Security Review of Ethereum Beacon Clients

JP Aumasson – Taurus, Switzerland – jp@taurusgroup.ch,
Denis Kolegov – Tomsk State University, Russia – d.n.kolegov@gmail.com
Evangelia Stathopoulou – University College London, UK – evangelia.stathopoulou.20@ucl.ac.uk

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Abstract

The beacon chain is the backbone of the Ethereum's evolution towards a proof-of-stake-based scalable network. **Beacon clients** are the applications implementing the services required to operate the beacon chain, namely validators, beacon nodes, and slashers. Security defects in beacon clients could lead to loss of funds, consensus rules violation, network congestion, and other inconveniences.

We reported more than **35 issues** to the beacon client developers, including various security improvements, specification inconsistencies, missing security checks, exposure to known vulnerabilities. None of our findings appears to be high-severity. We covered the four main beacon clients, namely Lighthouse (Rust), Nimbus (Nim), Prysm (Go), and Teku (Java).

We looked for bugs in the logic and implementation of the new security-critical components (BLS signatures, slashing, networking protocols, and API) over a 3-month project that followed a preliminary analysis of BLS signatures code. We focused on Lighthouse and Prysm, the most popular clients, and thus the highest-value targets. Furthermore, we identify protocol-level issues, including replay attacks and incomplete forward secrecy.

In addition, we reviewed the **network fingerprints** of beacon clients, discussing the information obtainable from passive and active searches, and we analyzed the **supply chain risk** related to third-party dependencies, providing indicators and recommendations to reduce the risk of backdoors and unpatchable vulnerabilities.

Our results suggest that despite intense scrutiny by security auditors and independent researchers, the complexity and constant evolution of a platform like Ethereum requires regular expert review and thorough SSDLC practices.

Contents

1 Introduction

1.1 Ethereum's Beacon Chain

The *beacon chain* is a chain separate from the main Ethereum blockchain that acts as the governance platform behind "Ethereum 2.0" new mechanisms, including proof-of-stake-based consensus and sharding. Software applications used to manage and interact with the beacon chain, sometimes just called "Ethereum 2.0 clients", are composed of two main components, as of Phase 0:

- A **beacon node** service, which maintains a view of the beacon chain from the genesis block, manages validators, contributes randomness for validator assignment.
- A **validator** service, which proposes blocks and signs attestations for blocks proposed by other validators. Validators work with a beacon node to receive chain state information and propagate changes to other beacon nodes. Running a mainnet validator requires the staking of 32 ETH, locked via a deposit smart contract.

New security components introduced with the beacon chain notably include:

- **BLS signatures**, the pairing-based, aggregation-friendly signatures used by validators to sign block attestations;
- **Slashing**, the punishing mechanism to prevent malicious behavior, implemented by certain beacon nodes ("slashers"), which submit slashing evidence to one or more validators for inclusion in an attested block.

These components and other new Ethereum features are extensively documented by the Ethereum project[1].

1.2 This Project

In March 2021, the Ethereum Foundation (EF) issued a "Beacon chain security+testing RFP"[2], calling for " proposals that further the security and robustness of Ethereum's beacon chain and the upcoming merge". Having followed the Ethereum developments, including BLS signatures implementations, we submitted a grant proposal for further in-depth security review of the beacon chain's critical components, covering (in rough order of priority)

- BLS signatures
- Slashing
- Peer-to-peer connections
- Beacon chain API

We covered the four clients listed as targets in the EF RFP, namely Lighthouse, Nimbus, Prysm, and Teku, with as agreed with the EF a greater focus on Lighthouse and Prysm, as these appear to be the most used clients and the ones on which depend the greater amount of ETH assets (and consequently, the ones on which attackers are likely to invest the most resources).

We also covered the main implementation of BLS signatures, and its bindings, namely blst. Both blst, Lighthouse, and Prysm have received intense security scrutiny and testing, from their development teams, from the Ethereum community, from security auditing firms, as well as from independent researchers. For example, a number of bugs were found using a dedicated differential fuzzing framework, based on Vranken's initial work[3].

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[1] https://docs.ethhub.io/ethereum-roadmap/ethereum-2.0/eth-2.0-client-architecture/
[2] https://notes.ethereum.org/@lsankar/security-rfp
[3] https://github.com/sigp/beacon-fuzz, https://github.com/guidovranken/eth2.0-fuzzing

1.3 Our Results

Table 1 lists the GitHub issues that we opened to notify project maintainers of potential security risks, in beacon clients, BLS back-end, other dependencies, or specifications. We excluded issues found to be invalid but listed some that, although they did not lead to a patch, include interesting discussions about the design choices. We also included issues in beacon clients other than the four ones that were the focus of our project.

Furthermore, we report a number of points that from our perspective need more work and/or improvement to reduce the risk to an acceptable level. These include cryptographically weak protocols (in §5.3, §6.4) and risks from vulnerable and outdated dependencies (in §7.4).

Disclaimer. Given the uneven amount of time spent on the respective projects, it makes little sense to draw conclusions from the relative number of issues in each client—if we found more issues in client A than on client B, it does not necessarily mean that A is less secure; we may have spent much more time on A than on B, we might have been more familiar with A's software stack, etc.

2 Beacon Clients

Table 2 shows an overview of the four beacon clients reviewed, and the sections below present further information about their security, their implementation of BLS and P2P protocols, public open issues, and previous security audits.

2.1 Lighthouse

Lighthouse's README describes it as "Security-focused. Fuzzing techniques have been continuously applied and several external security reviews have been performed." Fuzzing is not performed in CI but "All finalized crates are to go through a series of extensive fuzzing." [10]. The initial fuzzing setup is described in a 2019 post [9], notably using libFuzzer via `cargo-fuzz`. The fact that sigp/beacon-fuzz has fewer trophies for Lighthouse than for any of the three other clients reviewed here may be seen as an indicator of Lighthouse's care for security.

The April 2021 Lighthouse Research Report[5] contains a good introduction to the Lighthouse client design and implementation, and considers key challenges, engineering efforts, major optimizations, development process peculiarities, and the roadmap.

BLS. Rust bindings of blst (part blst's distribution).

Networking. Own Rust implementations of libp2p and discv5, in *beacon_note/eth2_libp2p* and the repository sigp/discv5.

Open Issues. At the time of writing, open GitHub Issues with the `security` label included low-risk issues[6] open between June and October 2020: "Fork choice timing attack", "Out-of-date dependencies", "Parasitic voluntary exits ", "Rethink and test fork handling in op pool". Among the other open issues, the following two are the only ones directly related to security risks: "Zeroize in BLST"[7] and "Incorrect zeroizing of newtype structs"[8].

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[5] https://drive.google.com/file/d/12flM_E_A3DldbOUe8EYEN6Bg2bi4Yl6w/view
[6] https://github.com/sigp/lighthouse/issues?q=is%3Aopen+is%3Aissue+label%3Asecurity
[7] https://github.com/sigp/lighthouse/issues/1908
[8] https://github.com/sigp/lighthouse/issues/1789

Issue Description	Component	Status
Specifications		
Bit security level < 128	BLS specs	Fixed
BLS parameters section number fix	BLS specs	Fixed
supranational/blst		
Enforce limitation on IKM length	BLS	Fixed
sigp/milagro_bls		
Check that IKM is more than 32B in KeyGen	BLS	Open
ChainSafe/bls		
BLS secret key validation is missing	BLS	Confirmed
ChainSafe/blst-ts		
Incomplete key validation	BLS	Fixed
Incorrect result for zero lengths arrays in aggregateVerify	BLS	Fixed
Detect unsafe coefficients in verifyMultipleAggregateSignatures	BLS	Fixed
sigp/lighthouse		
Missing check on seed and password length	BLS	Open
API token can be read from a log file by any user	API	Fixed
File permissions for validator client API keys are insecure	API	Fixed
Possible DoS via /eth/v1/validator/duties/attester	API	Fixed
VC: Requests may not contain Authorization header with API token	API	Fixed
VC: Response headers are not signed	API	Confirmed
status-im/nimbus-eth2		
Insufficient private key validation (covers nim-blscurve) – also reported in nim-blscurve	BLS	Fixed
Missing pubkey and signature validation for blsVerify()?	BLS	Fixed
Possible DoS via beacon node API endpoints if the API exposed to untrusted parties	API	Open
prysmaticlabs/prysm		
Missing input validation in SecretKeyFromBigNum	BLS	Fixed
Detect unsafe coefficients in VerifyMultipleSignatures	BLS	Fixed
No length check in AggregatePublicKeys	BLS	Fixed
Update go-libp2p-noise to release v0.2.0	Libp2p-noise	Fixed
jwt-go library is vulnerable to CVE-2020-26160	RPC	Fixed
Use golang-jwt/jwt implementation of JWT	RPC	Fixed
Possible DoS via beacon node API endpoints if the API exposed to untrusted parties	API	Fixed
Add certificate-based client-side authentication	API	Open
No TLS client authentication in gRPC	API	Open
Add HTTP Secure Headers	UI	Open
Logout endpoint doesn't require a valid JWT token	UI	Open
ConsenSys/teku		
Public key aggregation ambiguous infinite points handling	BLS	Fixed
Detect unsafe coefficients in fast BLS verification	BLS	Fixed
Incorrect BLS key validation	BLS	Won't fix
Detect unsafe coefficients in fast BLS verification	BLS	Fixed
Libp2p-noise		
Static key signature does not depend on a peer's challenge	Libp2p-noise spec	Confirmed
ChainSafe/lodestar		
No BLS public key validation due to validate parameter missing	BLS	Open
Improper nonce handling in Noise handshake	Libp2p-noise	Closed
Improper nonce handling	Libp2p-noise	Open
Improper nonce handling in Go	NoiseExplorer	Fixed
ethereum/trinity		
Incomplete BLS key validation	BLS	Won't fix[4]

Table 1: List of issues reported, including security improvements, specification inconsistencies, missing security checks, exposure to known vulnerabilities.

Client & Repository	Language	Developers	Repo Stars	Open/Closed Issues
Lighthouse sigp/lighthouse	Rust	Sigma Prime sigmaprime.io	1.3k	100/846
Nimbus status-im/nimbus-eth2	Nim	Status status.im	222	152/526
Prysm prysmaticlabs/prysm/	Go	Prysmatic Labs prysmaticlabs.com	2.2k	114/2016
Teku ConsenSys/teku	Java	ConsenSys consensys.net	281	82/1251

Table 2: Overview of the beacon clients reviewed, as of 20210913.

Audits. In June 2020 Trail of Bits completed a first security audit of Lighthouse, the report does not seem to have been published. Sigma Prime commented [11] that "no critical issues were found". In October 2020 Lighthouse cited [12] a second Trail of Bits audit round, as well as audit by NCC. These covered all the critical features of Lighthouse, such as the p2p protocol, the API, the validation logic, and deserializations.

