latter, the ordering (1^{st}, 2^{nd},..., 32^{th}) of flags is from right to left, to match the ordering of least significant bits (LSBs) of the 64-bit unsigned integer corresponding to the (big-endian) serialization of the bit-vector.

Example values. Let `0bX...X` be a sequence of bits `X...X`, where the i^{th} `X`, counting from right to left, represents the i^{th} LSB of (i.e., with additive weight 2^{i-1} in) the integer value

Table 6. Bit-flags of the `ext.status` field

LSB	Variable name	What?	if set (1)	if unset (0)
1^{st}	`FLE_extValUsed`	External value is used in this pulse?	yes	no
2^{th}	`FLE_SrcIdChan`	`ext.srcId` has changed?	yes	no
3^{th}	`FLE_extValChan`	`ext.value` has changed?	yes	no
4^{th}	`FL_extValOld`	`ext.value` failed to update?	yes	no
5^{th}	`FLE_WhyOld`	A missed update is internal fault?	yes	no
6^{rd}	`FLE_RegNewSrcId`	Registration of new `ext.srcId`?	yes	no
7^{th}–15^{th}	—	Reserved for future definition	—	—
16^{th}	`FLE_showsFirstPid`	Is `ext.FistPidSameExt` filled?	yes	no
17^{th}–32^{th}	—	Reserved for local definition (per Beacon)	—	—
33^{th}–64^{th}	`ext.FistPidSameExt`	`pulseId` (a 32-bit index) of the first pulse with same `ext.value`	(Optional use)	

LSB = least significant bit. The FLE prefix indicates a flag of the `ext.status` field.

`ext.status`. We enumerate several examples:

- `ext.status` = 0b0 = 0: No external value used; implies that `ext.value` and `ext.srcId` are all zeros.
- `ext.status` = 0b1 = 1: `ext.value` is in use (1^{st} flag is 1), filled with a (possibly hashed) value obtained from an external source, either in repetition (4^{th} flag is 0) or being in the first pulse in the chain (4^{rd} flag is 0).
- `ext.status` = 0b10 = 2: The `ext.srcId` field is filled with a new value, but there is no corresponding value in the `ext.value` field. This case is used to signal to users that the new `ext.srcId` value is the identifier of a new potential source, to be used later. This is called a registration of a new `ext.srcId`.
- `ext.status` = 0b1001 = 9: The `ext.value` in use (`FLE_extValUsed` = 1) was supposed to have already changed (`FL_extValOld` = 1), but it has not changed due to some external problem (`FLE_WhyOld` = 0).
- `ext.status` = 0x11 0000 8001 = $17 \cdot 2^{32} + 2^{15} + 2^{0}$: The current `ext.value` appeared in this chain for the first time in the pulse with `pulseId` = 0x11 = 17.

Recommendation (registration of new external source identifier). It is convenient to limit `ext.srcId` to be filled with values previously announced to users. For that purpose, whenever a new source identifier *scrNew* is devised by a Beacon, it **SHOULD** first be registered in a pulse, by issuing a pulse with `ext.srcId` = *scrNew*, `ext.value` = `ZeroH` and FLE_RegNewSrcId = 1. From that point onward, it becomes "non-surprising" to have an external value filled in `ext.value`, with a corresponding source Id `ext.srcId` = *scrNew*.

Flags for local definitions. The current definition of the `external.statusCode` field allows 16 bits to be defined locally by each beacon. This **CAN** for example be used to indicate additional useful information about how to interpret information of external values, or external source descriptions. For example, a beacon **MAY** decide to use several bits to indicate with more detail the reason for a missed update of an external value.

4.5.3 External Value

Field name: `external.value` or (abbreviated) `ext.value`

Default type. hashOut

Description. It is filled with the `hash`() of the sampled value of an external source of entropy whose description is committed (by a hash) in the `ext.srcId` field. The sampled value must be encoded as a UTF8 string, and used directly as the input of `hash`(), when used to compute `ext.value`, being interpreted directly as a byte-string (each UTF8 character **MAY** be between 1 and 4 bytes long). Notice that here we do not apply `Byt_serialize_string`, which would otherwise prefix the byte length of the text description.

Since the use of an external source is optional, when not in use the fields `ext.value`, `ext.status` and `ext.srcId` are set to zero (e.g., a string of integers zero when serialized as a byte-string).

4.6 Fields with past output values

The previous beacon format (1.0) had a single field (`previous`) containing the `outputValue` value of a past pulse (the previous one). This ensured that the sequence of pulses formed a hash chain. The new beacon format has five such fields, in order to support more efficient ways of proving consistency between pulses. These values are maintained within a single chain of pulses (that is, the sequence of pulses with the same `chainId` value from a given beacon operator).

The extra named fields permit a very efficient proof of an intact hash chain between pulses at any two timestamps T_1 and T_2, as will be further discussed in Section 5.

4.6.1 Previous

Field name: `previous` or `out.Prev`.

Field type. hashOut

Description. It is filled with the randOut value of the previous pulse. This field ensures that an unbroken sequence of pulses forms a hash chain. If the most recent pulse in the chain is known, an alteration of any earlier pulse in the chain **CAN** be easily detected. This hash-chaining ensure that even the beacon operator has no power to rewrite the history previous to a known pulse.

Chain-start values. When a new chain starts, if possible the previous field **SHOULD** be filled with the value in the randOut field of the last pulse of the previous chain. All other past-output fields (out.H, out.D, out.M, out.Y) are set to ZeroH.

4.6.2 Hour, Day, Month and Year

Each pulse replicates, besides the previous output value (out.Prev), several other past output values chosen in accordance to a relation of time values. Concretely, each pulse with index (pulseId) i includes the first representative pulse of each UTC timestamp component related to the timestamp of the previous pulse (i.e., with pulseId $= i-1$). There are four such fields, corresponding to the time components *hour*, *day*, *month* and *year*.

Field names: hour or out.H; day or out.D; month or out.M; year or out.Y.

Field types. hashOut

Description: Each pulse replicates several past output values, i.e., the randOut value from past previous pulses. For each of the named fields $x \in \{\texttt{hour}, \texttt{month}, \texttt{day}, \texttt{year}\}$, the past pulse from which to collect the randOut value is chosen as follows:

1. Look at the UTC timestamp T' of the pulse *previous* to the current one.
2. Let T'' be the first timestamp, present in some past pulse, whose truncation down to the precision of the x component (*hour*, *month*, *day* or *year*) is equal to the corresponding truncation of T'.
3. Fill $P[T].x$ with value $P[T''].\texttt{randOut}$. More concretely:
    - year gets randOut from the first pulse with timeStamp with the same UTC ***year*** as the timeStamp of the previous pulse.
    - month gets randOut from the first pulse with timeStamp with the same UTC *year* and ***month*** and as the timeStamp of the previous pulse.
    - day gets randOut from the first pulse with timeStamp with the same UTC *year*, *month* and ***day*** as the timeStamp of the previous pulse.
    - hour gets randOut from the first pulse with timeStamp with the same UTC *year*, *month*, *day* and ***hour*** as the timeStamp of the previous pulse.

In other words, for any field $\langle x \rangle \in \{$`hour`, `day`, `month`, `year`$\}$, the value $\langle x \rangle_i$ (i.e., $P_i.\langle x \rangle$) is filled with the $\texttt{randOut}_j$, where j is the `pulseId` of the first pulse whose truncation of `timeStamp`, down to the precision of the time component $\langle x \rangle$, equals the corresponding truncation of $\texttt{timeStamp}_{i-1}$. For example, $\texttt{year}_i = \texttt{outputValue}_j$, where j is the `pulseIndex` value in the first pulse whose UTC **year** in $\texttt{timeStamp}_j$ is equal to the UTC **year** of $\texttt{timeStamp}_{i-1}$.

Values in beginning of a chain. In the first pulse of a chain:

- The values `out.H`, `out.D`, `out.M`, and `out.Y` start out as `ZeroH`.
- When possible, the field `out.Prev` **SHOULD** be filled with the `randOut` of the previous chain, if it is available; otherwise, `previous` **MAY** also start as zeros.

In the second pulse of a chain, every one of the past output value fields (`out.Prev`, `out.H`, `out.D`, `out.M`, `out.Y`) is filled with the value of the `randOut` field in the first pulse, since that pulse is the *first* pulse of the chain with the same hour, day, month, and year as the previous (i.e., the first) pulse.

Conceivable future update of format. Various Beacons or chains **MAY** have different pulsating `period`. If as part of a chain a Beacon outputs a pulse once every 5 seconds, then the corresponding skiplists could be more efficient if the hash chaining also included the output value of the first pulse with the minute equal to the previous pulse. Correspondingly, if a Beacon outputs once every day, then the fields `previous`, `hour` and `day` would become redundant and the chain would be more efficient by removing the `hour` and `day` fields. Considering the above, it is conceivable a future update that enables some flexibility on the choice, for each chain, of which past pulses are selected, and including indexations fields (e.g., `pulseId` and `time`) for the included past pulses.

4.6.3 Example without gaps

The box on the right shows an example of how to fill the fields of past output values, when there is no interference from time gaps. We consider as example a chain whose first pulse was issued with timestamp 2018-07-23 19:26.

> **Example for P[2018-11-22 16:32]**
>
> `previous` $\leftarrow$ P[2018-11-22 16:31].`randOut`
>
> `hour` $\leftarrow$ P[2018-11-22 16:00].`randOut`
>
> `day` $\leftarrow$ P[2018-11-22 00:00].`randOut`
>
> `month` $\leftarrow$ P[2018-11-01 00:00].`randOut`
>
> `year` $\leftarrow$ P[2018-07-23 19:26].`randOut`

The only unexpected value is for the `out.Y` field, which does not have a date of 2018-01-01 (January 01, 2018) because the first pulse of the chain as a posterior date.

4.6.4 Example with skipped pulses

Beacons **SHOULD** be operational most of the time, but hardware failures, software failures, power outages, and other problems **CAN** occur from time to time, and so there are times when pulses **MAY** be skipped. This introduces some complexity in the rule for determining the value in fields `hour`, `day`, `month`, and `year`.

The general rule is to start from the `timeStamp` of the *previous* pulse, and then determine the first pulse in that hour, day, month, and year. However, the first pulse in an hour **MAY** have a timestamp with a minute component different from **00**.

Example with consecutive skipped pulses. Consider the example on the right, with a time-gap between 2018-12-26 16:08 and 2019-01-22 13:24. This time-gap existed in the chain with index 1 of the NIST Randomness Beacon version 2, due to a U.S. Government shutdown. The mentioned gap means that after the issued pulse with timestamp 2018-12-26 16:07 (and `pulseId` $= 220,394$) several expected pulses were skipped, such that the subsequent issued pulse has timestamp 2019-01-22 13:25 (and `pulseId` $= 220,395$).

2018-07-23 **19:26**
2018-07-23 **19:27**
⋮
2018-12-26 **16:06**
2018-12-26 **16:07**
[Gap (skipped pulses)]
2019-01-28 13:25
2019-01-28 13:**26**

Assuming no other pulses have been skipped, we **CAN** determine the linking fields for the first two pulses after the outage. The existing relations are depicted in Fig. 5.

- **First pulse after outage.** P[2019-01-28 **13:25**] is the first pulse produced after the exemplified outage. Highlighted in yellow background in Fig. 5 is the `previous` field, which was filled with the `randOut` value of the previous pulse, which had a surprising timestamp (because of the time gap). The link is to a pulse produced more than one month in the past, due to the exemplified outage. In relation to the previous pulse, all the other fields with past output values link to the output values of past pulses generated at the expected times. Specifically, they link to the first pulse produced in the {hour, day, month, year} specified in the timestamp of the *previous* pulse.
- **Second pulse after outage.** P[2019-01-28 **13:26**] is the second pulse produced after the outage. In this case, the potentially surprising linking timestamps (highlighted in yellow in Fig. 5) are those used to populate the `out.H`, `out.D`, `out.M` and `out.Y` fields. Those four fields contain the same value, since the gap crossed the year boundary.

4.6.5 If past output values are lost

It is conceivable, although unexpected, that a memory problem in the Beacon App **MAY** lead it to lose access to the past output values needed for hash-chaining of each new pulse. The Beacon **SHALL NOT** continue the same chain without a proper hash-chaining of all those fields. Thus, it the Beacon operator wishes to continue the chain, it **SHALL** update the state of the Beacon App with information about the past pulses (which by then **SHOULD** be

Example: During a U.S. Government shutdown, the NIST Beacon had a gap in chain 1 between times 2018-12-26 16:08 and 2019-01-28 13:24.

1st pulse after gap: P[2019-**01-28 13:25**]	2nd pulse after gap: P[2019-**01-28 13:26**]
`previous` ← P[**2018-12-26 16:07**].`randOut`	`previous` ← P[2019-01-28 13:**25**].`randOut`
`hour` ← P[2018-12-26 16:**00**].`randOut`	`hour` ← P[2019-01-28 13:**25**].`randOut`
`day` ← P[2018-12-26 **00**:00].`randOut`	`day` ← P[2019-01-28 13:**25**].`randOut`
`month` ← P[2018-12-**01** 00:00].`randOut`	`month` ← P[2019-01-28 13:**25**].`randOut`
`year` ← P[2018-**07**-23 19:26].`randOut`	`year` ← P[2019-01-28 13:**25**].`randOut`

Figure 5. Obtaining past output values after gaps

externally known, since they had already been released to the Beacon databases and possibly queried from the outside). This update is contrary to the usual logical flow of information, which is supposed to be unilateral between the Beacon Engine and the database of pulses.

4.7 The precommitment value

Field name: `precommitmentValue` or (abbreviated) `preCom`

Default type: hashOut

Relations: The field is defined as P_i.`preCom` = `hash`(P_{i+1}.`randLocal`)

Description: It is a hash commitment to the *next* pulse's `randLocal`. This requires the beacon to know `randLocal` of the *next* pulse before *this* pulse is output. The purpose of the field is to facilitate combining of outputs from multiple beacons, as discussed in Section 7.4.

Guidance (simple gaps). When there is a gap in the sequence of pulses, the beacon engine **SHOULD** have the next `localRandomValue` value stored. Under most circumstances, then, the next pulse, even if it appears after a lengthy gap in the sequence of pulses from the beacon, **SHOULD** have `randLocal` such that `precommitmentValue` = `hash`(`localRandomValue`).

For example, suppose there is a sequence of pulses with timestamps as exemplified on the right, with a time-gap of with pulses skipped between 2019-01-22 01:13 and 2019-01-22 05:24: Under normal circumstances, the beacon engine will have retained the `randLocal` value committed by P[2019-01-22 01:12].`preCom`. In such case we will have:

2019-01-22 01:**11**
2019-01-22 01:**12**
[Gap (skipped pulses)]
2019-01-22 **05:25**
2019-01-22 05:**26**

$$P[\text{2019-01-22 } \mathbf{01{:}12}].\texttt{preCom}] = \texttt{hash}(P[\text{2019-01-22 } \mathbf{05{:}25}].\texttt{randLocal}) \qquad (13)$$

and P[2019-01-22 05:25].`status` = $0b10$ will indicate that a time gap existed in the production of pulses and that the pre-image of `precommitmentValue` remained intact.

Guidance (gaps with loss of local random value). Very rarely, the Beacon engine **MAY** suffer a catastrophic failure such that the pre-generated randLocal value is lost. In that case, P[2019-01-22 05:25].status= 0b11 will indicate both a gap before 2019-01-22 05:25 and also a failure to reveal a pre-image of preCom. In this case, randLocal is set to all-zeros, implying P[2019-01-22 01:12].preCom $\neq$ hash(P[2019-01-22 05:25].randLocal).

4.8 Signature-related fields

4.8.1 Signature

Field name: signatureValue or (abbreviated) sig

Default type: sigOut

Relations: $\mathrm{F}_{20,i} = \mathtt{sig}_i = Sign_{SK}\left(\mathtt{hash}\left(||_{k\in\{1,\ldots,19\}}\overline{\mathrm{F}_{k,i}}\right)\right)$; or, as a sequence of three steps:

$$
\begin{aligned}
Z \leftarrow & \mathtt{Byt\_serialize\_fields}(\langle \mathtt{uri}, \mathtt{version}, \\
& \mathtt{cipher}, \mathtt{period}, \mathtt{certId}, \mathtt{chainId}, \mathtt{pulseId}, \mathtt{time}, \\
& \mathtt{randLocal}, \mathtt{ext.srcId}, \mathtt{ext.status}, \mathtt{ext.value}, \\
& \mathtt{previous}, \mathtt{hour}, \mathtt{day}, \mathtt{month}, \mathtt{year}, \mathtt{preCom}, \mathtt{status}\rangle) \quad (14) \\
H \leftarrow & \mathtt{hash}(Z) \quad (15) \\
\mathtt{sig} \leftarrow & \mathtt{SIGN}(SK, H), \text{ where } SK \text{ is the secret signing key.} \quad (16)
\end{aligned}
$$

Description: A (cryptographic) digital signature of the hash() of a concatenation of the byte-serialization of all previous fields in the pulse. When cipher $= 0$, the value produced is an RSA signature using PKCSv1.5 padding, encoded unambiguously as a byte string (see Section 4.1.2).

The signature allows a user to confirm that the pulse came from the beacon claimed in the uri field, and has not been altered since then. In the case of an attempt by the beacon operator to alter previous beacon pulses (aka, to rewrite history), the signature **CAN** be used to provide evidence of its misbehavior — the existence of a properly signed beacon pulse which is not on the chain of pulses is unambiguous evidence of misbehavior by the beacon. (It is not necessarily evidence of malfeasance, but it is unambiguous evidence that the beacon is not following the protocol.)

4.8.2 Certificate ID

Field name: certificateId or (abbreviated) certId

Default type: hashOut

Description. It is the hash() of a Base 64 encoded PEM formatted file (X.509 ASN.1 encoding), following the RFC 5280 [CSF+08] specification, containing the certificate(s) of the public counter-part of the Beacon signing key used to produce the value in the `signatureValue` field of the pulse. The signing key must always have a corresponding certificate, even if it is self-signed. However, it is recommended that certificates be attested by some external entity (a certification authority, the Certificate Transparency log, etc.).

Retrieving the certificate(s). The beacon must make available online the current certificate and all previous certificates, so that it is always possible to verify signatures and certificates of old pulses. This is handled by interface call 3g defined in Section 6.4.

4.9 The Output Value

Field name: `outputValue` or (abbreviated) `randOut`

Default type: hashOut

Relations: $\mathrm{F}_{21,i} = \texttt{randOut}_i = \left(\texttt{hash}\left(||_{k\in\{1,\dots,120\}}\overline{\mathrm{F}_{k,i}}\right)\right)$, that is:

$$\begin{aligned} Z \leftarrow & \texttt{Byt\_serialize\_fields}(\langle \texttt{uri}, \texttt{version}, \\ & \texttt{cipher}, \texttt{period}, \texttt{certId}, \texttt{chainId}, \texttt{pulseId}, \texttt{time}, \\ & \texttt{randLocal}, \texttt{ext.srcId}, \texttt{ext.status}, \texttt{ext.value}, \\ & \texttt{previous}, \texttt{hour}, \texttt{day}, \texttt{month}, \texttt{year}, \texttt{preCom}, \texttt{status}, \texttt{sig}\rangle) \qquad (17) \\ \texttt{randOut} \leftarrow & \texttt{hash}(Z) \qquad (18) \end{aligned}$$

Description: The value in the `randOut` field is called the *output value* of the pulse. It is the hash() of the values in all previous fields of the pulse. This accomplishes several goals:

1. Since it hashes `preCom`, which in turn is the hash of a fresh `randLocal` (to be released only in the next pulse), it contains fresh (and approximately) full entropy.
2. Even if a malicious Beacon operator controls any other field (e.g., `preCom`, `ext.srcId`, `ext.value`), controlling n bits of `randOut` would require computational effort exponential in n.
3. A sequence of consecutive pulses constitutes a hash chain, which means each pulse with a latest timestamp commits all previous pulses.

Guidance: User applications relying on a single Beacon **SHALL** use `randOut`, rather than `randLocal`, as the public randomness output of the Beacon (see Section 7 for details).

5 Hash Chains and the Skip List

Each pulse contains an `outputValue` field, which is the hash of all the other fields in the pulse. Each pulse also contains a `previous` field, which contains the `outputValue` of the previous pulse. Putting these two fields together, a sequence of pulses makes up a *hash chain*. A hash chain ensures that **once a single pulse is known, previous pulses CANNOT be changed** without leaving obvious evidence in the chain.

5.1 Hash Chains

A sequence of consecutive pulses makes up a hash chain, as shown in Fig. 6. The Figure also illustrates the relation between three fields in consecutive pulse:

- `timeStamp` — incremented by 1 minute in each pulse.
- `previous` — a copy of the `outputValue` field from the previous pulse.
- `outputValue` — the `hash()` of all other fields in its pulse.

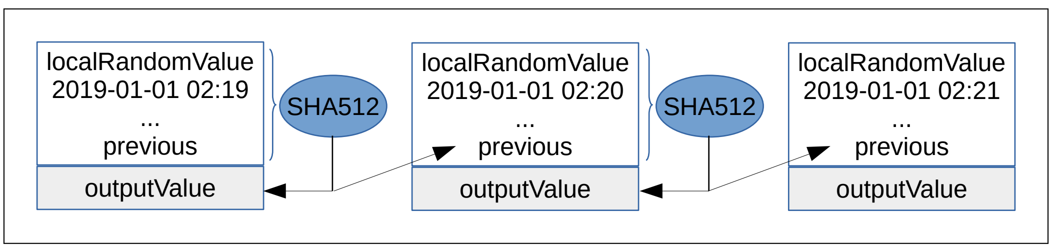


Figure 6. The sequence of pulses forms a hash chain

In order to make these diagrams legible, most pulse fields are omitted, some fieldnames are shortened, and `timeStamp` values are in the **yyyy-mm-dd hh:mm** (RFC3339) format. All examples in this document assume that the beacon is producing pulses once per minute.

The important security property of a hash chain is that **changing any record requires changing all future records.** That is, if we alter any field in a given pulse, this must change its `outputValue`, since that value is the hash of the other fields of the pulse. That `outputValue` is then included in the next pulse. A changed value there must lead to a changed value in the `outputValue` of the next *next* pulse. And so on — any change to a pulse propagates forward forever. Figure 7 shows an example of how this works. This property implies that, as long as beacon pulses are widely seen and recorded, it is impossible for even the beacon operator to alter a past pulse without detection.

5.2 Skiplists

Section 5.1 showed that, by verification of the hash-chain created across consecutive pulses, anyone who has recorded the pulse at time T CAN later review any previous pulse at time

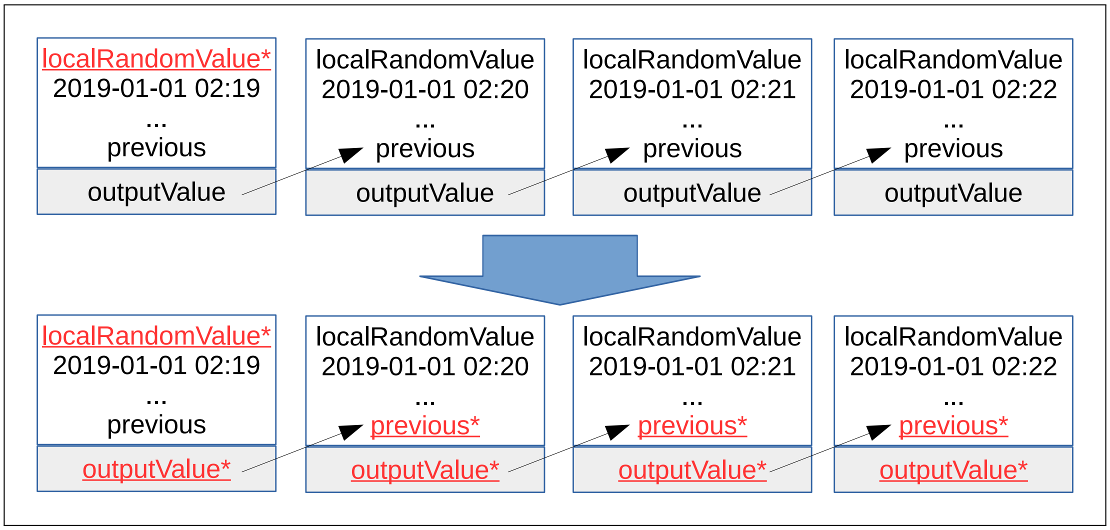


Figure 7. A change in one pulse propagates to all later ones via the hash chain

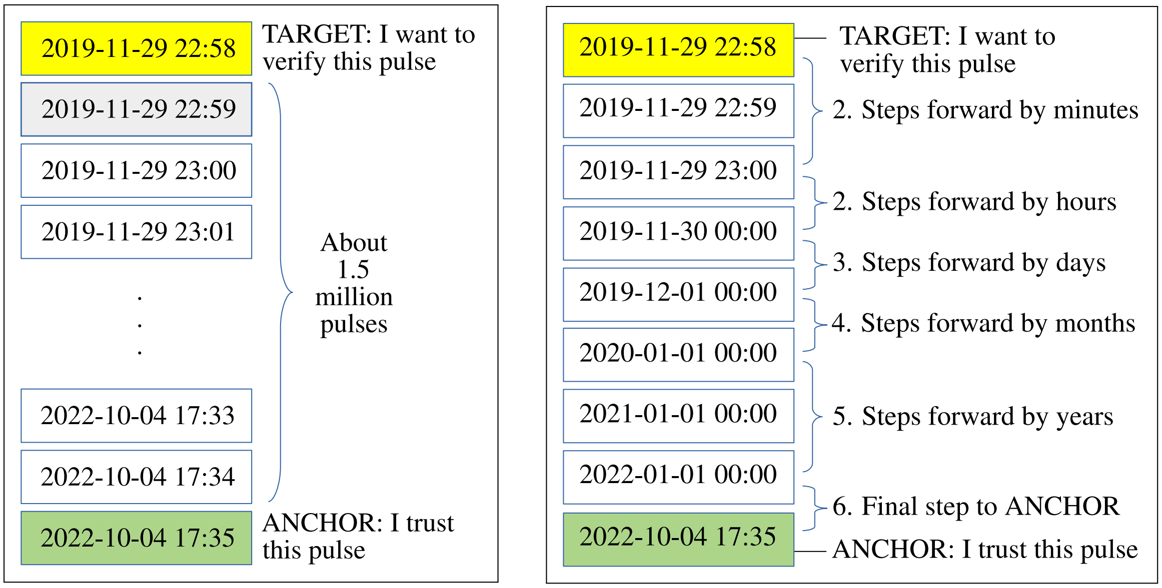
$T-K$, and verify that the latter has not been changed. However, checking the chain across every consecutive pulse requires examining *every pulse* from time $T-K$ through time T, as illustrated in Fig. 8a. Using this approach, verifying that a pulse from one year ago is consistent with the most recent pulse requires examining over *half a million* pulses, which can be unworkably long. A security mechanism that is impractically inefficient will seldom be used. The solution to this problem is a *skiplist*.