2.2   Nimbus

Nimbus targets resource-constrained platforms (citing Raspberry Pis and mobile devices) and is written in Nim, a language that "provides memory safety by not performing pointer arithmetic, with optional checks, traced and untraced references and optional non-nullable types."[9].

Nimbus offers an "Auditors' book" [20], which briefly describes its threat model, and provides useful information for security auditors, but is incomplete, having a number of sections left empty. A "Nimbus Eth2 Stack" diagram[10] describes its architecture and high-level implementation.

BLS.   status-im/nim-blscurve, a dedicated Nim interface to BLS implementation back-ends. This uses blst for x86_64 and ARM64 architectures, and MIRACL[11] for other architectures (including ARM Cortex-M0/M4, ESP32, MIPS32, RISC-V).

Networking.   Most of the networking logic is in another repository, status-im/nim-eth, also maintained by Status.

Open Issues.   At the time of writing, open GitHub Issues with the security included 9 improvement proposals[12], such as reduced exposure of private keys, integration of Clang sanitizers, and a discussion about invalid BLS signatures of more general interest[13].

Audits.   In May 2020, the Nimbus maintainers (Status) issued an RFP for a security audit [14], and a short summary was published in September [15], without sharing the report nor the audit team.

2.3   Prysm

Prysm integrates extensive fuzzing[14], using the standard Go fuzzing toolchain, with libfuzzer as fuzzing engine, and notably covering block validation, RPC endpoints, SSZ decoding. Fuzz tests are run in the

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[9]https://nim-lang.org/faq.html
[10]https://miro.com/app/board/o9J_kvfytDI=/
[11]https://github.com/miracl/core
[12]https://github.com/status-im/nimbus-eth2/issues?q=is%3Aopen+is%3Aissue+label%3Asecurity
[13]https://github.com/status-im/nimbus-eth2/issues/555
[14]https://github.com/prysmaticlabs/prysm/tree/develop/fuzz

GitLab CI via fuzzit.

Prysm is the only beacon client to sport a graphical UI, as a web application for local configuration[15].

BLS. Go bindings of blst (part of blst's distribution).

Networking. libp2p/go-libp2p, and its own implementation of the discv5 logic.

Open Issues. The open security-related issues only include two about version updates and a meta-issue tracking issues reported by the two audits as well as proposed improvements[16].

Audits. In October 2020 Trail of Bits completed a first security audit of Prysm [54]. The audit found no critical issues and one high-severity issue related to a failure scenario causing a user's password to be logged. In October 2020 Quantstamp also published an audit report [47], which contained 4 high risk issues (3 of them were fixed and 1 was acknowledged).

Both reports noted shortcomings in the SDLC process:

- Many dependencies (including core components like bbolt and libp2p) were outdated and included known bugs;
- Many pieces of the code lack unit tests.

2.4   Teku

Teku is advertized as "built to meet institutional needs and security requirements"[17] and includes basic fuzz test suites, which notably cover the slashing mechanism.

BLS. Teku uses blst's Java bindings, with an additional wrapper layer in *tech/pegasys/teku/bls/impl*.

Networking. Own Java implementation in *tech/pegasys/teku/networking/*.

Open Issues. We did not find open issues that appeared directly security-related.

Audits In October 2020, Quantstamp complete an audit of Teku, whose details were published [48], with documentation of issues' resolution.

3   BLS Signatures

What's known as "BLS signatures" encompasses the original 2001 Boneh-Lynn-Shacham pairing-based signatures [28] and the 2018 collective signing extensions [25, 26] based on the 2003 work on aggregate signatures. Under this umbrella term, BLS signatures are:

- Deterministic
- Non-interactive
- Short (one group element)
- Simple, given a pairing operator
- Easily adapted to support collective signing operations:
  - Aggregation of signatures and public keys for n-of-n signing
  - Threshold signing (t-of-n)

– Batch verification

For a similar security level, in the single-signature setting, BLS signing is about as fast as with ECDSA or Schnorr signatures, but verification is slower because of the two pairings involved[18]. Efficient aggregation is the feature that drove Ethereum to choose BLS signatures and was described as "a pragmatic medium-term solution to the signature verification bottleneck of sharding and Casper" [34]. Note that BLS signatures are not post-quantum.

We provide a high-level description of BLS signatures, where we tried to use notations close to those in the IETF draft. We only describe the functional operation and *do not include the security checks*.

BLS signatures use a non-degenerate bilinear pairing[19] $e : \mathbb{G}_1 \times \mathbb{G}_2 \to \mathbb{G}$, where $\mathbb{G}_1$ and $\mathbb{G}_2$ are distinct isomorphic groups, thus of same prime order. The pairing satisfies

- $e(P + Q, R) = e(P, R)e(Q, R)$
- $e(P, Q + R) = e(P, Q)e(P, R)$

which implies $e(nP, Q) = e(P, nQ) = e(P, Q)^n$ for a scalar n.

A key pair is (scalar SK, point $PK = SK \times P$), where P is a generator of the curve's group, which can be $\mathbb{G}_1$ or $\mathbb{G}_2$, but the beacon chain uses $\mathbb{G}_1$ so we'll stick to this convention (see details in §3.1).

Signing a message M consists in hashing the message to a curve point, denoted $H2C : \{0, 1\}^\star \to \mathbb{G}_2$ and multiplying it with the secret key:

$$SK \times H2C(M) \in \mathbb{G}_2$$

Verifying a signature S of a message M then consists in computing two pairings and checking their equality: $e(PK, H2C(M))$, and $e(P, S)$, where P is the generator of $\mathbb{G}_1$ such that $SK \times P = PK$. Indeed,

$$e(PK, H2C(M)) = e(SK \times P, H2C(M)) = e(P, H2C(M))^{SK} = e(P, SK \times H2C(M)).$$

3.1 Beacon Chain Integration

Ethereum adopted BLS signatures as specified in the IETF BLS signature draft [27, Ap.A], which uses the BLS12-381 parameters specified in [50, §4.2.1], including the group $\mathbb{G}_1$ and $\mathbb{G}_2$ definition. BLS12-381 is an instance of the Barreto–Lynn–Scott family BLS12 [24] proposed by Zcash [29][20]. But this is not alarming [22].

The hash-to-curve algorithm is the one specified in the v09 of the Internet Draft "Hashing to Elliptic Curves" [35] (based on [51,58]). Specifically, the variant used is BLS_SIG_BLS12381G2_XMD:SHA-256_SSWU_RO_POP_, which uses the "minimal-pubkey-size" parameter, or the convention of using public keys in $\mathbb{G}_1$ and signatures in $\mathbb{G}_2$.

The IETF draft not only describes the mathematical, functional operations but aims to be an implementable specification, including:

- Security pre-condition verification (such as checking that points belong to the right subgroup and are not the identity).
- Encoding and decoding to/from bytes.
- Clear subroutines for each operation.
- Mitigation against rogue-key attacks via proofs of private key possession.
- Cipher suites definition.
- Test vectors (to appear in the final version).

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[18]See benchmarks in https://www.mintlayer.org/news/2021-05-17-why-mintlayer-adopts-bls-signature/

[19]Although BLS signatures were proposed in the paper titled "Short Signatures from the Weil Pairing", they now usually rely on the Ate pairing, discovered after that paper was published, and are more efficient than Weil's pairing.

[20]Whereas a 128-bit security level is usually expected of BLS12-381 BLS signatures, it's strictly speaking allegedly lower than 120, as discussed in [50, §3.2] and [41, p8].

This is a challenging and commendable effort, that will likely contribute to more consistent and safer implementations. In practice, implementations may differ a bit, for example when implementing the following CoreVerify algorithm:

```
1. R = signature_to_point(signature)
2. If R is INVALID, return INVALID
3. If signature_subgroup_check(R) is INVALID, return INVALID
4. If KeyValidate(PK) is INVALID, return INVALID
5. xP = pubkey_to_point(PK)
6. Q = hash_to_point(message)
7. C1 = pairing(Q, xP)
8. C2 = pairing(R, P)
9. If C1 == C2, return VALID, else return INVALID
```

This returns the same INVALID for all error types, whereas implementations may return different error codes and/or messages. We can imagine scenarios where returning the same INVALID error could facilitate certain attacks (fault injection with inaccurate faults), but in Ethereum's use case it's unlikely to be an issue.

We reviewed that the security checks mandated by the IETF draft were done correctly in each implementation (and reported a number of issues):

1. "IKM MUST be infeasible to guess"

2. "IKM MUST be at least 32 bytes long."

3. "Implementations of the underlying pairing-friendly elliptic curve SHOULD run in constant time." (With respect to the key, not necessarily the message.)

4. The security checks defined by `pubkey_subgroup_check()`, `signature_subgroup_check()`, `KeyValidate()`, and `PopVerify()` are properly implemented, used where they must be, and their return value processed correctly processed.

5. `hash_to_point()` and `hash_pubkey_to_point()` functions implemented using a secure hash-to-curve algorithm.

6. Each implemented signature scheme is protected against rogue-key attacks [49], with the exception, by design, of `FastAggregateVerify()`

7. The secret key SK must be "such that $1 \leq SK < r$", and thus enforced at generation and signing.

Note that the second version of the IETF draft did not include the identity check in the key validation, only the subgroup check. This may be a source of confusion if implementers refer to an older version of the document.

Depending on the usage of BLS signatures, additional security checks may be needed. For example, in a use case where distinct signers jointly issue a signature, it may be valuable to check that all public keys are distinct. Also, "splitting-zero attacks" [46] highlight a property that an attacker can determine combinations of private keys such that the sum aggregate will be zero[21].

3.2 Aggregation and Rogue-Key Attacks

The Aggregate function of the IETF draft adds up signatures into a single point, then AggregateVerify takes a signature (aggregated) R, n public keys PK_i and as many messages M_i and verifies that all messages are distinct, and computes the product

$$\prod_{i=1}^{n} e(PK_i, H2C(M_i)) = \prod_{i=1}^{n} e(SK_i \times P, H2C(M_i)) = \prod_{i}^{n} e(P, SK_i \times H2C(M_i)) = e(P, R)$$

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[21]See also https://github.com/cryptosubtlety/zero.

and verifies that it matches $e(P, R)$.

When the same message is signed by all parties, the sequential computation of pairings can be replaced by additions and a single pairing. This is done in the FastAggregateVerify function, which must come with proofs of possession of the public keys' private keys, to thwart *rogue-key attacks*.