Consider that a user of the beacon starts out knowing the value of one pulse (the ANCHOR), from 2022-10-04 17:35. The user wants to verify that the value of a much earlier pulse (the TARGET), at 2019-11-29 22:08, is consistent with the later (ANCHOR) pulse. The user thus contacts the beacon frontend and requests a skiplist from the beacon. The beacon responds with a short sequence of pulses constituting an intact hash chain from TARGET to ANCHOR.

Why is it possible to construct a short intact hash chain between such distant pulses? Because of the additional linking fields added in version 2.0.0, namely `year`, `month`, `day`, and `hour`. These ensure that there are *many different* hash chains, of many different lengths, running through the sequence of pulses.

The existence of all these linking fields (`year`, `month`, `day`, `hour`, as well as `previous`), and all the corresponding combinations of hash chains, means that, between a given TARGET and ANCHOR, there are in general *many* different pulse sequences that contain an intact hash chain. Algorithm 5 gives a procedure for selecting a minimal-length chain. The same algorithm is illustrated in Fig. 8b.

Figure 8 compares, side by side, the case of a complete hash-chain (in Fig. 8a) vs.



(a) Long subchain (b) Short skiplist

Figure 8. Linking a trusted ANCHOR pulse to a TARGET pulse for verification

the case of a corresponding skiplist (in Fig. 8b). The efficiency improvement brought by the skiplist is huge: from about 1.5 million pulses to 9 pulses. However, this example was chosen to provide a relatively short skiplist, for ease of explanation. In general, for TARGET and ANCHOR points Y years apart (each on a uniformly random minute, hour and day of the corresponding year), we expect a skiplist to be about $Y+62$ pulses long. On average we need to obtain, besides the TARGET and the ANCHOR, about 28.5 pulses that are not first-in-an-hour, 11.5 first-in-an-hour pulses that are not first-in-a-day, 14.5 first-in-a-day pulses that are not first-in-a-month , 5.5 first-in-a-month pulses that are not first-in-a-year, and Y first-in-a-year pulses.

To verify the performance of the skiplists in the general case, we randomly selected TARGET and ANCHOR points which were different time-intervals apart: one day, 30 days, one year, and ten years. For each duration, we repeated the experiment 100,000 times, and found the shortest, average, and longest skiplists from all our experiments. The results are summarized in Table 7.

Table 7. Length of skiplists (in pulses), by duration

Time interval	Minimum	Average	Maximum
1 day	2	43.2	84
30 days	2	57.8	113
1 year	3	63.2	124
10 years	12	72.1	132

Algorithm 5 Construct a skiplist from TARGET to ANCHOR.

```
function MAKE_SKIPLIST(TARGET, ANCHOR)
    path ← []
    current ← TARGET
    while current < ANCHOR do
        path ← pp ||current
        if current is first pulse in its year then
            current ← first pulse in NEXT year
        else if current is first pulse in its month then
            current ← first pulse in NEXT month
        else if current is first pulse in its day then
            current ← first pulse in NEXT day
        else if current is first pulse in its hour then
            current ← first pulse in NEXT hour
        else
            current ← NEXT pulse
    path ← path ||ANCHOR
    return (path)
```

5.3 Verifying a Skiplist

The new beacon frontend supports requests for skiplists — when asked, it will produce a skiplist that provides an intact hash chain between a requested TARGET and ANCHOR value. The skiplists are short and efficient to construct, so supporting such requests imposes little burden on the frontend (web server).

Similarly, verifying a skiplist is very efficient. The requirement for a skiplist to be valid is simple: *each pulse in the skiplist must contain the* `outputValue` *field of the previous pulse in one of its linking fields (that is,* `year`*,* `month`*,* `day`*,* `hour`*, or* `previous`*).* We provide a procedure for verifying that a skiplist gives an intact hash chain in Algorithm 6.

Algorithm 6 Verify a skiplist from TARGET to ANCHOR.

```
function VERIFY_SKIPLIST(TARGET, ANCHOR, path)
    n ← number of entries in path.  // path is indexed from 1 to n
    Q ← path[1]
    for i ← 2...n do
        current ← path[i]
        if Q.out ∉ current.{year,month,day,hour,previous} then
            return False
    return True
```

6 The Beacon Interface

This section describes the interface that a beacon frontend **SHOULD** support for retrieval requests (a.k.a. calls or queries) by users. The Beacon Engine is not involved in the handling of queries, since it **SHOULD** be isolated as much as possible. Instead, queries received via a web-interface (frontend) are processed as queries to the external database of the Beacon. The section describes first a general syntax for queries (Section 6.1) and then the mandatory and optional queries. The calls are organized according to the type of requested data: individual pulses (Section 6.2), sequences of pulses (Section 6.3), related to certificates (Section 6.4), related to external values (Section 6.5), and related to local functioning (Section 6.6). The calls identified as optional **MAY** be changed, deprecated or promoted to mandatory in future sub-versions (2.0.z) or versions (2.y.z) of the Beacon Reference.

6.1 General syntax for queries and replies

A deployed Beacon **SHOULD** use an *application programming interface* (API) based on *representational state transfer* (REST) calls conveyed through URIs. Queries are transformed into GET operations, then resulting in a reply in some expected language/format. It is intended that users **CAN** use a regular web-browser to query a beacon.

6.1.1 General query-format

Any query must be specifiable via an appropriate URI that contains as prefix a URL that identifies the beacon. This URL prefix, denoted hereafter as $\langle beaconURL \rangle$, is not a field of the pulse format but is a prefix of the value in the `uri` value of the most recent pulses. Recalling the definitions in §4.2.1, the value $\langle beaconURL \rangle$ **CAN** be described as:

$$\langle beaconURL \rangle = \langle webPrefix\text{:str} \rangle / \texttt{beacon} / \langle version\text{:str} \rangle. \quad (19)$$

For example, this value is https://beacon.nist.gov/beacon/2.0 in the current NIST beacon.

The full URI is composed of the mentioned prefix and additional elements that specify the parameters of the query. These additional elements **MAY** for example include timestamp values, or pulse and chain indices. Each query indicates a type of intended response, such as a single pulse (§6.2), or a sequence of pulses (§6.3). There are also queries for associated data, such as for an X.509 certificate (§6.4), or for the text that describes an external source (§6.5).

6.1.2 General reply-format

Possible reply formats include *bare* (a simple concatenation of byte-serialized fields, similar to what was described in Section 4.1.3), *txt* (a MIME type text/plain document, assembled in a .txt file with UTF8 encoding), *hypertext markup language* (HTML), *javascript object notation* (JSON), and *extensible markup language* (XML).

This document defined the *bare* and *txt* formats. The specification of the remaining formats is currently deferred to a future external document.

The reply format **MAY** either be implicitly decided by the Beacon or explicitly specified by the user when making a query. For the latter, the user appends to the query URI the string "?format=$\langle$*format*$\rangle$", where $\langle$*format*$\rangle$ is a short identifier of the intended format, e.g., `bare`, `html`, `json`, `txt`, `xml`. For example, a URI ending with "?format=xml" will specify a query whose output **SHOULD** be produced with an XML format.

Mandatory support. In the current beacon reference version (2.0.0), a beacon is only required to satisfy at least one of the above mentioned formats. Future reference updates (2.0.z and 2.y.z) **MAY** require that the support for some specific formats becomes mandatory. Section 6.6 specifies an optional (recommended) query (5j) whose reply enumerates/describes the types of format supported by the Beacon for each type of query.

When a reply format is specified explicitly, the reply **SHOULD** enable saving the output as a file with a name extension (.txt, .json, .xml, ...) that identifies the format.

Remark on types of format. Fieldnames are not part of the content of a pulse, and so do not appear in the bare format. However, some reply formats (e.g., xml) contain a structure that labels each field value with is a corresponding field name. This motivates distinguishing two types of reply format:

- **Untagged.** Some formats contain an implicit structure that is not obvious from the output alone and does not explicitly identify the type of included components. For example, in the case of replies containing a pulse, this happens with the *bare* and the *bare-txt* formats, similar to what was described in Section 4.1.3. Those formats do not specify any fieldname, and instead consist simply of a concatenation of serialized field values, in an expected order and length.

- **Tagged.** Some formats contain a structure of tags that enable explicit identification of the type of content. For example, in the case of replies containing a pulse, the reply will contain tags that identify each field by fieldname. This intends to make easier the parsing and consistency checking of of values of each field of a pulse.

Error responses. Each of the described calls returns either a suitable reply, when one exists, or an error message.

6.2 Queries for single pulses

Table 8 enumerates the mandatory calls for single pulses, showing their designations and the corresponding URIs. Each of the described queries returns either a suitable pulse (if one exists) or else a 404 error message.

Table 8. Interface calls for individual pulses

#	Designation	URI
1p	Pulse ⟨*pid*:dec⟩ in Chain ⟨*cid*:dec⟩	⟨*beaconURL*⟩/chain/⟨*cid*:dec⟩/pulse/⟨*pid*:dec⟩
1q	Pulse at Time GEQ to ⟨*ts*:str⟩	⟨*beaconURL*⟩/pulse/time/⟨*ts*:str⟩
1r	Pulse at Time Previous to ⟨*ts*:str⟩	⟨*beaconURL*⟩/pulse/time/previous/⟨*ts*:str⟩
1s	Pulse at Time Next to ⟨*ts*:str⟩	⟨*beaconURL*⟩/pulse/time/next/⟨*ts*:str⟩
1t	Latest Pulse	⟨*beaconURL*⟩/pulse/last

Below follows a description of the output of each call:

1p. Pulse ⟨*pid*:dec⟩ in Chain ⟨*cid*:dec⟩. Returns, from within the chain with index ⟨*cid*:dec⟩ (or, if ⟨*cid*:dec⟩=last, from the chain with maximal index), the pulse P that has pulse index P.`pulseIndex`=⟨*pid*:dec⟩ (or, if ⟨*pid*:dec⟩=last, the pulse with maximal pulse index). Although the fields ⟨*pid*:dec⟩ and ⟨*cid*:dec⟩ are here described as requiring decimal format, they **MAY** also be filled with the four-character string "last" to denote a query for the corresponding largest produced value(s) (of `chainId` and/or `pulseId`, respectively).

1q. Pulse at Time GEQ to ⟨*ts*:str⟩. Returns the pulse that has the smallest `time` value *greater or equal* (GEQ) to the timestamp specified by ⟨*ts:str*⟩. Particularly: if there is a pulse P satisfying P.`time`=⟨*ts*:str⟩, then that pulse is returned; otherwise the pulse with smaller ⟨*ts'*⟩=P.`time` satisfying ⟨*ts'*⟩ $>$ ⟨*ts*⟩ is returned, if one exists.

1r. Pulse at Time Previous to ⟨*ts*:str⟩. Returns the pulse that has the larger `time` value that is smaller than the time specified by ⟨*ts*:str⟩.

1s. Pulse at Time Next to ⟨*ts*:str⟩. Returns the pulse that has the smaller `time` value that is larger than ⟨*ts*:str⟩.

1t. Latest Pulse. Returns the last available pulse on the last chain, i.e., the pulse $P_{j,i}$ satisfying P.`chainId` $= j$ and P.`pulseId` $= i$, such that there is no other pulse with larger chain index (in `chainId`), and such that within the chain with index j there is no pulse with pulse index (in `pulseId`) larger than i. Note that this query is an abbreviation of what **CAN** also be obtained with the query 1p, as ⟨*beaconURL*⟩/chain/`last`/pulse/`last`

6.3 Queries for sequences of pulses

Table 9 enumerates the mandatory calls for sequences of pulses. The currently defined sequences are skiplists and subchains. Each of the described queries returns either a suitable non-empty sequence of pulse (if one exists) or else a 404 error message.

Table 9. Interface call for sequences (skiplists and subchains) of pulses

#	Designation	URI	Opt?
2m	Skiplist between Times $\langle ts_1$:str$\rangle$ and $\langle ts_2$:str$\rangle$	$\langle beaconURL\rangle$/skiplist/time/$\langle ts_1$:str$\rangle$/$\langle ts_2$:str$\rangle$	
2n	Skiplist in Chain $\langle cid\rangle$ between Pulses $\langle pid_1$:dec$\rangle$ and $\langle pid_2$:dec$\rangle$	$\langle beaconURL\rangle$/skiplist/chain/$\langle cid$:dec$\rangle$/pulse/$\langle pid_1$:dec$\rangle$/$\langle pid_2$:dec$\rangle$	
2o	Subchain across Times $\langle ts_1$:str$\rangle$ and $\langle ts_2$:str$\rangle$	$\langle beaconURL\rangle$/subchain/time/$\langle ts_1$:str$\rangle$/$\langle ts_2$:str$\rangle$	yes
2p	Subchain of Chain $\langle cid$:dec$\rangle$ across Pulses $\langle pid_1$:dec$\rangle$ and $\langle pid_2$:dec$\rangle$	$\langle beaconURL\rangle$/subchain/chain/$\langle cid$:dec$\rangle$/pulse/$\langle pid_1$:dec$\rangle$/$\langle pid_2$:dec$\rangle$	yes

"Opt?=yes"means that the support is optional (i.e., not mandatory).

2m. Skiplist between Times $\langle ts_1$:str$\rangle$ and $\langle ts_2$:str$\rangle$. Returns a sequence of pulses, in ascending chronological order of the value in the `timeStamp` field, and such that:

i) the first pulse in the sequence has timestamp exactly $\langle ts_1$:str$\rangle$;

ii) any pair (P,P') of consecutive pulses in the sequence satisfies P.`randOut` = $P'.\langle field\rangle$, for some $\langle field\rangle$ in {`out.Prev`, `out.H`, `out.D`, `out.M`, `out.Y`};

iii) the last pulse in the sequence has timestamp exactly $\langle ts_2$:str$\rangle$.

2n. Skiplist in Chain $\langle cid\rangle$ across Pulses $\langle pid_1\rangle$ and $\langle pid_2\rangle$. Reply is similar to the case of query 2m ("Skiplist between Times $\langle ts_1\rangle$ and $\langle ts_2\rangle$"), but the anchor and target pulses in the query are instead defined by pulse indices (in `pulseId`), within the scope of a particular chain index (in `chainId`).

2o. Subchain across Times $\langle ts_1$:str$\rangle$ and $\langle ts_2$:str$\rangle$. Similar to call 2m ("Skiplist between Times") but changing condition ii) as follows: "any pair (P,P') of consecutive pulses in the sequence satisfies P.`randOut` = P'.`previous`.

2p. Subchain of Chain, across Pulses $\langle pid_1$:dec$\rangle$ and $\langle pid_1$:dec$\rangle$. This is a dual of the call 2o ("Subchain across Times"). The reply is similar to that of the call 2n ("Skiplist in Chain, across between Pulses"), but changing condition ii) as follows: "any pair (P,P') of consecutive pulses in the sequence satisfied P.`randOut` = P'.`previous`.

6.4 Queries associated with certificates

Table 10 enumerates queries related to certificates.

Table 10. Interface calls for associated data

#	Designation	URI	Opt?
3g	Certificate with ID ⟨*certId*:hex⟩	⟨*beaconURL*⟩/certificate/⟨*certId*:hex⟩	
3h	List certIDs in Chain ⟨*cid*:dec⟩	⟨*beaconURL*⟩/listCertIds/chain/⟨*cid*:dec⟩	yes

3g. Certificate with ID ⟨*certId*:hex⟩. Returns a Base 64 encoded RFC 5280 PKIX Certficate (PEM Format) file whose `hash()` is equal to ⟨*certId*:hex⟩.

3h. List certIDs in Chain ⟨*cid*⟩. Returns a list of all distinct `certId` values used by the Beacon in the chain(s) with `certId` indicated by ⟨*cid*⟩. Using ⟨*cid*⟩="All" indicates that the reply **SHOULD** cover all values `certId` used across all chains. For each distinct `certId`, it also shows the values `version`, `cipher`, `chainId`, `pulseId` and `time`, of the pulses where the corresponding `certId` was first used and/or when the previous pulse had a different certificate. Thus, the reply is actually a list of sixtets.

6.5 Queries associated with external values

Table 11 enumerates calls related to external values.

Table 11. Interface calls related to usage of external values

#	Designation	URI	Opt?
4m	External Source Description with Identifier ⟨*extSrcId*:hex⟩	⟨*beaconURL*⟩/extSrcId/⟨*extSrcId*:hex⟩	
4n	Pre-image of extSource ⟨*extValue*:hex⟩	⟨*beaconURL*⟩/extValue/⟨*extValue*:hex⟩	yes
4o	List first PulseIds for all extValues with Source Identifier ⟨*extSrcId*:hex⟩	⟨*beaconURL*⟩/listPulseIds/extSrcId/⟨*extSrcId*:hex⟩	yes
4p	Range of PulseIds in Chain ⟨*cid*:dec⟩ using extValue ⟨*extValue*:hex⟩	⟨*beaconURL*⟩/listPulseIds/chain/⟨*cid*:dec⟩/extValue/⟨*extValue*:hex⟩	yes

4m. External Source Description with Identifier ⟨*extSrcId*:hex⟩. Returns a MIME type text/plain document whose `hash()` is (in hexadecimal format) ⟨*extSrcId*:hex⟩. The document contains a description of an external source and provides guidance to when and how to include content generated therefrom. The content generated in that form, from time to time, is the one whose `hash()` is to be placed in the field `external.value` of some pulses. If the beacon does not recognize ⟨*extSrcId*:hex⟩ as a used `ext.srcId`, then it returns a 404 error.

4n. Pre-image of extSourceValue ⟨*extValue*:hex⟩. Returns the content whose `hash()` is, in hexadecimal format, the value ⟨*extValue*:hex⟩ that is used in the field `ext.value` of some pulse produced by the Beacon. If ⟨*extValue*:hex⟩ is the all-zeros string (64 hexa-decimal characters "0" if the used `hash()` has 512 bits of output), then the reply is a message explaining that the all-zeros string is the default value when an external source has not been used in some chain. If the Beacon does not recognize the provided ⟨*extValue*:hex⟩, then it returns a 404 error response.

4o. List first PulseId for all extValues with Identifier ⟨*extSrcId*:hex⟩. Returns a list of triplets ⟨`chainId`, `pulseId`, `time`⟩ of the first pulses that have used each external-source value corresponding to the identifier ⟨*extSrcId*:hex⟩.

4p. Range of PulseIds in Chain ⟨*cid*:dec⟩ using extValue ⟨*extValue*:hex⟩. Returns an abbreviated list (range) of the `pulseId` indices of all pulses, within chain ⟨*cid*:dec⟩, than have the value ⟨*extValue*:hex⟩ in the field `ext.value`. The elements of the abbreviated list are written succinctly as ranges, where for example $p_1 : p_2$ denotes the sequence p_1, $p_1 + 1$, ..., p_2.

6.6 Queries about local functioning

Table 12 enumerates calls related to local properties of the Beacon functioning.

Table 12. Queries about local properties of the Beacon

#	Designation	URI	Opt?
5j	Supported queries	⟨*beaconURL*⟩/queries	yes
5k	Local status flags	⟨*beaconURL*⟩/status/flags	yes
5l	Local history	⟨*beaconURL*⟩/history/	yes

5j. Supported queries. Returns a structured description of the supported queries, explaining for each the syntax of the URI query and the default and supported reply formats (containing some non-empty subset of {bare, bare-txt, html, json, xml}).

5k. Local status flags. Returns a MIME type text/plain document containing a human readable description of the defined bit flags of the `statusCode` field. The output is a file named "beacon-status-flags.txt" Each new line is of the form: "Flag #n (the n^{th} LSB of the `statusCode` field): additive value equal to 2^n: set (1) if ⟨*describe if 1*⟩; unset (0) if ⟨*describe if 0*⟩." In this description, n is to be replaced by a corresponding integer between 1 and 32.

5l. Local history. Returns a MIME type text/plain document containing a human readable description of relevant information about the local functioning of the Beacon. This **MAY** include anything deemed useful by the Beacon operator, including an explanation about past or planned outages, existing time-gaps, chain terminations, external repositories storing past pulses.

7 Using a Beacon

A beacon is useful in many situations. For example:

1. When multiple parties want to coordinate some action based on a random number, but do not want any one among them to be able to exert control over the random number.
2. When someone wants proof that some computation could not have been started before a particular time T.
3. When one party wants to demonstrate to the world (including many people who will only become interested much later) having carried out some random process fairly, without "cooking" random numbers.
4. When multiple parties want to run some cryptographic protocol based on a shared random string, but do not want the added communications overhead of establishing a shared random string.

In this section, we discuss useful techniques for using a beacon intelligently. This is simply an attempt to provide a cookbook for people who are not cryptographers, but would like to know how to use a beacon. It may also act as a kind of Schelling point, helping different people to efficiently coordinate on doing things the same way without a lot of negotiation.

7.1 Direct usage — sampling a single integer using the modulo technique

When a single random integer is needed, it **CAN** be extracted very simply from the field `randOut` of a single pulse, by using the *modulo technique*. If the integer is to be sampled from within the range $Range = [0, N-1]$, with the number of bits of N being significantly smaller than the number of bits (512) in `randOut`, then an application **CAN** use

$$\texttt{randOut} \mod (N). \tag{20}$$

The application software needs to support arithmetic with precision large enough to handle the 512 bits of the `randOut` field (a hash output).

To sample an integer from a more general range $Range = [L,\ L+N-1]$, where L is any non-negative integer, and N is limited as before, the application **CAN** compute

$$L + (\texttt{randOut} \mod (N)). \tag{21}$$

As hinted above, the suitability of the modulo technique is conditioned to a limitation on the size of N, as compared to 2^{512}. This relates to the *distribution bias* (e.g., see Ref. [NIS13b]) induced by taking the modulo, when N is not a power of 2.

As a simple rule, to ensure that the bias is negligible, we recommend that the modulo technique be used only if N is not greater than 2^{384}. This guarantees a bias smaller than

2^{-128} (i.e., under the working assumption that the hash output randOut is uniformly random in $[0, 2^{512} - 1]$). Exceptionally, the technique **CAN** also be used if N is an exact power of two, not larger than 2^{512}, since then the modulo does not produce bias.

Section 7.3 discusses the case where the range is of width larger than 2^{512}, or when more than one random number is required.

7.2 Ex post facto-verifiable random sampling

Random sampling is used extensively in industry, research, and activities like lotteries. After the sampling has been done, it may be hard to convince a distrusting third person that the sampling was indeed random. In this section we discuss how this **CAN** be achieved using a public source of randomness.

In order to conduct random sampling that is ex post facto-verifiable, the user must first derive a seed, Z, from the output of the beacon. The seed needs to be derived in a way that includes all relevant information. Often, it will be worthwhile to cryptographically bind some particular information into the seed. That seed **MAY** then be used to generate a longer sequence of pseudorandom output bits, or to select some value from a set of possible values.

We **CAN** thus split the process of using the beacon outputs into three phases:

1. **commit upfront —** commit upfront, before the time of the required beacon pulse(s), to how the seed will be obtained and what will be done with the seed;
2. **derive a seed —** receive the intended pulses and derive a seed from them;
3. **use the seed —** use the seed to do something previously committed to.

7.2.1 Committing upfront

An essential principle for secure use of beacon randomness is that **everything about the use of the future random number from the beacon needs to be specified in advance.**

High-level example. If a user plans to use the beacon to select a subset of polling places to audit from an election, the user needs to specify, in advance:

1. Which beacon will be used, e.g., by specifying the administrative domain, e.g., specified with the help of the *webPrefix* sub-field included in the uri (see Section 4.2.1).
2. Which beacon pulse (specifying the chainId and time) will be used (assuming the chain remains active and without gaps including the intended timestamp and vicinity).
3. The set of polling places and how many of them will be selected.
4. The program for using a seed to select a subset of polling places for audits.

5. How to handle exceptional conditions, e.g., if the beacon fails to produce a pulse at the specified time (due to a time gap), or if the chain ends before the intended time.

Procedure. In order to make the commitment clear, we recommend the following steps:

1. Write a single program, *Prog*, which will take as input a seed Z to be obtained from the beacon pulse(s) used, and which will produce the desired output from this step.
2. Write a *committing statement* M, containing:
   (a) A text, M_1, explaining how the seed Z is to be constructed from a beacon pulse (and which pulse) and from the hash H (not yet computed) of the committing statement M. For Example:

   `The seed Z shall be obtained as the SHA512 hash of the concatenation of: the SHA512 hash (H) of the committing statement M; and the randOut value (P[T].randOut) of the NIST Beacon pulse with timestamp T equal to 2018-07-04 12:00:00.000.`

   (b) The `hash()` (in hex string representation) of the program *Prog*.