Rogue-key attacks allow an attacker to forge aggregate signatures of the same message given one or more public keys of other signers. The idea is that given a public key PK_1, an attacker can create $PK_2 = r \times P - PK_1$, therefore $r \times H2C(M) = (SK_1 + SK_2) \times H2C(M)$ will be a valid aggregate signature of M—with the caveat that the attacker doesn't know $SK_2 = r - SK_1$.

This attack works when the aggregation includes duplicate messages. A mitigation is thus to ensure that all messages signed are distinct, but this eliminates large classes of important use cases. Another mitigation is to force each user to prove that they know their private key, which is why the IETF draft includes proofs of possession (the routines PopProve, PopVerify), which are essentially single-signer signature and verification. However, it may be unclear to readers that the "fast" verification routine FastAggregateVerify must be accompanied with some assurance, as a previous proof of possession, that signers know the private key.

Note that [25] describes a trick to create an aggregation mechanism that does not require proofs of possession to be safe against rogue-key attacks, by multiplying each signature by the hash of its corresponding public key. However, this variant is not specified in the IETF draft and is not used in Ethereum clients.

3.3 Fast Batch Verification

To verify multiple aggregate signatures efficiently, Buterin proposed an efficiency optimization [31], which is implemented by all the clients we reviewed in this paper. However, no formal specification or security analysis is available, and the IETF draft does not describe it. This technique works as follows, given n aggregate signatures S_i, each over m_i messages:

$$e(S_i, P) = \prod_{j=1}^{m_i} e(P_{i,j}, M_{i,j}), i = 1, \dots, n$$

The naive method thus consists in checking these n equalities, which involves $n + \sum_{i=1}^{n} m_i$ pairing operations.

One can further aggregate signatures to slightly reduce the number of pairings, as follows: the verifier generates n random values $1 \le r_i < n$, and aggregates all aggregate signatures into a single one:

$$S^\star = r_1 S_1 + \cdots r_n S_n$$

the verifier also "updates" the signed messages (as their hashes to the curve) to integrate the coefficient of their batch, defining
$$M'_{i,j} = r_i M_{i,j}, i = 1, \dots, n, j = 1, \dots, m_i$$
Then verification can be done by checking

$$e(S^\star, G) = \prod_{i=1}^{n} \prod_{j=1}^{m_i} e(P_{i,j}, M'_{i,j})$$

Verification thus saves $n - 1$ pairing operations, but adds $n + \sum_{i=1}^{n} m_i$ scalar multiplications. However, if the verification fails then the verifier can't tell which (aggregate) signature is invalid.

The security goal of batch verification is that it should succeed if and only if all signatures would be individually successfully verified, when one or more (possibly all) of the signers may be maliciously colluding. See [32] for a rigorous treatment of batch verification security.

The post and thread [31] include a basic analysis and discuss variants and optimizations. It is easy to verify that this rewriting of the verification works, as long as the r_i's are in $[1, r)$ and that group

elements have been properly validated to be non-zero. We noted that several of the beacon clients did not include this safety check, but they added it after we reported the problem.

As the post describes, random coefficients are required to prevent a trivial attack:

> the randomizing factors are necessary: otherwise, an attacker could make a bad block where if the correct signatures are C_1 and C_2, the attacker sets the signatures to $C_1 + D$ and $C_2 - D$ for some deviation D. A full signature check would interpret this as an invalid block, but a partial check would not.

Furthermore, we note that a generalization of this attack will work *regardless of the random coefficient size* if subgroup validation is not done: if deviations D_1 and D_2 are chosen as element of an order-p subgroup, and signatures submitted are $S_1 = (C_1 + D_1)$ and $S_2 = (C_2 + D_2)$, then $r_1 D_1 = -r_2 D_2$ with chance $1/p$, in which case the weighted deviations will cancel themselves out, and verification will pass.

Details and further analysis appear in a recent post that we contributed to [23].

3.4 Implementations

The main implementation of BLS signatures is the blst project[22] ("blast") from Supranational. blst's BLS logic is written in C, with some x86_64 and ARMv8 assembly for core arithmetic operations, and the project provides bindings for Go, and Rust, as well as partial support for Python, Java, and Node.js.

blst is described as "focused on performance and security", and indeed shows good attention to security, with safety checks and a number of comments in the code related to security mitigations and design choices. For example, the blst team attempts to document how to use its APIs and the users' responsibilities, as in the following:

> The essential point to note is that it's the caller's responsibility to ensure that public keys are group-checked with `blst_p1_affine_in_g1`. This is because it's a relatively expensive operation and it's naturally assumed that the application would cache the check's outcome. Signatures are group-checked internally.

Different clients have a different approach, but most validate the key upon deserialization of the bytes object and creation of a public key object (see for example the discussion in https://github.com/ConsenSys/teku/issues/4025). Worth noting too, blst warns users of confusing aspects of the API, noting for example that

> unlike what your intuition might suggest, `blst_sign_*` doesn't sign a message, but rather a point on the corresponding elliptic curve

and that

> Another counter-intuitive aspect is the apparent g1 vs. g2 naming mismatch, in the sense that `blst_sign_pk_in_g1` accepts output from `blst_hash_to_g2`, and `blst_sign_pk_in_g2` accepts output from `blst_hash_to_g1`. This is because, as you should recall, public keys and signatures come from complementary groups.

blst was audited by NCC, covering all the code from the assembly arithmetic up to the Go and Rust bindings [40], reporting mostly low-severity issues. Third-party bindings exist for Java (ConsenSys/jblst used in Teku), Nim (status-im/nim-blscurve, used in Nimbus), and TypeScript (ChainSafe/blst-ts).

4 Slashing

The *slashing* mechanism aims to disincentivize "bad" behavior from the validators by applying penalties on the validator revenue and eventually excluding it from the network. At the same time, slashing

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[22]https://github.com/supranational/blst

incentivizes reports of such behavior by offering a "whistleblower reward" to the validator that submits a proof of a validator's misbehavior.

Slashing is part of the Ethereum reward and penalty mechanism, but should not be confused with the penalty mechanism that punishes a node for being offline or for a miscast vote, which are unlikely to be malicious activities. Instead, slashing punishes behavior that violates the protocol definition and that could potentially jeopardize the consensus' security. Specifically, slashing punishes validators that

- As proposers, propose different beacon blocks for the same slot
- As attesters, sign conflicting attestations

The high-level workflow is then the following:

1. *slasher* services monitor proposed blocks and attestations for invalid ones

2. When a slasher detects a slashable event among proposed blocks and attestations, it communicates to a validator (other than the one guilty) a `ProposerSlashing` or `AttesterSlashing` object

3. The validator submits the slashing into a block

4. Other validators verify the slashing proposal correctness, and if the block is validated then the validator that proposed the slashing receives a *whistleblower reward*

A list of slashing events is available at https://beaconscan.com/slots-slashed.

The logic of Ethereum's slashing actions is defined[23], in `slash_validator()` and `process_slashings()`, while processing of slashing objects is defined in `process_proposer_slashing()` and `process_attester_slashing()`.

4.1 Protection

Slashing happens when a slasher detect a behavior similar to a potentially malicious one, but in practice such behavior may occur accidentally rather than maliciously. For example, validators may attempt to minimize downtime (and associated penalties) by running multiple instances behind a load balancer, however a faulty setup can lead to two instances proposing conflicting blocks. The first slashing event allegedly happened for such a reason[24]. Accidental slashing can be in part due to a missing or compromised attestation history, for example, when migrating a validator's database. The Ethereum specifications include some recommendations, such as[25]:

> before a validator client signs a message it should validate the data, check it against a local slashing database (do not sign a slashable attestation or block) and update its internal slashing database with the newly signed object.

EIP-3076 [2] ("Slashing Protection Interchange Format") was created to prevent such accidental slashing, by defining a standard JSON-based record format to migrate validator histories across instances' of a beacon client. All the beacon clients reviewed support EIP-3076: Lighthouse and Nimbus store data in an SQLite database, Teku in a YAML file, and Prysm in the validator's BoltDB instance. Validators then attempt to prevent accidental slashing by identifying contradictions between new events and previously recorded events (proposals, attestations) to prevent accidental slashable events. Note that different clients may implement slightly different policies[26].

Such protections work when multiple client instances use the same data directory (datadir) and database, but are ineffective if instances run independently with the same key, for example, failover instances on another infrastructure.

Given EIP-3076-based protection, as users get more experienced, and risks are better documented, we can expect accidental slashings to vanish on the long run.

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[23]https://github.com/ethereum/eth2.0-specs/blob/dev/specs/phase0/beacon-chain.md#slash_validator
[24]https://beaconcha.in/validator/20075
[25]https://github.com/ethereum/eth2.0-specs/pull/2107/files
[26]https://ethereum-magicians.org/t/eip-3076-validator-client-interchange-format-slashing-protection/4883/2

4.2 Security Model

The security goals of the slashing mechanism are to disincentivize adversarial abuse, and to prevent circumvention of the detection mechanism:

1. A dishonest validator should not be able to misbehave in such a way that they can't be detected (and then slashed), or that another (innocent) validator is slashed instead of them. This would happen if all slashers were ineffective at a given epoch, for example.

2. A malicious validator should not be capable of enticing another validator into unknowingly committing a slashable offense, so that the malicious validator receives the whistleblower reward. This may happen if circumstances are such that a validator switches to a failover instance with no slashing protection.

Examples of attacks on slashing have been described[27]. However, under the assumptions described, an attacker can do more damage than just collecting whistleblower rewards or blackmailing the validator.
Additionally, potential issues can come from

- Errors, such as miscalculations of rewards, when receiving multiple slashing attestations, and including multiple in a block (note that MAX_ATTESTER_SLASHINGS=2 and MAX_PROPOSER_SLASHINGS=16)
- Leverage of invalid slashing attestations for malicious purposes; note that a validator proposing an invalid slashing attestation is not penalized, let alone slashed.

Failures of slashing can come from:

- Flaws in the slashing logic, as specified,
- Implementation errors of said logic, or
- Via the creation of a state under which slashing is ineffective.

Our review focused on the second aspect, the implementation, which consists mainly in:

- Detection of slashing conditions, by slasher services. (See [38] for detection methods, and [21, 30] for fundamental analysis and the concept of weak subjectivity.)
- Processing of slashing attestations, by validators.

4.3 Implementations Review

In all clients' validator implementations, we checked the correct implementation of the specification's is_slashable_validator(), is_slashable_attestation_data, slash_validator(), process_slashings(), process_attester_slashing(), process_proposer_slashing(), as well as use of the correctness of the constants' values.

We found implementations to be consistent with the specifications, and only noted that Nimbus' implementation can bypass signatures verification in check_proposer_slashing() (which implements the logic of the specs' process_proposer_slashing()) when the skipBlsValidation is set. This flag seems to only be used for test routines, but otherwise it would allow the slashing of innocent validators (from the perspective of a Nimbus validator).