   (c) A text, M_3, describing what will be done with the outputs of *Prog*. For example:

   `Each of the 16 outputs is the number of a precinct to be audited by hand.`

   (d) A text, M_4, that indexes (order and file name) and explains the content of the auxiliary documents needed to specify what is happening. For example:

   `File #1, named precincts.pdf, with 372,824 bytes, contains the precinct map that labels each precinct and its polling place. File #2, named voters.ods, with 142,193 bytes, contains a spreadsheet with the number of registered voters per polling place.`

   (e) A text, M_5, that describes the `hash()` (as hex strings) of each of the auxiliary files, in the same order they are described. For example:

   `The auxiliary files have the following SHA512 hashes: File #1 --- efda3b6628211e02 aba9cdae11fcff5f 34550211f54558ef fd13687ab204e4db 5b9121332e5931c8 564bc858ec9545bd 8dc81d9da5b2eaa3 7e7e9bf251307dc7; File #2 --- 27881a1d15e0df72 cbc4aa8ed393dbd4 7de5b6fde72d8cfe 0e9da389af1e6c7c c95089c7bdc52c38 cee79bb3473a90e8 2fb96968b9978700 b7438e53b9059797.`

3. Commit in public to $H = \texttt{hash}(Prog \parallel M)$. Optionally, one **CAN** also publish immediately the actual program *Prog* and committing statement M. Nonetheless, they are both already committed by the hash H.
4. When the intended beacon pulse ($P[T]$) becomes available, derive the seed Z as described and use it as the input to the program *Prog*.

5. Report the results of the program.

Requirement: *A program that will run based on a future beacon pulse must be entirely deterministic, given the beacon pulse and other inputs.*

Although a committing statement M **SHOULD** be published before the timestamp of the pulse being used to generate the seed, it is important to have a clearly defined committing statement, even if not published ahead of time.

When the committing statement will not be published ahead of time, it is specially important that a "distinguished" (i.e., default) timestamp be used, to mitigate the possibility (or appearance) that someone might try many timestamps until they found one that fits their purposes unusually well. That is

1. On each day, the default timestamp to use is yyyy-mm-dd 12:00:00.000.
2. On each month, the default timestamp to use is yyyy-mm-01 12:00:00.000.

If a specific reason justifies using a different timestamp, such as 2018-09-13 17:35:00.000, that reason **SHOULD** be explained ahead of time by the user of the beacon. (An example of a good reason would be some predetermined schedule for using the beacon pulse, which needed to start immediately after 17:35.)

When a committing statement is not being published before the pulse to be used, the user **SHOULD** choose the timestamp with UTC of noon (yyyy-mm-dd 12:00:00.000) on a day, and if possible **SHOULD** use the one on the first of the month. If the committing statement is published or committed to in public (by revealing H, for example) at least a day in advance, then this is not necessary. However, users of the beacon **SHOULD** use these distinguished/default timestamps whenever possible, and **SHOULD** explain any other choices made. (For example, if some auditing process must start promptly at 10:14 PM local time, that would be a good reason to use a different pulse.)

7.2.2 Deriving a Seed

The simplest way to derive a seed, which is appropriate in almost all cases, is to hash together a committing statement with the `randOut` of the beacon pulse described in the committing statement. Thus, if we have a committing statement that says we will use the pulse at 2019-02-22 12:00, then we compute the seed as

$$H \leftarrow \texttt{hash}(\text{committing statement referencing NIST beacon pulse at 2019-02-22 12:00})$$
$$Z \leftarrow \texttt{hash}(H \,\|\, P[\text{2018-07-04 12:00}].\texttt{randOut})$$

Recall that the `randOut` field is the `hash()` of all other fields in the beacon pulse. This limits the ability of even a crooked or subverted beacon to exert control over the results.

7.3 Using the Seed

When a seed Z needs to be used to generate a very long output string, such as might be used for many different individual outputs, we recommend the procedure based on Algorithm 7.

Algorithm 7 Generate distinct values from a short seed.

```
function EXPAND(Z, i)
    V ← hash(0x00 || Z)
    return (hash(0x01 || V || encode_uint(i, 64)))
```

For each new index i, Algorithm 7 outputs a new distinct output $Y_i = \text{EXPAND}(Z, i)$, with n bits (the bit-length of the output of hash()). Thus, by incrementing the index i, the function **CAN** be used to generate, from a single seed Z, as many pseudo-random n-bit values as desired.

If the range of output values needed is within $[A, \ldots, B-1]$ and if $\log_2(B-A) \leq n-128$, then each value **CAN** be mapped into a *result* in that range, with a bias less that 2^{-128}, as:

$$\text{result} \leftarrow A + (Y_i \pmod{B-A}) \tag{22}$$

7.4 Combining Beacons

The preCom and randLocal fields are used to derive a seed from a combination of beacons. The procedure also uses the field randOut, in order to achieve security against misbehavior by one of the beacons.

The procedure specification requires identifying the involved beacons, e.g., A and B (preferably administratively independent) and the future sampling timing T. These parameters are described in a (committing) statement M and then the statement is hashed into a commitment $H = \texttt{hash}(M)$ of the procedure.

The process is then as follows (exemplified for the case of only two beacons operating on the same pulsating schedule):

1. Within the time window T and $T + 3\pi/4$, sample pulses $A[T]$ and $B[T]$ and check their standalone correctness. If any of $P_A[T]$ and $P_B[T]$ is not obtained until time $T + 3\pi/4$, or if any of them is *invalid*, then abort this attempt to combine beacon pulses, else continue. The notion of valid vs. invalid needs to be unambiguously identified by the user application. In any case, the case of a gap or lost randLocal in any of the required pulses of any of the Beacons (A and B) **SHOULD** invalidate the combination.

   Note: Since Promise 1 requires beacons to not release the next pulse before $T + \pi$, the sampling window ensures that the user either gives up or learns $A[T]$.preCom and $B[T]$.preCom before anyone knows $A[T + \pi]$.randLocal and $B[T + \pi]$.randLocal.

2. Within the time window $T+\pi$ and $T+2\pi$, sample pulses $P_A[T+\pi]$ and $P_B[T+\pi]$ and check their standalone correctness. If any of $P_A[T]$ and $P_B[T]$ is not obtained until time $T+2\pi$, or if any of them is invalid, then abort this attempt to combine beacon pulses, else continue.

3. If for any Beacon the 1st bit-flag of `statusCode`$[T+\pi]$ is set to 1 (indicating that exceptionally `randLocal` is not a pre-image of the previous `preCom`), i.e., if $d[T+\pi]$.`statusCode`$\&1 = 1$ for any $d \in \{A,B\}$, then abort this attempt to combine beacon pulses, else continue.

4. Verify that $P_d[T]$.`preCom` $=$ `hash`($P_d[T+\pi]$.`randLocal`) for both beacons $d \in \{A,B\}$. If this is false for some Beacon (which is publishable evidence of a Beacon misbehavior), then abort this attempt to combine beacon pulses, else continue.

5. Verify that $P_d[T+\pi]$.`previous` $= P_d[T]$.`randOut` for both beacons $d \in \{A,B\}$. If this is false for some Beacon (which is publishable evidence of a Beacon misbehavior), then abort this attempt to combine beacon pulses, else continue.

6. Output the seed Z, defined as:

$$Z \leftarrow \texttt{hash}(A[T].\texttt{randOut} \parallel B[T].\texttt{randOut} \parallel A[T+\pi].\texttt{randLocal} \parallel B[T+\pi].\texttt{randLocal} \parallel H)$$

When everything goes correctly, the result is a seed that incorporates as pre-image the hash of the committing statement. It also incorporates the `randOut` fields from $A[T]$ and $B[T]$, which in turn incorporate the `sig` and `ext.value` fields from those pulses. The latter two provide authenticity and timeliness guarantees.

Security against one malicious Beacon. The described procedure enables security even in the face of one malicious beacon (but not both). Suppose beacon A is honest but beacon B is dishonest. Once B has sent $B[T]$, it has committed to at most one value x (satisfying $B[T]$.`preCom` $=$ `hash`(x)) to be used in the $B[T+\pi]$.`randLocal` of the next pulse. This means that if it uses any different value x' in the $B[T+\pi]$.`randLocal` field of the next pulse the verifications performed by the user will fail in step 4.

Additional considerations. Additional aspects are deferred to a future separate document. This **MAY** include:

- how to combine many beacons (namely more than two), while being resilient against time-gaps in a few beacons.
- how to combine beacons with different periods and/or with different time offsets (e.g., a beacon that outputs at each 30 seconds mark)?
- possible distinct guidelines for distinct settings, e.g., a user is obtaining randomness for a one-time non-auditable use, vs. a user intends to obtain randomness for future auditability / ability to prove correctness to third parties.

8 Security

In this section we consider the security of the randomness Beacon service. A security analysis is important to enable reflecting on expressive security claims, helping trust to be leveled with trustworthiness. Even if beacon operators believe that the system is initialized in a safe state, we want security to hold in the long run, against conceivable adversarial threats. For example, some components of the beacon may be compromised as a result of an external attack, or upon intentional misbehavior of an insider (beacon operator). Some components of the beacon architecture may also fail spontaneously.

Section 8.1 introduces a characterization of our security model of interest, categorizing security properties and adversaries. Section 8.2 describes an operational baseline for the beacon functioning. Attackers may be able to affect the security of the beacon service by inducing a departure from this baseline. Section 8.3 considers several intrusion scenarios where essential components of the beacon become compromised. This analysis illustrates some limits of the beacon security when facing various types of intrusion. Section 8.4 concludes with a few miscellaneous observations.

8.1 Security model

Types of security properties. Based on the pulse format and beacon interface, we can conceive an enumeration of desired security properties. We can also consider categories to which those properties pertain, such as for example:

- **relations** — correct hash chaining and signing, incremental sequencing of indices and timestamps, consistent record keeping (authentic past history);
- **availability** — *timely* pulse releases, *accessible* past pulses, *automatic* operations (reduced human operator intervention);
- **“rands” quality** — unpredictable, unbiased, fresh and/or independent randomness in the `randLocal`, `preCom` and `randOut` fields. (Note: we sometimes use the term *rands* as a shortname for the two main random values of interest: `randOut` and `randLocal`)

Baseline. Intuitively, the above mentioned properties follow from the pulse format, in a baseline uncompromised implementation in which:

- the Beacon App and HSM compute as expected;
- the internal state of the Beacon App and HSM are unbreached;
- the RNGs provide fresh randomness with full entropy;
- the local clock is synchronized with UTC;
- communication is fast and synchronous;
- the databases are available and correct.

Adversary. But how to withstand an adversarial compromise of system components? A security analysis needs to consider cases where subsets of components are compromised, e.g., due to adversarial intrusion that makes the system depart from the baseline uncompromised scenario. It thus matters to characterize the *capabilities* and *goals* of the adversary.

We consider two main types of adversarial behavior upon compromise:

- *semi-honest*, also known as *honest-but-curious* or *passive*, meaning it can exfiltrate internal state, but without deviating from the protocol specification with respect to interaction with non-compromised components;
- *malicious*, also known as *active*, meaning that it may have an arbitrary behavior, including contrary to the beacon specification.

In the remainder, the terms "adversary" and "attacker" are used interchangeably to denote either a compromised component of the beacon architecture, or an entity that coordinates information and actions with one or more compromised components. An act of intrusion / compromise can occur at the onset of a beacon implementation (e.g., by inadvertently using hardware with an unknown malicious sub-component), or during the beacon operation.

Adversarial capabilities. An important characterization of each idealized adversary is its capability, which includes the control it has over the computational and communication capabilities of compromised components (e.g., parts of the beacon engine, web frontend, time server, database, and/or even users) and also the possible access it has to covert communication channels, computational resources and illegitimately obtained information.

Adversarial goals. We focus on five categories of what an attacker "wants":

1. know the future in advance — to predict (or share knowledge of) some randomness before the time indicated in the timestamp of a pulse;
2. influence the future — to induce with non-negligible probability some property (e.g., a bias in 0's) of the random values (`randOut` or `randLocal`) in a pulse;
3. change the past — to alter a previously released pulse without detection, i.e., making users believe that the pulse in a past time is different from what had already been fixed;
4. fork a chain — to make different users believe in the validity of two different pulses (e.g., different `randOut`) with same indices (pulse and chain) and timestamp;
5. deny service — to induce the beacon service to become unable to pulsate with the intended period, possibly even forcing it to end a chain.

This is not an exhaustive list, but it helps us reason about a number of desired operational defensive-features of the beacon.

Crypto assumptions. We also assume the satisfiability of cryptographic assumptions:

- a cryptographic hash is one-way and collision resistant and its output is indistinguishable from random when the input is unpredictable;
- the signature scheme is unforgeable and the public-key is unforgeably certified, such that security against forging signatures depends only on secrecy of the signing key.