We did not find flaws in Teku's slashing implementation, but it's the implementation we found the hardest to parse, and the one we are the least confident in.

⚠ Recommendation: Review the way slasher services detect slashing conditions, and how it could be abused. (We did not thoroughly review this part.)

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[27] https://ethresear.ch/t/global-slashing-attack-on-eth2/6703

5 P2P Networking

Ethereum uses [3] the libp2p [8] multi-transport stack for secure transport between peers. Specifically, Ethereum uses the libp2p-noise [17] Noise-based [18] protocol, which superseded the SECIO protocol[28].

libp2p-noise uses the Noise XX pattern over the curve Curve25519, with a few twists. libp2p-noise bootstraps from long-term *identity keys*, as opposed to Noise static keys, and updates Noise static keys regularly, signing new keys with the identity key, and including this signature in a handshake payload.

The Ethereum networking specification [3] defines the following network security goals:

- Peer authentication
- Confidentiality
- Integrity
- Non-repudiation
- Non-replayability
- Perfect forward secrecy

Let's review to what extent these are satisfied.

5.1 libp2p-noise Implementations

At the time of writing, libp2p has 7 native implementations [7] including implementations in Go, Rust, Nim, TypeScript, and one in Java. There are three ways to implement a Noise pattern:

- Implement a Noise version (called "pattern") from scratch
- Use a reference implementation in the corresponding programming language
- Use the automatically generated template for a target pattern

Prysm, Lighthouse and Teku use libp2p-noise versions based on the corresponding reference implementations of Noise: flynn/noise[29], mcginty/snow[30], and rweather/noise-java[31], respectively. Nimbus' libp2p-noise reimplements Noise XX pattern from scratch[32], which is arguably riskier than using an established implementation. Lodestar uses a Noise XX implementation generated from Noise Explorer.

We reviewed the implementations' security and correctness with respect to the Noise XX specification, using as a baseline the flynn/noise Go package, recently audited[33]) and the Noise specification document. We discovered a nonce overflow issue in the js-libp2p-noise library[34] (used in the Lodestar client) , which we traced back to a bug in Noise Explorer[35], which js-libp2p-noise is using. The problem is the following: the Noise specification[36] says in §5.1 that

> n: An 8-byte (64-bit) unsigned integer nonce. The maximum n value ($2^{64} - 1$) is reserved for other use. If incrementing n results in $2^{64} - 1$, then any further EncryptWithAd() or DecryptWithAd() calls will signal an error to the caller.

However, the Noise Explorer templates use the following code:

```
type cipherstate struct {
    k [32]byte
    n uint32
}
(...)
func encryptWithAd(cs *cipherstate, ad []byte, plaintext []byte) (*cipherstate, []byte) {
```

---

[28]https://blog.ipfs.io/2020-08-07-deprecating-secio/
[29]https://github.com/flynn/noise
[30]https://github.com/mcginty/snow
[31]https://github.com/rweather/noise-java
[32]https://github.com/status-im/nim-libp2p/blob/master/libp2p/protocols/secure/noise.nim
[33]https://cure53.de/pentest-report_turbotunnel.pdf
[34]https://github.com/NodeFactoryIo/js-libp2p-noise
[35]https://noiseexplorer.com/patterns/XX/
[36]https://noiseprotocol.org/noise.html#the-cipherstate-object

```
        e := encrypt(cs.k, cs.n, ad, plaintext)
        cs = setNonce(cs, incrementNonce(cs.n))
        return cs, e
}
```

The lack of integer overflow check combined with the shorter nonce can cause the session key and nonce to be reused after multiple messages. Despite the fact that js-libp2p-noise uses the "number" type instead of real `uint32` type, the implementation is still vulnerable since nonces are converted to bytes[37] using the fixed number of bytes. Noise Explorer acknowledge the issue and fixed it.

5.2   libp2p-noise Protocol Security

5.2.1   Static Keys Signatures Replay

Libp2p-noise extends the Noise XX pattern by introducing *identity keys*, or long-term keys, and using Noise static keys between ephemeral and long-term keys: implementations may generate a new static keypair for each session or a single static keypair may be generated when libp2p-noise is initialized and then used for all sessions.

To authenticate the static key used in the Noise XX handshake, libp2p-noise includes in the handshake protocol $\mathsf{NoiseHandshakePayload} = (\mathsf{id\_key}, \mathsf{id\_sig}, \mathsf{data})$ message containing a signature of the static public key computed with the identity private key: in Noise terms $\mathsf{id\_sig} = \mathsf{Sig}(\mathsf{id\_key}, \mathsf{data})$, where $\mathsf{id\_key}$ is the sender's identity private key and data is the "noise-libp2p-static-key:" string followed by sender's static public key $\mathsf{s\_pub}$ [38].

The signature is computed over the sender's static public key without any unpredictable challenge from the corresponding peer. So, the used static key authentication mechanism violates the basic authenticated key agreement protocol design principle: "Ephemeral leakage should not allow for long-term impersonation" [39]. In this case, the sender proves knowledge of the signature over the static public key, but not access to the identity private key within the current session. For example, if an attacker finds a triple $(\mathsf{s\_pub}, \mathsf{s\_priv}, \mathsf{Sig}(\mathsf{id\_key}, \mathsf{s\_pub}))$ for the identity key $\mathsf{id\_key}$ of the target user then they will be able to impersonate this user without any limitation in the future. As a result, if an attacker is able to sign a static public key once then they will be able to impersonate the identity key owner forever. This may occur if the attacker has temporary access to a signing module, or if the static key and the signature are leaked to the attacker.

⚠ Recommendation: Consider implementing mitigation such as using a peer's ephemeral public key (re) as an unpredictable challenge in signing $\mathsf{data} = "noise\text{-}libp2p\text{-}static\text{-}key:" \,\|\, \mathsf{re} \,\|\, \mathsf{s}$.

5.2.2   No DoS Countermeasures

Libp2p was designed to support multiple transport protocols (TCP, UDP, QUIC, etc.). All datagram-based secure transport protocols (e.g., DTLS, IPsec, WireGuard) provide protection against denial-of-service (DoS) attacks. For instance, WireGuard's Noise IK-based protocol uses cookies to authenticate a session initiator and has a second message that is smaller than the first message to prevent amplification attacks.

No such defense is implemented in libp2p-noise, thus an attacker could flood the responder with session initiation messages and force them to compute exponentiations. The initiator could also spoof its origin address and exploit the data amplification provided by Noise XX, whose first is 32-byte and the second is 192-byte, or a potential 6× amplification factor (without early data).

We believe that at present time this risk is mitigated by TCP mechanisms.

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[37]https://github.com/NodeFactoryIo/js-libp2p-noise/blob/master/src/handshakes/abstract-handshake.ts#L50
[38]https://github.com/libp2p/specs/tree/master/noise#the-libp2p-handshake-payload

5.2.3 Early Data Insecurity

The libp2p-noise specification states the following related to early data (payloads): "These payloads MUST be inserted into the first message of the handshake pattern that guarantees secrecy. In practice, this means that the initiator must not send a payload in their first message. Instead, the initiator will send its payload in message 3 (closing message), whereas the responder will send theirs in message 2 (their only message)"

According to Noise XX security properties [18], the second message with payload provides forward secrecy, however, the sender has not authenticated the responder, so this payload might be sent to any party, including an active attacker. So an active attacker can just establish a connection with the responder host and get the early data.

5.2.4 Identity Hiding

The Ethereum specification doesn't mention identity hiding as a security goal, but we observed that it inherits identity hiding from Noise XX. many Noise patterns by design including Noise XX. The payload security and identity-hiding properties of the original Noise XX handshake pattern are as follows:

- The responder's static public key is encrypted with forward secrecy but can be probed by an anonymous initiator
- The responder's handshake payload is encrypted with forward secrecy, depending on an ephemeral key, but the payload might be sent to any party
- The initiator's static public key is encrypted with forward secrecy to an authenticated party
- The initiator's third handshake message payload is encrypted with forward secrecy for an authenticated party

The static public keys and handshake payloads in libp2p-noise thus have similar security properties. Note however that libp2p-noise transmits identity keys in handshake payloads, and uses them instead of Noise temporal static keys, while statics keys are updated for each session (and are thus not long-term peer identifiers). The identity hiding of Noise XX with respect to static keys thus applies as well to identity keys in libp2p-noise.

5.2.5 No Non-Repudiation

Although non-repudiation is stated as a security goal, libp2p-noise does not provide non-repudiation for transport messages. This would require digital signatures with the sender's (identity, static, or ephemeral) key, however only the second and third handshake messages are signed.

5.3 discv5 Handshake

Ethereum consensus nodes [3] discover each other using the Node Discovery Protocol Version 5.1 (discv5) [16]. discv5 is a UDP protocol that works with self-certified, flexible Ethereum node records (ENRs) and topic-based advertisement, both of which are requirements in this context. At the time of writing, the discv5 specification is still a work in progress.

discv5 aims to provide:

- Network traffic encryption to protect against passive observers
- Authentication, insofar as peers are known and trusted on a TOFU basis
- Network traffic obfuscation to prevent traffic mangling, naive blocking of the protocol messages using hard-coded packet signatures, and trivial sniffing

Most of the design requirements and security goals of discv5 are devoted to the protocol application logic (e.g., Kademlia redirection, replay of NODES or PONG response packets, traffic amplification, Sybil/eclipse attacks), and don't address secure transport mechanisms. An implicit assumption is that

all communications should be encrypted and authenticated, protecting topic searches and record lookups against passive observers. The discv5 design document states the following:

- The handshake protocol protects against passive observers but is not forward-secure and active protocol participants can access node information by simply asking for it
- Since the handshake performs cryptographic operations (ECDH, signature verification for different algorithms) performance of the handshake is a big concern
- discv5 handshake reduces the risk of computational DoS because it costs as much to create as it costs to verify and cannot be replayed.

5.3.1 Protocol

This is a simplified description of the discv5 handshake from a cryptography perspective, based on its specification[39]. The handshake protocol involves the sending of the following discv5 messages, whose headers include a fixed-length field `static header` defined as `protocol-id || version || flag || nonce || authdata-size`, where nonce is a random 96-bit value, used for AES-GCM authenticated encryption.

In the following, node A (initiator) wishes to communicate with node B (responder). Node A knows node B's identity (that is, its identity key). In our description, B does not know A and never communicated with A.

1. A sends its identity key and a nonce to B, as a FINDNODE message.

2. B initiates the actual handshake by sending as a challenge a WHOAREYOU packet comprising:

   - A random 128-bit `id-nonce` field.
   - A sequence number field `enr-seq` set to zero.

3. A then:

   - Generates an ephemeral key pair $(\text{ephemeral-key}, \text{ephemeral-pubkey})$ (using the specs' notations).
   - Uses B's identity key `dest-pubkey` to derive session keys from $\text{DH}(\text{ephemeral} - \text{key}, \text{dest} - \text{pubkey})$ (using HKDF).
   - Computes the `signature` field using its identity private key (and the elliptic-curve signature scheme used by the instance), signing a message comprising the challenge data (as sent by B), ephemeral-pubkey, and B's identifier.
   - Sends `ephemeral-pubkey`, `signature`, and a payload encrypted with the derived keys.

4. B verifies `signature`, derives keys and decrypts the payload, and responds with a NODES message (encrypted using the derived `recipient-key`).

5. A verifies that it can decrypt B's message, and then considers B's identity verified and the session keys valid.

5.3.2 Security

The discv5 specification claims that protocol messages are secure against "passive observers". However, the security goals and design rationale are unclear, in particular regarding:

- The authentication asymmetry: a responder uses static Diffie-Hellman, while the initiator uses signatures.
- The use of static Diffie-Hellman (and no ephemeral-ephemeral combination). An authenticated key agreement doesn't necessarily require static Diffie-Hellman, a signature and ephemeral Diffie-Hellman can be used instead.

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[39]https://github.com/ethereum/devp2p/blob/master/discv5/discv5-theory.md

- If the protocol considers a passive attacker only then the handshake protocol may not use authentication at all, since Diffie-Hellman key agreement is secure against a passive attacker but insecure against an active attacker.

It follows that forward secrecy holds for sender compromise only: if the responder's static private key is compromised, the past messages can be decrypted. Moreover, a passive observer can decrypt all future messages sent by a sender to the responder on the fly.

We believe that the protocol's security can be improved without any changes in the current flow or RTT number and slightly affecting performance. As an illustration, we show how the Noise KK pattern can be used as a basis.

First, note that "Ordinary message packet"[40] contains A's identifier `id-nonce` corresponding to the static public key. So, on the step 3, A and B knows identities (static public keys) of each other. So, the new protocol can be defined as follows:

1. A sends its identity key and a nonce to B, as a FINDNODE message

2. B initiates the actual handshake by sending as a challenge a WHOAREYOU packet comprising:

   - A random 128-bit `id-nonce` field.
   - A sequence number field `enr-seq` set to zero.

3. A then:

   - Generates an ephemeral key pair (source-ephemeral-key, source-ephemeral-pubkey).
   - Performs DH(source-ephemeral-key, dest-pubkey), DH(source-key, dest-pubkey).
   - Mixes the outputs of DH using HKDF and derives session keys.
   - Computes `signature` using its identity private key, signing a message comprising the challenge data (as sent by B), source-ephemeral-pubkey, and B's identifier.
   - Sends `source-ephemeral-pubkey`, `signature`, and a payload encrypted with the derived keys.

4. B:

   - Verifies `signature`, performs DH(dest-key, source-ephemeral-pubkey), DH(dest-key, source-pubkey), derives keys and decrypts the payload.
   - Generates an ephemeral key pair (dest-ephemeral-key, dest-ephemeral-pubkey).
   - Performs DH(dest-ephemeral-key, source-ephemeral-pubkey), DH(dest-key, source-ephemeral-pubkey).
   - Mixes the outputs of DH using HKDF and derive session keys.
   - Responds with `dest-ephemeral-pubkey` and a NODES message (encrypted using the derived key).

5. A:

   - Receives B's ephemeral public key, performs DH(source-ephemeral-key, dest-ephemeral-pubkey), DH(source-ephemeral-key, dest-pubkey).
   - Verifes that it can decrypt B's message, and then considers B's identity verifed and the session keys valid.

This pattern seems to provide the highest security guarantees (number 2 and 5) in Noise terms for all next messages (e.g., FINDNODE, PING, PONG, etc.), but a more thorough analysis is needed if discv5 will consider using it.

Another concern is that "sig-size" (signature size), and "eph-key-size" (ephemeral key size) fields of a handshake message's "authdata-head" are not authenticated: the values are not used either in

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[40] https://github.com/ethereum/devp2p/blob/master/discv5/discv5-wire.md#ordinary-message-packet-flag--0

key agreement or signing. At the time of writing, "sig-size" and "eph-key-size" are constants in the v4 scheme. The traditional approach is to compute the handshake transcript hash, by hashing the concatenation of all messages sent and received during a handshake. If both sides do not compute the same transcript hash, the connection must be aborted.

5.4 Gossipsub Peer Scoring

Gossipsub is an extensible publish/subscribe protocol over libp2p. The v1.0[41] implements a publish/subscribe model in peer-to-peer networks. The v1.1[42] is a set of security extensions addressing protocol attacks. In June 2020, Least Authority completed an audit[43] of the Gossipsub v1.1 design and its implementation built on the libp2p library. The report identified the peer scoring mechanism as high risk for the following main reasons:

- A node can leak scoring information
- The peer scoring mechanism can adjust the network and increase its centralization

The risk is that the peer scoring mechanism be abused to prevent detection of malicious nodes, or flag honest nodes as malicious or unreliable. The current mechanism is similar to a linear regression model: weights (coefficients) are estimated by an algorithm based on the past behavior of the system. However, the weights of the score function are theoretically evaluated, the violation thresholds are fixed heuristically. For instance, the Lighthouse team writes[44]:

> These are initial values based on theoretically expected numbers and are likely to change during further simulations (...) We theoretically calculated expected scoring parameters based on reasonable network variables (such as expected delay between packets, expected duplicates, rate of messages, and topic sizes).

It is hard to determine and empirically evaluate to what extent such weights are "good enough" to prevent abuse and to adequately model the notion of good behavior in order to maintain a reliable system. Theoretical estimates risk not representing reality accurately enough, while purely empirical ones risk "overfitting" by expecting future behavior to reflect the past.

Evaluation and simulations validated the soundness of the proposed model, but may not be sufficient in an adversarial scenario. We shared our concerns with the authors of the original Gossipsub research [57].

6 API Implementations

Beacon clients expose the Beacon Node API [4] for querying the beacon node, as API used by validators to determine their assigned duties, submit block proposals, etc. Each beacon client has its own specificities regarding the API:

- Nimbus uses JSON-RPC 2.0[45] and HTTP-JSON interfaces, and listed some security recommendations[46].
- Lighthouse implements the standard and non-standard RESTful APIs[47] for the beacon node and the validator client[48].
- Prysm implements the API (used only by Prysm) using gRPC[49] and also exposes HTTP-JSON version of the API.

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[41]https://github.com/libp2p/specs/blob/master/pubsub/gossipsub/gossipsub-v1.0.md
[42]https://github.com/libp2p/specs/blob/master/pubsub/gossipsub/gossipsub-v1.1.md
[43]https://leastauthority.com/blog/audit-of-gossipsub-v1-1-protocol-design-implementation-for-protocol-labs/
[44]https://hackmd.io/FxenPiVmT5WR3c7eScR-gA
[45]https://github.com/status-im/nimbus-eth2/blob/stable/docs/the_nimbus_book/src/api.md
[46]https://github.com/status-im/nimbus-eth2/issues/1665
[47]https://lighthouse-book.sigmaprime.io/api-lighthouse.html
[48]https://lighthouse-book.sigmaprime.io/api-vc.html
[49]https://docs.prylabs.network/docs/how-prysm-works/ethereum-2-public-api/

- The both API services of Prysm may be secured by TLS with default cipher suites.
- Teku implements additional API endpoints (e.g., log_level, peer_scores, etc.).

6.1 Requests Validation

We evaluated the API implementation based on industry-standard best practices, notably relying on the OWASP lists [43, 44] of security controls[50]. Applicable controls from this reference include for example signaling errors with appropriate response statuses, checking Content-Type correctness, and so on. The Ethereum specifications [4, 5] says little about the security requirements of the API, but mentions these aspects: "All requests by default send and receive JSON, and as such should have either or both of the "Content-Type: application/json" and "Accept: application/json" headers." However, not all clients do this:

- Teku handles requests with arbitrary Content-Type and Accept headers ignoring them and using application/json.
- Lighthouse rejects requests with wrong Content-Type header but accepts arbitrary Accept headers and also uses application/json.
- Prysm ignores those headers.

Another requirement is that "JSON schema validation is in place and verified before accepting input":

- Teku performs JSON validation and responds with "Unrecognized field" error message if unknown fields are found.
- Lighthouse and Prysm accept requests with unknown fields and process input ignoring them, at the same time they do respond with a deserialize error message if a field value has a wrong type.

6.2 Exposure

The beacon node API specification [4, 5] does not specify authentication requirements, and claims that the API is public: "The API is a REST interface, accessed via HTTP, designed for use as a public communications protocol"[51]. Exposing the API publicly leaves the service potentially vulnerable to external attacks and abuse, and is in general not necessary. Some clients thus recommend to only serve the API locally, or to authorized hosts, for example:

- Teku: "Only trusted parties should access the REST API. Do not directly expose these APIs publicly on production nodes."[52]:
- Lighthouse: "the API should only be exposed to localhost or a restricted set of IPs on an internal network"[53], and "Do not expose the beacon node API to the public internet or you will open your node to denial-of-service (DoS) attacks."[54].

We nonetheless identified a few hosts exposing the API publicly, by scanning IPv4 addresses for beacon API endpoints on the ports known to be used for this API (e.g., 3500, 5051, 5052). We found 20 Lighthouse instances, 0 Nimbus, 5 Prysm, and 5 Teku. See §8 for methodology details.

6.3 Authentication

Prysm protects gRPC connections using TLS[55], allowing a validator to authenticate a beacon node (but not the other way). Otherwise, clients don't provide authentication mechanisms to restrict access to the beacon node API. At best, they inform users via a warning in the documentation that the API must not

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[50]https://github.com/OWASP/ASVS/blob/master/4.0/en/0x21-V13-API.md
[51]https://github.com/ethereum/eth2.0-APIs#outline
[52]https://docs.teku.consensys.net/en/latest/Reference/Rest_API/Rest/
[53]https://github.com/sigp/lighthouse/issues/2468#issuecomment-882936767
[54]https://lighthouse-book.sigmaprime.io/api-bn.html#security
[55]https://docs.prylabs.network/docs/prysm-usage/secure-grpc/

be exposed to untrusted parties. Note that in some contexts, server-side request forgery (SSRF) could be exploited to access the beacon node API, if an authorized service is vulnerable to SSRF.