8.2 Operational baseline

A number of procedures needed by randomness beacons **CAN** be modularly conceptualized in order to describe a reference mode of operation. Some procedures are inherently related to the rules for generating pulses and the definition of interfaces (as described in Sections 3 through 6). Other procedures are somewhat independent of the syntax of pulses and interfaces and apply more generically to operational aspects of putting together all the components of a beacon implementation. This subsection deals with the latter: key management, network protocols, time synchronization, and administrative actions (e.g., updates, backups and maintenance) and physical configuration.

Each beacon **MAY** have unique implementation characteristics, regarding the supporting hardware and software components. This subsection covers high-level operational aspects that are likely to be applicable to most beacon implementations.

8.2.1 Management of signing keys and certificates

Key generation and isolation. Since the authenticity of pulses relies on cryptographic signatures, it is essential to protect the private signing key in use for each chain. By a *separation of concerns* principle, the private signing key **SHOULD** be isolated from the overall Beacon App. In other words, the ability to sign **SHOULD** be modularly protected and separated from the remaining complexity of pulse generation. The Beacon App **SHOULD** thus be able to request signatures and obtain a corresponding reply, but **SHOULD NOT** be able to to access the actual signing key.

Certification. A signing key **CAN** either be self-signed (self-certified); or certified by an external certification authority (CA). There **MAY** exist more than one certificate for each key, e.g., in order to handle the renovation of certificates across time (ensuring no certification time-gaps) and/or for applicability to users with different validation requirements. The set of all certificates for all signing keys ever used to sign pulses must be available to users upon request — to enable users to validate any past pulse. More concretely, each value ever used in the `certId` field of a pulse must correspond to a certificate (or vector thereof) that the beacon service is able to find and provide to a requesting user. Since certificates are public, they are stored in the publicly accessible Database, and **CAN** be backed up anywhere else.

The following items are not mandatory for a beacon to operate, but are recommended:

1. **Certification authority (CA).** A Beacon **SHOULD** obtain from a widely trusted CA a certificate for its public (signature-verification) key; at least one such public certificate (but possibly more) **SHOULD** be valid in any period of pulse generation by a beacon.

2. **Certificate transparency (CT).** The signing-key certificate **SHOULD** be logged into a CT [LLK13] log, to promote the detection of conceivable issuance-and-use of rogue Beacon-signing-key certificates produced by compromised CAs.
3. **Certificate expiration.** It is recommended that any certificate has a validity period no longer than 5 years from the time of issuance, including because of conceivable future revisions of approved signature algorithms and parameters.
4. **Certificate revocation.** A Beacon **SHOULD** publicize its certificate-revocation policy.

Isolation of the signing capability. Given the paramount importance of protecting the signing key, it is important to ensure its secure isolation and access. This justifies the use of a signing module, with a controlled interface allowing signature requests by the Beacon App. This module **SHOULD** provide a well-defined access-control mechanism, and be capable of securely performing signatures without key leakage. For example, this **MAY** be implemented using a *hardware security module* (HSM) with FIPS 140-2 level 3 certification.

It nonetheless conceivable that a beacon is implemented without the use of a certified HSM. However, in the remainder we continue referring to an HSM as a possible hardware device providing intended security properties. Ideally, an HSM would allow generating and containing the key without it ever leaving the HSM, and possibly even allowing a limitation of the rate of signatures per amount of time.

8.2.2 Network Security

The flow of information between components of the Beacon requires control. At a first logical level, some flows are unidirectional, using a push model. For example, the database receives data sourced at the Beacon App, but not the other way around. There are however exceptional designated circumstances (e.g., see Section 8.2.4) that warrant a special administrative mode of operation where, for example, the Beacon App accepts additional input, e.g., for reposition of accidentally lost state.

The network connections **SHOULD**, as much as possible, be dedicated and isolated from unrelated services. This can be particularly helpful in reducing the surface for potential attack initiated from other components. It can also help with reducing the delay of communications.

8.2.3 Time synchronization

A secure beacon service offers two main features related to time: it generates pulses as late as possible to enable a timely release; it releases pulses not before the time indicated in the `timeStamp` field. These features require the ability to reliably measure time. At a logical level, this can be comprised to an assumption that the local clock of the beacon engine has (relative to an intended precision) a small enough offset from UTC. At a practical level, the implementation must explicitly provision for a correct synchronization of the local clock.

We enumerate here three vectors for accomplishing synchronization:

1. use the network time protocol (NTP) to interactively synchronize with a time server assumed to have the correct UTC time;
2. use a non-interactive protocol, using the time read from a receive-only signal, such as based on the global positioning system (GPS);
3. use a local clock certified to have time drift less than a certain threshold, throughout a long duration;

These three options are not mutually exclusive, and **CAN** conceivably be combined. Correspondingly, some adversarial capabilities may enable time manipulation attacks [MCBG16].

8.2.4 Maintenance, availability and recoverability

Updates and downtime. The software and hardware platform of an implemented Beacon service **MAY** require updates (e.g., security patches, replacement) at diverse moments in time. Such actions **CAN** induce downtime of the beacon service, e.g., if an update requires a reboot of the operating system that underlies the Beacon App. For example:

- **Power outages in beacon engine.** If the Beacon Engine temporarily losses of power, then then the pulse generation will be stopped temporarily. Skipping the generation of pulses for some time leads to time *gaps* in an active chain.
- **Externally-inaccessible database.** If the external database is temporarily unavailable frmo the outside, then users will not have access to the beacon pulses during some time. In the latter case the generation of pulses **CAN** still remain without gaps, and at a later stage the produced pulses become available for consultation.

Since availability is itself a security aspect, the above considerations justify a balance between frequency of updates and the resulting frequency of gaps.

Backups and recoverability. It is crucial to ensure the long-term availability of public records of the beacon, including pulses and associated data. Thus, an essential aspect of availability pertains to actual loss of information, e.g., a database loss due to problems with the underlying storage medium. Since the records have an "unlimited" lifetime, there must exist backups of the database(s). Two distinct possibilities are enumerated here:

- to enhance continuous (and real-time) availability, a state-machine replication implementation **CAN** enable data access even when one database replica (out of several) fails;
- to enhance long-term availability, regardless of possible temporary downtimes, a state recovery protocol **CAN** define how to replace a failed component, and how to setup its initial state to match that of an offline or online backup replica.

A special case pertains to the Beacon App memory, which in normal functioning **SHOULD** not receive information (about pulses) from outside of the Beacon Engine. Some of the records therein, pertaining to some past pulses (`previous`, `hour`, `day`, `month`, `year`), are needed for the generation of new pulses. If this memory is lost, e.g., if the memory modules irrecoverably fail, then a replacement will have to be updated with an initial state (unless a new chain starts). Such setup is an example of an administrative action with a flow of information contrary to the one mentioned in Section 8.2.2.

With respect to the internal storage of the beacon app, it is worth noticing a difference between the loss of `randLocal` and the loss of past output values. Since `randLocal` is (by design) not present in previous pulses, it **CANNOT** be recovered from them. For this reason, there is an exception provisioned for the case of loss of `randLocal`: the next pulse proceeds by filling the first bit-flag of `status` with value 1, meaning "`randLocal` without corresponding `preCom`", and omitting the `randLocal` value (i.e., filling it with all zeros). Except for the first pulse in a chain, we do not allow not including past output values.

8.2.5 Boundaries and Physical Security

Recommendation (access boundaries). The access boundaries of the system **SHOULD** be well defined, to help enumerating conceivable attack vectors that may exploit permeabilities thereof. A relevant defense line pertains to physical security measures, limiting the possible physical attacks and deterring certain types of insider attacks. It is thus encouraged that each administrative domain of a beacon defines a physical security policy for its beacon implementation. This **MAY** include defining rules of access to the beacon machinery, and corresponding audit rules (e.g., based on access logs). For example, should there be a guard determining who can enter the room and logging all entries? How should the access logs be audited, and by whom?

Recommendation (ability to shutdown). A Beacon **SHOULD** be setup with the ability for human beacon operators to physically shutdown the service, and to be able to signal to the outside world that such shutdown will, is or has occur(ed) (somewhat equivalent to a key revocation operation). Conversely, it is possible to conceive a fully virtualized beacon implementation, following the reference format and running in completely autonomous mode, without human operators being able to shut it down after bootstrap.

8.3 Intrusion scenarios

We now consider intrusion scenarios where a subset of components becomes compromised:

1. Malicious Beacon App → full-bias attack on `randLocal`
2. Malicious Beacon App → full prediction and exfiltration attack
3. Malicious Beacon App → bias attack on `randOut`
4. Malicious time along with compromised database → "rands" prediction attack
5. Semi-honest Beacon App → "rands" prediction attack
6. Malicious database knowing the signing key → change-history attack

8.3.1 Malicious Beacon App → full bias on randLocal

Specification. The value $r_{i+1} = P_{i+1}$.randLocal released in pulse P_{i+1} is the hash pre-image of the value $C_i = P_i$.preCom released in pulse P_i. Supposedly, this randLocal value r_{i+1} is computed as $\rho_i' \equiv \text{Hash}(\rho_{1,i} \,||\, \rho_{2,i} \,[||\, \rho_{3,i}])$, where the (at least two) values $\rho_{j,i}$ are the "raw" outputs from the several RNGs learned by the Beacon App (but not revealed outside) during the process of generating pulse P_i.

Attack vector. Since the "raws" are not revealed outside, a malicious Beacon App can undetectably ignore them and decide an arbitrary randLocal ρ_i and then hash it to obtain C_i. The compromise scenario is depicted in Fig. 9.

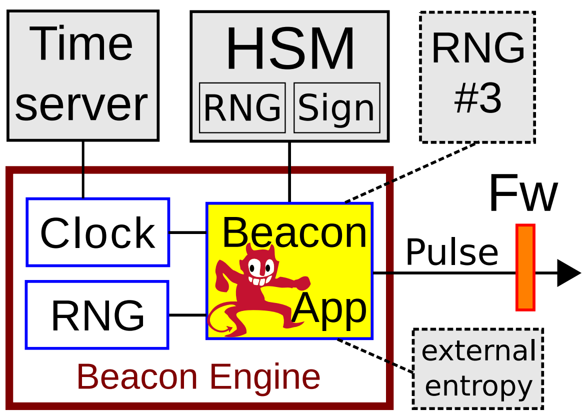


Figure 9. Illustration of malicious Beacon App

Mitigation in place. The rules for combining beacons (Section 7.4) specify that randLocal **SHOULD** only be used to combine randomness from different beacons. The result of the combination leads to good randomness if at least one beacon is uncompromised. Nonetheless, the fact the randLocal can be fully biased by a malicious beacon **SHOULD** be an explicit consideration by users. This is specially relevant in the face of adversaries capable of affecting several beacons.

The trustworthiness on a beacon providing unbiasable randomness **SHOULD** be distinct when comparing randLocal vs. randOut. A malicious Beacon App can fully determine the value randLocal, while it only has limited bias on randOut (see Section 8.3.3). In particular, such compromise **CAN** lead the beacon to become deterministic (if using a deterministic signature algorithm), during the periods without change of external.value and certificateId.

A conceivable mitigation requiring changing the calculation of a field value. The mentioned attack would be prevented with a conceivable simple redefinition of the calculation of randLocal (without additional fields). This, however, requires a change in the format specification and is thus conceived only for a potential future version of the format.

The idea is to make $\texttt{randLocal}_{i+1}$ not be simply the pre-image of $\texttt{preCom}_i$ but rather the XOR of the pre-image and $\texttt{randOut}_i$. Then, even a malicious Beacon App could not fully control the value randLocal, while still committing to it in a verifiable manner. Concretely, we would have the following:

- (as currently done) $\rho_i = \texttt{hash}(\rho_{i,1}||\rho_{i,2}[||\rho_{i,3}...])$
- (as currently done) $P_i.\texttt{preCom} = \texttt{hash}(\rho_i)$
- (as a change) $P_{i+1}.\texttt{randLocal} = \rho_i \oplus P_i.\texttt{randOut}$ (instead of $P_{i+1}.\texttt{randLocal} = \rho_i$)

This means that when a malicious Beacon App chooses the value randLocal it still does not know the resulting value P_{i+1}, which will then be obtained upon a hash calculation. Since $\oplus$ is a computationally-invertible permutation, the verification by users is still straightforward, by simply defining $\rho_i = P_i.\texttt{randOut} \oplus P_{i+1}.\texttt{randLocal}$ and then checking that $\texttt{hash}(\rho_i) = P_i.\texttt{preCom}$.

As a further benefit, in this scenario the value of randLocal depends on the use of the HSM, which allows limiting further the possible bias that a malicious Beacon App can induce, as already described in Section 8.3.3 for randOut. This mitigation thus equalizes the amount of bias that the Beacon has with respect to the two rands (randOut and randLocal).

8.3.2 Malicious Beacon App → full prediction and exfiltration attack

As mentioned in Section 8.3.1, a malicious Beacon App can undetectably decide in advance the value randLocal of each pulse, provided it presents a corresponding preCom in the previous pulse.

In fact, a malicious Beacon App can for example define randLocal as an enciphering of a counter, e.g., $\rho_i = \mathrm{Enc}_K(i)$, where Enc is a block-cipher with appropriate output length, K is a secret key shared with an outside adversary, and i is the counter. The adversary can then predict in advance all values $P_i.\texttt{randLocal}$ for any i. This also means there is no assurance on randOut being fresh, unbiased or unpredictable.