Lighthouse uses logging to deliver authentication tokens (described below) for Web UI, and Prysm has a feature request [56], suggesting the same approach ("the validator client can generate a random auth token and log it to stdout + write it to a file to persist it"). This approach is insecure by design and is considered known as unsafe practice in web application security.

6.4 Lighthouse Validator Client API

Lighthouse implements a custom API, called Validator Client API [13]. Since the validator client (VC) can be used to access validator keys, the GUI accessing it must be authenticated. The security protocol between a VC and a browser-based GUI is described in a GitHub issue[57] and in the Lighthouse book [13]. In this protocol, the VC has a key pair and signs its responses (ECDSA-secp256k1), while the public key is passed by the GUI in the request. Note that these two references differ slightly: the former requires a signature over HTTP response headers and body, but the latter for its body only.

A problem with this protocol is that replays of signed responses are possible, because the signed data does not include an unpredictable challenge or a timestamp. Adding a "Date" header in the HTTP headers would partially mitigate this.

We also reported some bugs in the implementation of the protocol:

- The implementation doesn't require an API token for POST and PATCH requests[58].
- A signature is computed over HTTP response body without headers[59].
- API keys[60] and tokens[61] are stored locally with insufficient permissions restrictions (644).

6.5 API Denial of Service

The Ethereum networking specification [3] comments on potential DoS vectors and corresponding protection. For instance, it contains a BeaconBlocksByRange request/message potentially vulnerable to DoS. All clients have already implemented or are implementing[62] rate limiting for P2P network and RPC mechanisms.

However, we found other endpoints vulnerable to DoS and not protected in clients' implementations: For example, /eth/v1/validator/duties/attester/{epoch} requests the beacon node to provide a set of attestation duties, which should be performed by validators, for a particular epoch. Its request body contains an array of the validator indices for which to obtain the duties. So epoch and validator indices parameters directly affect performance and liveness.

We used two tests to assess response time. Tests were performed on clients with default settings.

In the first test, we send requests where the payload is a big array of the validator indices for which to obtain the duties (e.g., an array with n indices $[1, 2, ..., n]$, where n is 300, 600, 1000) and the epoch is the current epoch. We observed that some client nodes responded with delay (e.g., for 830 indices payload the delay was 100 seconds), others stopped responding to all requests for a long time.

```
time curl -i -s -k -X 'POST' \
  -H 'accept: application/json'
  -H 'Content-Type: application/json'
  -d '[$Payload]' \
'http://$BeaconNodeAPIHost:$Port/eth/v1/validator/duties/attester/$CurrentEpoch'
```

---

[56]https://github.com/prysmaticlabs/prysm/issues/9188
[57]https://github.com/sigp/lighthouse/issues/1269#issuecomment-649879855
[58]https://github.com/sigp/lighthouse/issues/2512
[59]https://github.com/sigp/lighthouse/issues/2511
[60]https://github.com/sigp/lighthouse/issues/2437
[61]https://github.com/sigp/lighthouse/issues/2438
[62]https://github.com/status-im/nimbus-eth2/issues/1359

The second test, where the payload contains one index, but the epoch is a historic epoch. For instance, we observed requests completed in more than 40 seconds if the distance between epochs is 5 (e.g., the current epoch is 64555, the old epoch is 64550). If the distance between epochs is 155 (e.g., the current epoch is 64555, the old epoch is 64400) the response time was about 3 minutes. The problem here is that it is necessary to load historic data from a database.

```
time curl -i -s -k -X 'POST' \
  -H 'accept: application/json'
  -H 'Content-Type: application/json'
  -d '[1]' \
'http://$BeaconNodeAPIHost:$Port/eth/v1/validator/duties/attester/$OldEpoch'
```

We reported this issue to Lighthouse[63], Nimbus[64], and Prysm[65]. There are beliefs that such attacks can not be prevented by input validation in the considered application domain. Because of that, the issue is a good example of why authentication is needed as a mitigation mechanism and what an attacker can perform if the beacon node API is accessible on the internet.

6.6   BLS Remote Signer HTTP API

This simple API[66] allows a validator client to request signatures to a service storing private keys, such as a key vault or a hardware security module (HSM). In most deployments, such a signing service should explicitly authenticate the requester, to prevent signing data from any party.

The API has been implemented by Teku[67], Prysm[68], and Lighthouse[69].

Lighthouse does not yet implement security mechanisms, Teku implements mutual authentication (mTLS), and Prysm's documentation says it also authenticates both parties, however the implementation only authenticates the services. We reported[70] the latter issue.

7   Supply Chain Risk Analysis

Software vulnerabilities can be in the project's own code, or in any component of its "supply chain", that is, third-party code that the application depends on, down from the CPU microcode, hypervisor, operating system, language runtime, external APIs, but mainly from explicitly called packages, modules, libraries, which we'll just call *dependencies*. In our context, as far as we know, all dependencies are open-source[71].

External dependencies increase the security risk, because of:

- The sheer amount of dependencies (and thus of code) in modern applications; the more code, the more bugs.
- The automatic download and update from remote hosts which, although authenticated, can break compatibility, introduce new pre-conditions or security limitations.
- The uneven maturity of dependencies' development lifecycle, and the varying reliability of their test suites.
- The common open-contribution model, where changes can be proposed by any stranger, with often little quality assurance or accountability
- The lack of guarantee or liability of any kind, as typically stated in open-source licenses

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[63] https://github.com/sigp/lighthouse/issues/2468
[64] https://github.com/status-im/nimbus-eth2/issues/2734
[65] https://github.com/prysmaticlabs/prysm/issues/9247
[66] https://eips.ethereum.org/EIPS/eip-3030
[67] https://docs.teku.consensys.net/en/latest/Tutorials/Configure-External-Signer-TLS/
[68] https://docs.prylabs.network/docs/wallet/remote/
[69] https://github.com/sigp/lighthouse/tree/stable/remote_signer
[70] https://github.com/prysmaticlabs/remote-signer/issues/14
[71] Closed-source dependencies bear different types of risks, which have been discussed at length in multiple articles and posts.

- Security audits of an application usually not covering its dependencies
- Application developers' testing framework focused on the application's code
- Many abandoned, deprecated, unmaintained projects
- Version pinning to vulnerable and outdated components [33]

The risk can then materialize as:

- A greater density of bugs in dependencies than in the parent application
- A greater delay between a bug identification/reporting and patching in dependencies
- Active sabotage, such as via "hypocrite commits" [59]
- "Dependency confusion" attacks[72]
- Software "supply chain" attacks injecting malicious code into a software package to compromise the dependent systems [42,55]
- Typosquatting and "combosquatting" attacks through package manager ecosystems [53,56]

To better understand this risk, we propose a number of indicators that we considered in our evaluation of the beacon clients, but that are generally applicable to software projects. We describe how to partially automate the collection of indicators, then discuss the values observed and the limitations of our approach, finally, we offer concrete recommendations for beacon clients developers.

7.1 Related Work

The security assurance level of modern software is scary: "80% or more of most applications' code comes from dependencies", reported GitHub's 2020 Octoverse study [6]. Synopsys reported [52] that 85% of audited projects contained components that were outdated for over four years or inactive for over four years. The 2020 Linux Foundation & Harvard FOSS contributor survey revealed that only 32% of respondents used dependency analysis tools and that security measures (signed commits, 2FA) are rarely enforced.

Several initiatives were created to raise awareness and reduce the risk associated to dependencies, for example:

- Google created the Open Source Vulnerabilities (OSV) platform https://osv.dev, which offers an API to query if a given version of a component has known vulnerabilities. Google also created the Open Source Insights tool at https://deps.dev, which provides information about the dependencies, including security advisories, and dependency graphs.
- GitHub maintains the https://github.com/advisories database of security advisories and offers extensive documentation about supply chain security[73], including dependency graph and automatic version update (with Dependatbot).
- The Linux Foundation created http://sigstore.dev, to provide free certificates and tools to automate and verify signatures of software components, to defend software supply chain attacks.
- OWASP provides the Dependency Check platform[74], a tool " tool that attempts to detect publicly disclosed vulnerabilities contained within a project's dependencies"

In addition to these, there are a lot of commercial and free open-source software composition analysis tools (such as Synopsys's Black Duck), which will attempt to inventory open-source dependencies and more generally identify third-party code, in order to match it against databases such as the National Vulnerability Database[75].

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[72]https://medium.com/@alex.birsan/dependency-confusion-4a5d60fec610
[73]https://docs.github.com/en/code-security/supply-chain-security
[74]https://owasp.org/www-project-dependency-check/
[75]https://nvd.nist.gov/

7.2 Characterizing Dependencies

In this section, we list the characteristics of a dependency and discuss how they relate to the risk of failure or sabotage from a beacon client perspective.

As we describe in detail in §7.3, it is in general easy to automatically enumerate all dependencies via language-specific tools, or simple scripts (see Appendix B). To better assess the relative importance of dependencies for a project, it would be valuable to determine how much of the code and API of a dependency is used by the parent project. But this requires more complex tools, so we restricted ourselves to identifying dependencies.

A further limitation is when dependencies are not inventoried by the package manager, but are directly copied into the code tree as source code or compiled libraries. Specific software is then needed to identify these.

Version. Outdated versions are indisputably an indicator of potential security issues. Indeed, older versions can contain unpatched vulnerabilities, and also have lower performance and general quality (although recent versions can also be less stable). However, some projects might refrain from updating to newer versions unless the older versions create a security risk: newer versions may be less stable and include performance or stability regressions.

It is generally easy to automatically determine dependencies versions, via the package manager or simple scripts.

Known Vulnerabilities. Known vulnerabilities include all the unpatched *known to exist* security issues in a project, as published via security advisories, online articles, and public issue trackers, for example. This does not include documented security limitations and design choices.

Of course, relying on a vulnerable component does not mean that the parent project can be exploited via this vulnerability: the affected code in the dependency may not be used, or the parent project may not provide an attack vector to exploit the vulnerability. As noted in [45]:

> The vast majority (81%) of vulnerable dependencies may be fixed by simply updating to a new version, while 1% of the vulnerable dependencies in our sample are halted, and therefore, potentially require a costly mitigation strategy.

To automate the detection of known vulnerabilities, language-specific platforms can be used (such as RustSec for Rust, via `cargo-audit`. However, these won't report bugs for which an official advisory wasn't created, for example, bugs in the issue tracker.

Degree. The set of actual dependencies of a project is not a flat list, but a graph that includes direct dependencies as well as all dependencies-of-dependencies. We call direct dependencies *first-degree*, dependencies of a direct dependency *second-degree* ones, and so on. Note that the same dependency may occur at different places in the dependency graph, and under different versions (for example, code auditors will be familiar with multiple versions of the rand in Rust).

As a rule of thumb, a parent project is likely to be dependent on a direct dependency than a higher-degree one (a greater fraction of the code and API are used than for a high-degree dependency), but this varies a lot. However, higher-degree dependencies are less visible to developers, less likely to be noticed by auditors, and thus better targets for backdoors.

Dependency listing tools and scripts usually provide a way to determine the dependencies of a given degree.

Language. Memory-safe languages are intrinsically safer than (say) C/C++, because memory-safety (almost) eliminates the whole class of memory corruption bugs, which are arguably the main cause of exploitable vulnerabilities.

The beacon clients reviewed are written in memory-safe languages, and so are most of their dependencies, but they may still be exposed to memory corruption bugs via dependencies in other languages (Prysm has C++ dependencies, for example), language limitations (Go can SIGSEV[76], for example), or "unsafe" components such as Rust's unsafe blocks[77].

It is, in general, easy to automatically determine if a project has direct dependencies in other languages, but it is trickier for dependencies. Indeed, third-party code in a different language may not be managed via the language's package manager, or might be directly embedded in the code as C (e.g. via cgo) or assembly.

Criticality.   It is tempting to categorize dependencies in categories such as

- Critical: Code that performs cryptographic operations or processes attacker-controlled input (deserialization, parsers, etc.).
- Non-critical: The rest.

Indeed, a failure of or bug in such critical components is more likely to have more severe consequences for users. However, when it comes to sabotage and backdoors, the situation is a bit different. Indeed, maintainers and code auditors will likely pay less attention to non-critical dependencies, such as a package to change the color of a button in the UI. On the one hand, ultimately all dependencies execute code at the same privilege level, and can potentially (for example) access the filesystem. On the other hand, a harmful modification in a non-critical component will likely be more visible and obvious than one in a critical component, where a change of a single line or single character may have a dramatic impact.

Identifying critical components generally requires manual review, and is hard to extend to the whole dependency graph. In the beacon clients reviewed, critical components include for example BLS signatures logic (blst and wrappers thereof).

Popularity.   The more a project is used and established, the more likely bugs are to be detected and fixed. A simple indicator of an open-source project's popularity is its number of GitHub stars (or equivalent rating on other platforms). This can be easily collected via GitHub's API.

SSDLC Quality.   Does the project have a CI pipeline with extensive testing and code coverage estimates? Are static analysis tools used? Has the project been audited by external experts? Are reported issues addressed in a timely manner? These aspects, and others related to secure development lifecycle, are a major indicator of a project's risk assurance. We discuss some of these points in §2.

7.3   Methodology

This section describes how we collected information about each project's dependencies, providing reproducible instructions and documenting the limitations of our approach.

Lighthouse (Rust).   Rust's package manager is Cargo and the dependencies are defined in *Cargo.toml* files, wherein the [dependencies] section lists the project's dependencies. The *Cargo.lock* lockfile is generated by Cargo to provide a deterministic state of the build, Lighthouse's *Cargo.toml* looks like this:

```
[package]
name = "lighthouse"
version = "1.3.0"
authors = ["Sigma Prime <contact@sigmaprime.io>"]
edition = "2018"

[features]
```

---

[76]https://blog.stalkr.net/2015/04/golang-data-races-to-break-memory-safety.html
[77]https://shnatsel.medium.com/auditing-popular-rust-crates-how-a-one-line-unsafe-has-nearly-ruined-everything-fab2d837ebb

```
(...)

    [dependencies]
    beacon_node = { "path" = "../beacon_node" }
    tokio = "1.1.0"
    slog = { version = "2.5.2", features = ["max_level_trace"] }
    sloggers = "1.0.1"
    types = { "path" = "../consensus/types" }
    bls = { path = "../crypto/bls" }
(...)
```

Various Cargo extensions help in analyzing dependencies:

- `cargo-audit` utility[78] reviews dependencies for known vulnerabilities recorded in the RustSec database [19].
- `cargo-tree` creates a tree view.
- `cargo-depgraph`[79] creates dependency graphs using `cargo-metadata` and Graphviz.
- `cargo-deps`[80] is another tool to create graphs, requiring though the manifest to not be virtual.
- `cargo-real-deps`[81] lists dependencies for specific packages in the workspace and specific build parameters (which proved useful for Lighthouse, as its workspace has a virtual manifest);
- `cargo-geiger` utility[82] reviews the usage of unsafe blocks.
- `cargo-udeps` finds which dependencies in *Cargo.toml* are unused.
- `cargo-outdated`[83] reveals which components have a newer version available.
- `cargo vendor` can vendor all dependencies in a local directory.

Not all of these proved applicable to our analysis, and we notably used `cargo-update` to look at the *Cargo.lock* lockfile and update all the dependencies that have a higher version than the one defined. Although not exactly the desired functionality, the output can prove useful to find and count the outdated dependencies. Appendix B.1 contains the script we used.

Prysm (Go). Go projects list dependencies in the *go.mod* file and the command `go list -m all` provides additional information. The *-u* flag can be used to fetch the latest version available for each module required is listed. Some projects might include the legacy method with a *vendor/*, but Prysm uses Go modules. A project using Go modules can vendor all its dependencies in a local directory using the command `go mod vendor` Prysm's *go.mod* looks like this:

```
module github.com/prysmaticlabs/prysm

go 1.16

require (
        contrib.go.opencensus.io/exporter/jaeger v0.2.1
        github.com/StackExchange/wmi v0.0.0-20210224194228-fe8f1750fd46 // indirect
        github.com/allegro/bigcache v1.2.1 // indirect
        github.com/aristanetworks/goarista v0.0.0-20200521140103-6c3304613b30
        github.com/bazelbuild/buildtools v0.0.0-20200528175155-f4e8394f069d
(...)
```

The *go.mod* file includes only the direct dependencies and some indirect (with the suffix // indirect), when those are not listed in the *go.mod* file of the direct dependency or if the direct dependency does not have a *go.mod* file. Also, any dependency that is not imported in the module's source files is marked as // indirect. To collect all Prysm dependencies, we also used the `go-mod-outdated`[84] utility, which produces a Markdown table view of the `go list -u -m -json all` listing all dependencies

---

[78]https://github.com/RustSec/rustsec
[79]https://crates.io/crates/cargo-depgraph/
[80]https://crates.io/crates/cargo-deps
[81]https://github.com/Geal/cargo-real-deps
[82]https://github.com/rust-secure-code/cargo-geiger
[83]https://crates.io/crates/cargo-outdated
[84]https://github.com/psampaz/go-mod-outdated

of a Go project and their available minor and patch updates. Our script to collect information on Prysm Appendix B.2 uses that tool.

The *nancy* utility[85] by Sonatype can then be used to automatically search for entries in vulnerability databases, from the output of go list -json -m all.

Furthermore, as noted in $DEPENDENCIES.md$[86], "Prysm is go project with many complicated dependencies, including some c++ based libraries." The latter are managed via Bazel, including precompiled libraries for convenience, for which the source code is not included. Bazel is also used to integrate local patches to Prysm's dependencies, "to make a small change (...) for ease of use in Prysm".

Teku (Java). The two main package managers in Java are Gradle and Maven. Teku uses Gradle, which describes the dependencies in the *build.gradle* configuration file. A list of dependencies (direct and indirect) can be obtained via gradle -q dependencies [37] which provides a good visualization of the dependency tree. Also, a useful tool is the build scans for the Gradle feature provided in https://scans.gradle.com/ as well as developers can find information about the artifacts and their versions in https://mvnrepository.com/. Teku's *teku/build.gradle* looks like this:

```
dependencies {
    implementation 'com.google.guava:guava'
    implementation 'org.apache.commons:commons-lang3'
    implementation 'org.apache.logging.log4j:log4j-api'
    runtimeOnly 'org.apache.logging.log4j:log4j-core'
    runtimeOnly 'org.apache.logging.log4j:log4j-slf4j-impl'
    testImplementation 'org.apache.tuweni:tuweni-junit'
    testImplementation 'org.assertj:assertj-core'
    testImplementation 'org.mockito:mockito-core'
    testImplementation 'org.junit.jupiter:junit-jupiter-api'
    testImplementation 'org.junit.jupiter:junit-jupiter-params'
    testRuntimeOnly testFixtures(project(':infrastructure:logging'))
    testRuntimeOnly 'org.junit.jupiter:junit-jupiter-engine'
    testFixturesImplementation 'org.assertj:assertj-core'
(...)
  }
```

Note that Gradle, unlike Cargo, resolves "version conflicts" when two or more components use different versions of the same dependency: Gradle will choose the most recent version of all versions appearing in the dependency graph, as described in Gradle's documentation[87].

Additionally, each dependency is characterized by a *Configuration* that defines its scope[88] (for example, for runtime, testing, building). Each configuration has a specific configurable name, however, many Gradle plugins have pre-defined configurations. This is the case for Teku. Based on their scope, we decided to count only the direct dependencies with implementation configuration.

Our script in Appendix B.4 finds the number of direct dependencies, the number of total dependencies and their maximal degree.

Nimbus (Nim). The Nim language has a package manager called Nimble, which lists dependencies in *.nimble* files [89]. However, Nimbus does not use Nimble but instead lists dependencies as git submodules in a *vendor/* directory[90]. These include:

```
NimYAML @ ca82b5e
asynctools @ c478bb7
eth2-testnets @ 5b4e327
jswebsockets @ ff0ceec
karax @ 32de202
news @ 002b21b
```

---

[85] https://github.com/sonatype-nexus-community/nancy
[86] https://github.com/prysmaticlabs/prysm/blob/develop/DEPENDENCIES.md
[87] https://docs.gradle.org/current/userguide/dependency_resolution.html
[88] https://docs.gradle.org/current/userguide/dependency_resolution.html
[89] https://github.com/nim-lang/nimble
[90] https://github.com/status-im/nimbus-eth2/tree/stable/vendor

Metric	Lighthouse	Nimbus	Prysm	Teku
Language	Rust	Nim	Go	Java
GitHub Stars	1.2k	212	2.2k	257
Direct dependencies	121	43	93	48
Total dependencies	440	56	665	230
Max degree of dependencies	15	3	13	13
Outdated versions	59	0	353	N/A
Vulnerable versions	5	0	5	18
CVEs	6	0	11	23
Last commit	10/06/21	05/08/21	10/08/21	06/08/21
Last release	10/06/21	05/08/21	03/08/21	28/07/21
Open issues	100	150	97	81
Closed issues	816	514	1999	1215

Table 3: Overview of the risk metrics, as of 20210810.

```
nim-bearssl @ 0a7401a
(...)
```

The *vendor* folder approach avoids incompatibilities in the case that two projects use a different version. For most dependencies, the version integrated is not a release but a certain commit, which may introduce extra risks (non-release versions are likely to be less stable) if it is not frequently updated. In comparison, the Nimble package manager always fetches and installs the latest release of a repository or the latest commit if there are no releases or there is the #head as suffix.