This attack vector also allows the beacon App to exfiltrate internal state that it may learn about the Beacon Engine. Particularly, it can use it to covertly communicate with an outside party, encrypting information into a ciphertext that is inditinguishable from random and which can only be read by the outsider.

It is worth noticing that the mitigation technique (different calculation of randLocal) presented in Section 8.3.1, while capable of preventing the full bias of randLocal is not sufficient to prevent the exfiltration or full prediction attack.

8.3.3 Malicious Beacon App → bias on randOut

Attack vector. A malicious Beacon App, with access to a honest HSM, can generate many pulses in advance, by simply not waiting enough between each signing request. The Beacon App can thus try many different values of randLocal and produce different signature requests to the HSM, until obtaining a signature whose respective hash — the `randOut` value — will have a particular property. For example, if the HSM has the capability (e.g., as a feature of rapid cryptographic operations) to perform about 2^{20} signatures per minute, then the malicious Beacon App can induce the result of the final `randOut` to satisfy a predicate that happens about once in a million in average (e.g., all zeros in the twenty least significant bits). Since the Beacon App can also accelerate the generation of pulses, it can conceivably first compute a full day worth of pulses and then perform the bias attack on the pulse for the next day, therefore gaining control over about 10 more bits.

Mitigations. One possible mitigation is to have an HSM (or even simply a proxy) that induces a mandatory delay between signing requests, and/or which limits the number of allowed signing requests per established session.

Another conceivable mitigation is to partition the Beacon App in a way that a component that requests the signature never gets to see the signature result. If the beacon operator has control over the network communication flow, then it may prevent a malicious intruder from communicating across those two components, therefore effectively preventing the signature-requester component from knowing whether or not it should request a new signature.

8.3.4 Malicious time along with compromised database $\rightarrow$ rands prediction

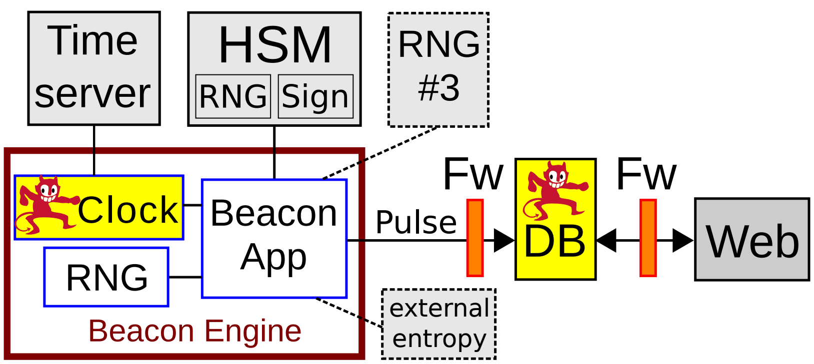


Figure 10. Illustration of malicious clock and database

Attack vector (malicious local-clock). We describe an attack where the Beacon App and HSM remain honest, but the local clock and the (internal or external) database become compromised. The compromise scenario is depicted in Fig. 10.

A malicious local clock can for example induce the generation of an entire-day pulse-set in a single hour. For each generated pulse, the honest Beacon App then releases the pulses to the internal database, unaware that they were released ahead of time. After enough generated pulses in advance, the malicious clock can slow down until becoming again synchronized with UTC.

A semi-honest database can leak the anticipated knowledge to an adversary, thus breaking the unpredictability property. A malicious database and-or web interface can also delay the release of the anticipated pulses to users, thereby making the compromise undetectable. The beacon operators and users never detect that a time-skew occurred and that pulses were generated in advance.

Possible mitigations.

- **Authenticated clock.** By having the Beacon App use an external authenticated clock, the forward time skew would not possible. The Beacon App would only accept timestamps already validated by some trusted signature.
- **Authenticated timestamps, via `ext.value`.** Another mitigation is to periodically incorporate authenticated timestamps into the pulse, via the `ext.value` field mechanism. Concretely, one **CAN** define an external source (`ext.srcId`) that describes using an authenticated timestamp as the hash pre-image of `ext.value`, at particular moments in time. This would allows external users to verify that the pulses were only generated after the Beacon App had knowledge of the authenticated timestamp. Conceivably, this **CAN** also be done based on randomness values from different beacons, which by the specification in this document are authenticated by the respective beacons. The use of an authenticated/timestamps output value from at least one uncompromised beacon would be sufficient to guarantee unanticipated pulse generation.

Another attack vector (honest local-clock, malicious time-server). Even with an intact beacon engine, a timing attack can be launched from a malicious external time-server, outside of the beacon engine. Suppose that the Beacon App relies on its underlying operating system (OS) to control "sleep" system calls, trusting that the OS will "awake" the App at the intended time. Suppose also that the OS, in control of the local clock, is responsible for initiating the time-synch protocol with the time-server. The time server can then induce an undetectable skew rate, which will depend on the time-synch scheduling frequency.

For simplicity we assume the case of a 1 minute period between pulses. For an undetectable attack, each synchronization cannot skew the time forward by more than one minute, or otherwise it would induce a time gap in the chain, which would be detectable. For example, suppose the OS only requests synchronization approximately once every two minutes. The local-clock time is then limited to advance, in average, at 1.5 times the speed of regular time. This means that for a single hour the clock is not able to skew more than 30 minutes, i.e., about 30 pulses. If instead the synchronization happens once every 10 seconds, then the rate can be has high as about 6 times. The consequences are more restricted than the case of the attack described with a fully malicious clock. Some consequences / detectability of the attack may be implementation-specific, e.g., depending on whether the sleep/awake actions depend on timestamps vs. computation cycles. If the communication in the time-synchronization protocol is not protected, then it is enough to have a malicious intrusion of the network channel.

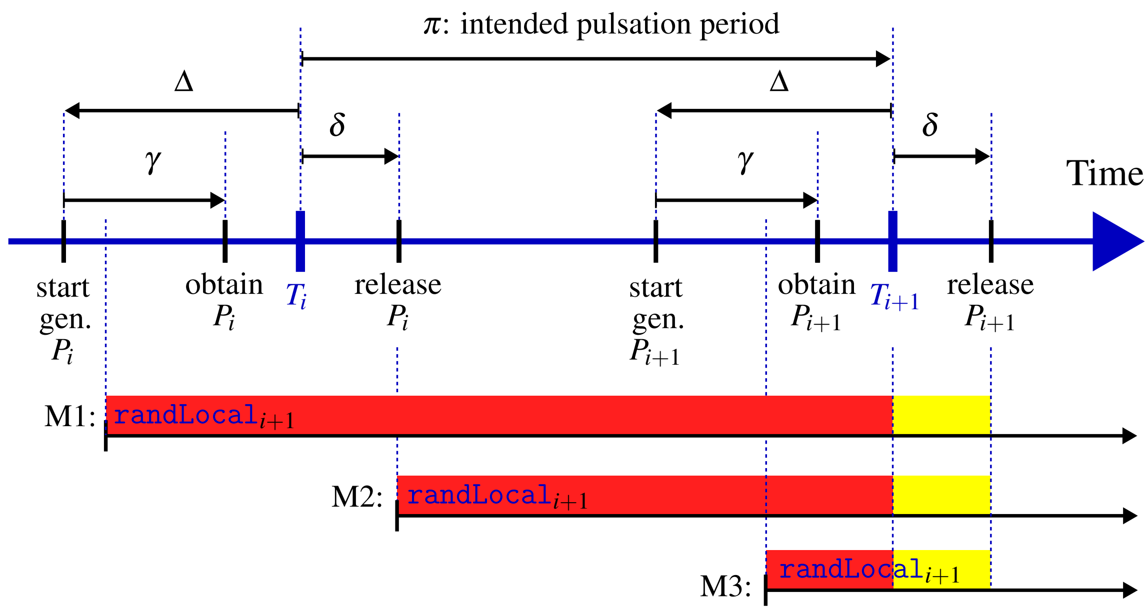
Mitigation. The attack described in the case of a malicious local clock included a second phase where the clock would slowly get back into the correct time. A Beacon App **CAN** conceivably be programmed to analyze clock adjustments and throw an exception when detecting too many (too large) time-skews, backward and forward. For example, a Beacon App **CAN** be defined to alert the Beacon operator if detecting that in a 2 minute span (according to local-clock time) the time-synch operation lead to a time-skew greater than 10 seconds. This would further reduce the possible skew rate of anticipated production/release of pulses.

8.3.5 Semi-honest Beacon App → rands prediction

Advanced knowledge of rands. Within the operational guidelines for timely generation and release of pulses (see Fig. 3 in Section 3.3), it is unavoidable that a semi-honest Beacon App has privileged knowledge of `randLocal` during a time window up to $\pi + \Delta$ (i.e., in advance of allowed time for pulse release); it also has privileged knowledge of `randOut` for a time window of up to $\max(0, \Delta - \gamma)$.

Some mitigations — possible and conceivable.

- **M1 (possible). Adequate parametrization of generation and release time.** As already recommended in Section A.1, the generation and release parameters **SHOULD** be adjusted to allow smaller windows of predictability. Making $\gamma > \Delta$ removes the predictability of `randOut` by a semi-honest Beacon App. (Compare Fig. 11 vs. Fig. 3.) However, this does not eliminate the predictability of `randLocal`. Even in the extreme of choosing $\Delta \leq 0$ (not depicted in Fig. 11), i.e., starting the generation only after the allowed release time, $\texttt{randLocal}_{i+1}$ would still be learned before the whole pulse P_i.
- **M2 (conceivable): A slight change in `randLocal` definition.** Section 8.3.1 suggested a simple change in the calculation of $\texttt{randLocal}_{i+1}$, where it becomes equal to the XOR of $\texttt{randOut}_i$ and the pre-image of $\texttt{preCom}_i$. Then, the value of `randLocal` would only be learned after the pulse is generated. This reduces slightly the time-window of advanced knowledge (See "case M2" in Fig. 11)
- **M3 (conceivable future). A radical change in `randLocal` definition.** The predictability of `randLocal` against a semi-honest Beacon App could be eliminated upon a significant change in the definition of `randLocal`, and depending on further capabilities by the HSM. The idea is to let $\texttt{randLocal}_{i+1}$ be defined as a pre-image of a one-way permutation with trapdoor that requires the help of the HSM only after a pulse has been computed, and such that the value is nonetheless still committed by $\texttt{preCom}_i$. Let (K_{sec}, K_{pub}) be a new secret/public key pair for a one-way trapdoor permutation $\mathscr{P}$; let K_{sec} be protected by the HSM, never revealed to the Beacon App, but usable by the HSM upon request the Beacon App. The new `randLocal` is computed by the Beacon App as follows:
  - as usual, obtain $r_{i+1} = \texttt{hash}(\rho_{i,1}||\rho_{i,2}[||\rho_{i,3}...])$;
  - as usual, publish $\texttt{preCom}_i = \texttt{hash}(r_{i+1})$ in pulse P_i;



Legend: red rectangles (window of predictability of randLocal); Let $r_{i+1} = \texttt{hash}(\rho_{i,1}||\rho_{i,2}[||\rho_{i,3}...])$ and $\texttt{preCom}_i = \texttt{hash}(r_{i+1})$. Then, $\texttt{randLocal}_{i+1}$ equals: r_{i+1} in M1; $r_{i+1} \oplus \texttt{randOut}_i$ in M2; $\mathscr{P}^{-1}_{K_{sec}}(r_{i+1})$ in M3.

Figure 11. Different predictabilities for different randLocal formulas

– as part of computing P_{i+1}, and by using $\gamma \approx \Delta$, wait till very close to $\texttt{timeStamp}_{i+1}$ to query the HSM for $\texttt{randLocal}_{i+1} = \mathscr{P}^{-1}_{K_{sec}}(r_{i+1})$.

– continue the computation of P_{i+1} and release it shortly after time $\texttt{timeStamp}_{i+1}$

The verifiability equation for users is then $\texttt{hash}(\mathscr{P}_{K_{pub}}(\texttt{randLocal}_{i+1})) =^? \texttt{preCom}_i$, because $r_{i+1} = \mathscr{P}_{K_{pub}}(\mathscr{P}^{-1}_{K_{sec}}(r_{i+1}))$. Since a semi-honest Beacon App queries the HSM only after $\texttt{timeStamp}_{i+1}$, it only learns $\texttt{randLocal}_{i+1}$ at that time, therefore reducing the predictability time-window. By using appropriate timing parameters, this could effectively reduce to 0 the window of predictability, with respect to the allowed release time $\texttt{timeStamp}+_{i+1}$.

8.3.6 Malicious database and leaked signing key → change-history attack

A conceivable stealing of the HSM key. Suppose an insider attacker has temporary physical access (e.g., less than a minute) to the HSM and to the administrator and operator cards of the HSM, along with corresponding pass-phrases. By connecting to the HSM using the stolen credentials, the attacker can backup the module key. Suppose the attacker also gains access to the key-blob (which is also backed up, in encrypted format, possibly in the cloud). The attacker can now hide, decrypt the key-blob offline and produce signatures on its own.

A complementary attack vector is conceivable depending on the policy for renewing/backing up/copying the module key. If there is a secondary HSM with the same module key, there is a larger attack surface to steal/replicate the module key.

The compromise scenario is depicted in Fig. 12.

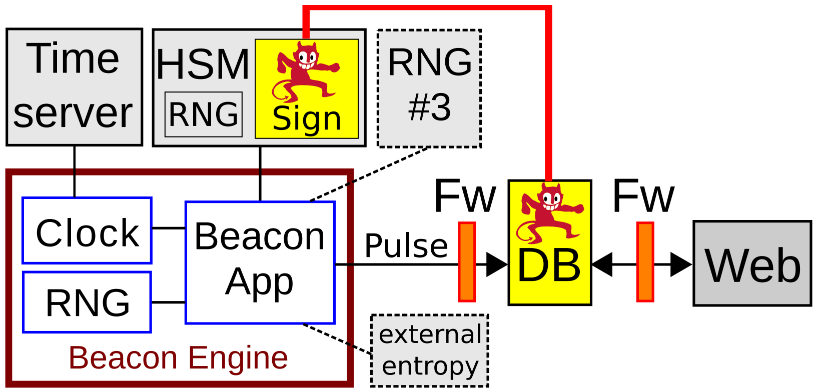


Figure 12. Illustration of malicious database and leaked signing key

A conceivable change-history attack. Suppose the attacker is further able to maliciously compromise the internal or external database (already away from the beacon engine). If the attacker knows the HSM signing key, it is then able to choose any past or present point in the chain (pulse i) and replace the whole chain from that point onward. The new chain satisfies all needed relational properties. The different chain produced by the Beacon App never gets out.

The attack can then completely ignore future pulses produced by the Beacon App. This succeeds because the Beacon App does not receive feedback from the outside.

A possible mitigation. If the attacker changes past pulses that have already been sent outside, then it is at risk of a user finding a non-repudiable inconsistency. However, there is no guarantee that a single user tricked by the a ttacker is able to confirm what other users have already received. A mitigation to this is to improve the ability for users to obtain pulses stored by external repositories. For example, if the first pulse of each day is stored in some high-reliable public website, then it CAN serve as anchor to verify any past pulse. A beacon CAN provide information about these anchors in order to have the user verify a skiplist connecting the anchor to the target past value.

8.4 Other recommendations

- **Not a random oracle.** A theoretical public random oracle (in the usual sense) would not know the hash pre-image of the outputted randomness. However, in the case of the Beacon here defined the actual pre-image is part of the procedure of verifying correctness. This means that the randomness CAN be used in applications where the knowledge of the hash pre-image is not a problem.
- **Code review.** Since the Beacon is a public service, it is recommended that the software code of the Beacon App be published (e.g., open source) for external review by the community. This CAN be done without prejudice of retaining privacy of certain security parameterizations, such as firewall configurations, time-synch schedules, etc.

9 Future considerations

In settling a concrete version 2.0.0, some design decisions were taken on the side of restricting functionality. This section describes a few identified items whose consideration may benefit from feedback from stake-holders, and may motivate changes in future versions.

1. **Cipher suite values.** Allow new values for the `cipher` field. Any update **SHOULD** reflect an update of the sub-version (value z in the version number $2.y.z$), while y **NEED NOT** change. Existing chains continue as is, since the `cipher` value **SHALL NOT** change within a chain. Conceivable updates include allowing ECC-based signatures, post-quantum safe signatures, threshold signatures and SHA3 hashes. Advantages include reducing the size and increasing the security; disadvantages include increased complexity for supporting the full suite of allowed algorithms.
2. **Hash values zero.** For conciseness, allow a hash zero to be serialized as a simple (uint64) encoding of length 0, i.e., indicating that no hash follows. In the current specification, whenever a hashOut field is not applicable (e.g., sometimes for `ext.srcId`, `ext.value`, `randLocal`, ...) it is instead being filled with an all-zeros string (i.e., exactly $BLenHash$ bytes with value zero).
3. **Other past output values.** Enable a dynamic specification of which past output values are included in the pre-image of the `randOut`. For example, if a chain outputs pulses with a period of five seconds (12 times faster than the current NIST beacon), then it may be useful to also include as past value the first pulse with the same time-with-minute-precision as the previous pulse. Conversely, a chain that outputs one pulse per hour could dispense the `out.H` field; a chain that outputs one pulse per day could also dispense the `out.D` field. This can be achieved with a change in format that would enable parsing the number of past output values that follow, and identifying the time relation with the previous pulse (and/or the pulse index difference with the current pulse).
4. **Multiple certificates.** Explain how the reply to a query for the certificate(s) corresponding to a `certificateId` value **CAN** include multiple certificates. In the current document, the description of the PEM file (the hash pre-image of `certId`) assumes a single certificate for the signature key. Advantages in allowing several simultaneous certificates to be valid (and verifiable), for the same key in use, include:
   (a) It widens the scope of acceptability of pulses, since it allows validation of pulses by different external users that have different requirements on certificate acceptance. This is likely to happen when different external users are from administratively independent jurisdictions, e.g., different countries, with stringent legal requirements (e.g., what can be accepted in a court of law).
   (b) It allows for simultaneous use of different certification technologies, e.g., conceivable future use of some experimental post-quantum secure certificate, along side with continuing to use a standard certification technology.
   (c) It allows use of several keys in some kind of multi/threshold signatures where it may be useful to account for several public keys.

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Appendix A Implementation recommendations

A.1 Recommendations about generation and release timeline

The promises in Section 3.3 leave some implementation flexibility. For example: in an extreme with $(\Delta, \delta) = (\pi, \pi/4)$, a slow pulse generation could use time equal to up to five fourths of a period (i.e., $\gamma \leq 5\pi/4$); in the opposite extreme, an ideal generation/release timeline would, if assuming no skew to UTC, have $(\Delta, \delta, \gamma) \approx (0,0,0)$, with $\delta \geq 0$.

In contrast to the allowed flexibility, it is useful that a Beacon has a predictable rate and that it releases pulses as close as possible to the indicated timestamp, provided it satisfies the promises. Therefore, in the following we put forward several recommendations to promote more concrete expectations and interoperable implementations.

The following *recommendations* represent *aspirational implementation goals*, rather than promises. The goals **MAY** possibly be overruled by other implementation concerns specific to each Beacon implementation. For example, some time uncertainty about asynchronous communications in the beacon engine **MAY** lead a beacon operator to set additional safety margin with respect to generation or release time (while compliant with the promises).

Need to handle the clock skew. A detailed analysis **SHOULD** consider the maximum estimated skew (σ), of the local clock, with respect to UTC. The actual skew will depend on the quality of the local clock, on the synchronization frequency, and on the synchronization protocol. For the most part, we simply assume that the time-server used as reference for UTC synchronization is itself accurately synchronized with UTC, but in Section 8.3.4 we consider the case of malicious compromise of the time server.

Hard time-recommendations. Let σ^+ and σ^- respectively represent reasonable majorants for the maximum absolute skew ahead (σ^+) and behind (σ^-) of UTC. Then, take the necessary precautions to ensure:

- **R1 — Avoid too-large skew:** $\sigma^+ < \pi/10$ and $\sigma^- < \pi/10$.
- **R2 — Avoid too-early release (≈ Promise 1):** $\delta \geq \sigma^-$
- **R3 — Avoid too-late release (≈ Promise 3):** $\max(\delta, \gamma - \Delta) < \pi/4 - \sigma^+$
- **R4 — Avoid too-early generation start (≈ Promise 4):** $\Delta < \pi - \sigma^+ -$

Soft time-recommendations (fine-tuning). Conditioned to the hard time-recommendations, try to fine-tune the implementation to enable timing parameters to minimize η and η', subject to the following conditions:

- **R5 — Minimize the skew:** $0 \leq \sigma^-, \sigma^+ \leq \eta$
- **R6 — Minimize the release instant:** $0 \leq \delta - \sigma^- \leq \eta$
- **R7 — Maximize the generation start instant:** $0 \leq \Delta - \gamma - \sigma^+ \leq \eta$

- **R8 — Minimize the generation duration:** $0 \leq \gamma \leq \eta'$

Recall that in R8 the parameter γ denotes the time taken between initiating the sampling of randomness from the local RNGs and obtaining the full pulse (including the signature and respective hash).

Definition (tuning slack) A Beacon engine satisfying recommendations (R5, R6 and R7) for some parameter value η is said to be within *tuning slack* η. Except when noticed otherwise, η is expressed in seconds.

Note that recommendations R5, R6 and R7 are about deciding when to do something, whereas recommendation R8 is about the time that a computation takes.

Definition (time accuracy) A Beacon Engine is said to have *time accuracy* within α if $\alpha \geq \max(\Delta - \gamma - \sigma^-, \delta' + \sigma^+)$, where $\delta' = \max(\delta, \gamma - \Delta)$. In other words, *time accuracy* within α means that the generation-time start time and the maximum release time are both (relative to the assumed duration γ and to the `timeStamp` value of the corresponding pulse) distanced to the optimal values by a value that is bounded by α. Except when noticed otherwise, α is expressed in seconds.

Note: the auxiliary definition for δ' is just to account for a possible misconfiguration of other parameters; in practice, it does not make sense to define (δ, γ, Δ) such that $\gamma - \Delta > \delta$; in regular parameterizations one will always have $\delta = \delta'$.

Examples of acceptable and non-acceptable parametrizations. As a way of example for beacon operators, Table 13 exemplifies several conceivable timing parameterizations that are acceptable within the scope of promises and hard recommendations. Correspondingly, Table 14 shows unacceptable parameterizations, when some hard recommendation fails. The values are merely illustrative. In practice it is always desirable to ensure that the skew is lower than 1 second.

Generation-start not after `timeStamp`. Row #4 is an example where there is an inactivity gap between the end of the generation (at $t = 2$) and the release (at $t = 3$), since $\delta > \gamma - \Delta$. It would be conceivable to decide $\Delta = -1$ (i.e, to have a negative value) to remove the gap, without delaying the release. However, while ensuring that the important promise of no early release is met, we decide for having a gap as a way to ensure that a correct clock (i.e., without skew during this generation, regardless of σ^- and σ^+) starts the generation process not after `timeStamp`.

Other factors to consider. A decision of timing parameters **CAN** depend on other factors, such as the possible variability in the duration of pulse generation (γ), and/or the accuracy of "awake" times ($T - \Delta$ and $T + \delta$) upon a "sleep" system call. Other timing adjustments **MAY** also happen after a time synchronization, and/or due to asynchronous interactions.

Table 13. Examples of **acceptable** timing parametrizations

#	π	Δ	γ	δ	σ^-	σ^+	Recomm.				Conceivable intervals		Slack (η)	Accuracy (α)
							R1	R2	R3	R4	Generation	Release		
1	60	0.2	0.1	0.1	0.1	0.1	Y	Y	Y	Y	$[-0.3, 0]$	$[0, 0.2]$	0.1	0.2
2	60	2	1	1	1	1	Y	Y	Y	Y	$[-3, 0]$	$[0, 2]$	1	2
3	60	0	1	1	1	1	Y	Y	Y	Y	$[-1, 2]$	$[0, 2]$	1	2
4	60	1	2	1	1	1	Y	Y	Y	Y	$[-2, 2]$	$[0, 2]$	1	2
5	60	5	2	3	3	1	Y	Y	Y	Y	$[-8, 2]$	$[0, 4]$	3	4
6	60	30	15	8	2	2	Y	Y	Y	Y	$[-32, -13]$	$[6, 10]$	28	13
7	60	59	5	0.5	0.5	0.5	Y	Y	Y	Y	$[-59.5, -53.5]$	$[0, 1]$	58.5	53.5

Legend: All values are in seconds; N (No); Y (Yes). The conceivable intervals of generation = $[-\Delta - \sigma^-, -\Delta + \gamma + \sigma^+]$ and release = $[\delta' - \sigma^-, \delta' + \sigma^+]$ (with $\delta' = \max(\delta, -\Delta + \gamma)$), are relative to `timeStamp`.

Table 14. Examples of **unacceptable** timing parametrizations

#	π	Δ	γ	δ	σ^-	σ^+	Recomm.				Conceivable intervals		Slack (η)	Accuracy (α)
							R1	R2	R3	R4	Generation	Release		
8	60	5	3	1	2	1	Y	N	Y	Y	$[-7, -1]$	$[-1, 2]$	3	2
9	60	11	3	5	8	5	N	N	Y	Y	$[-19, -3]$	$[-3, 10]$	8	10
10	60	10	5	14	3	3	Y	Y	N	Y	$[-13, -2]$	$[11, 17]$	7	17
11	60	55	5	10	8	2	N	Y	Y	N	$[-63, -48]$	$[2, 12]$	48	42
12	60	57	2	12	3	3	Y	Y	N	N	$[-60, -52]$	$[9, 15]$	54	52

Legend from Table 13 applies.