Our script in Appendix B.3 lists the direct dependencies of a project through the `.nimble` file. However, this was not used for Nimbus, for which we just listed the content of *vendor/*. As the direct dependencies were few and the max degree of them was three, the total dependencies were counted by inspecting each component's `.nimble` file.

7.4 Dependencies Review

This section describes the results of our dependencies review for the four beacon clients.

Table 3 describes the risk indicators to the four beacon clients reviewed. Below we comment further on these results, and how we observed them evolve over time, which provides insights into the dependency management of the projects.

Lighthouse (Rust). As of 20210730, Lighthouse had 5 dependencies with vulnerable versions.

- *libsecp256k1* v0.3.5 was affected by CVE-2021-38195
- *prost-types* v0.7.0 was affected by CVE-2021-38192
- *tokio* v0.3.7 and v1.5.0 were affected by CVE-2021-38191
- *crossbeam-deque* v0.8.0 is affected by CVE-2021-32810
- *hyper* v0.13.10 and v0.14.7 are affected by CVE-2021-32714
- *hyper* v0.13.10 and v0.14.7 are affected by CVE-2021-32715

Except for the vulnerable crates, there were reported 13 unmaintained crates, the 9 of them were merged to different crates, 3 were totally unmaintained (one for over three years) and one was deprecated. However, running the same analysis one month later gave different results.

As of 20210824, Lighthouse had only 1 dependency with known vulnerabilities:

- *openssl-src* version *111.15.0+1.1.1k* is affected by CVE-2021-3711 and CVE-2021-3712
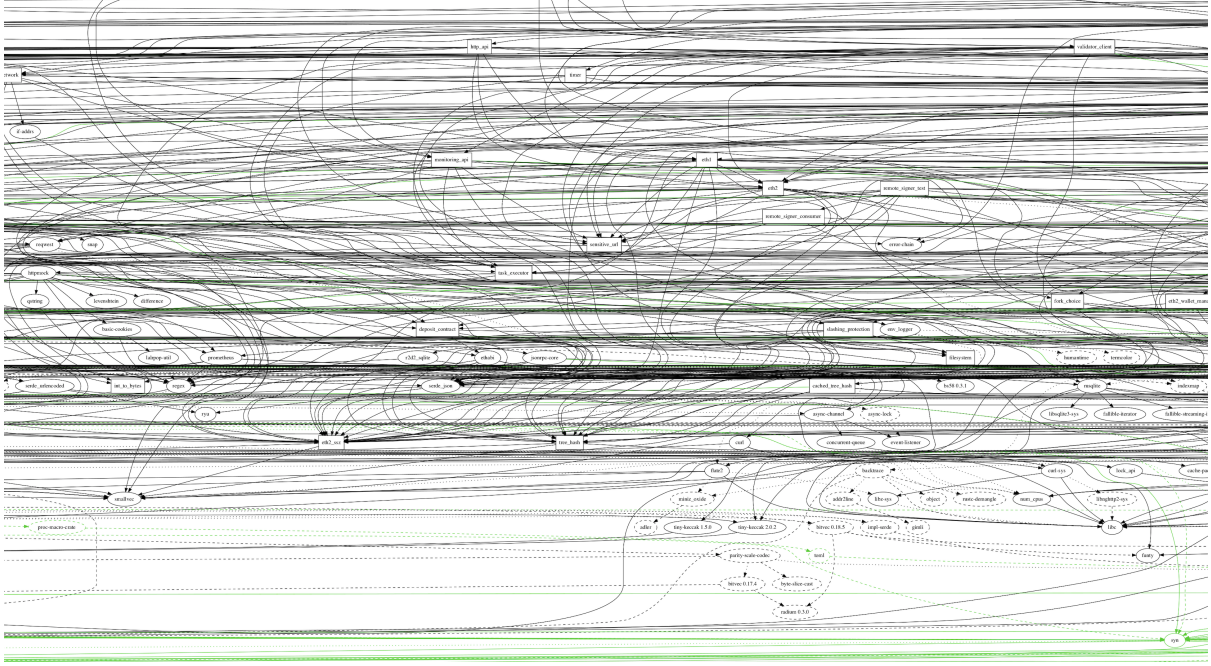
Figure 1: Lighthouse dependencies graph (excerpt).

This time, the tool reported only 2 unmaintained crates. Checking only after few days, developers had patched the vulnerable component the next day of the CVE release in the Rust vulnerability database and the report of the `cargo-audit` found no vulnerabilities. This suggests that the maintainers regularly review their dependencies and upgrade the vulnerable components to their higher versions which fix the security bugs. After searching several pull requests for Lighthouse, it was found that they make use of bors bot [1] to run automated CI tasks. For Lighthouse, this includes both `cargo-audit` and `cargo-udeps`.

As of 20210825, after running the `cargo-update`, Lighthouse was found to have 59 of the total dependencies outdated. Figure 1 depicts a small part of the graph generated by using the `cargo depgraph`. The fact that almost nothing is discernible confirms the complexity of dependencies in such big projects and how difficult it is to monitor them and eliminate the attack vectors through them. Finally, the max degree of the dependencies was 15, which was found by observing the different alignments as printed by the `cargo-tree` (see the script in Appendix B.1).

Prysm (Go). Figure 2 shows Prysm's dependency graph. As of 20210731, Prysm had 93 Go direct dependencies, 45 out of which were outdated. In total, it had 599 dependencies, 332 out of which were outdated. As of 20210831, a month later, the state was almost the same. 43 out of 91 direct dependencies were outdated, as well as 369 out of the 658 total dependencies. Most of the outdated components were the same.

As of 20210811, the *nancy sleuth* utility reported 2 vulnerable components. As of 20210605, OWASP's Dependency-Check reported 37 vulnerable dependencies out of the 596 scanned. However, after careful manual inspection, 32 of the 37 were found to be false positives. We also matched vulnerabilities against the Snyk[91], and OSV databases. Table 4 reports the CVEs found in those 5 components.

Note that these results were obtained on the latest commit of the development branch at the time of the test. It is possible that, prior to issuing a new release, the Prysm developers update all dependencies, but we could not verify it.
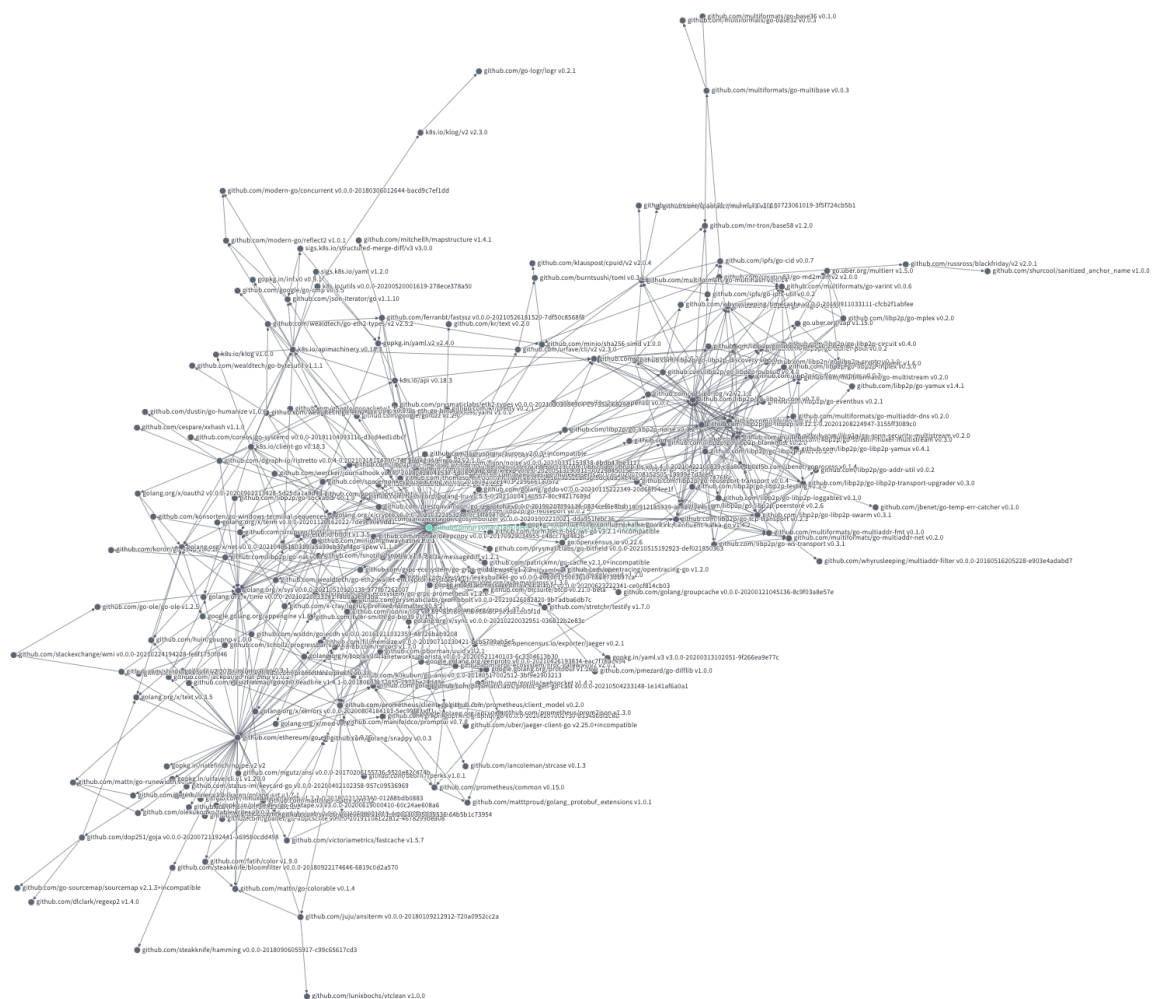
---

[91]https://snyk.io

Figure 2: Prysm dependencies graph, generated using https://deps.dev/.

Dependency	Version	Versions affected	CVE
coreos/etcd	v3.3.13	prior to v3.3.23	CVE-2020-15114
coreos/etcd	v3.3.13	prior to v3.3.23	CVE-2020-15113
coreos/etcd	v3.3.13	prior to v3.3.23	CVE-2020-15112
coreos/etcd	v3.3.13	prior to v3.3.23	CVE-2020-15106
dgrijalva/jwt-go	v3.2.0	prior to v4.0.0-preview1	CVE-2020-26160
hashicorp/consul/api	v1.3.0	$\geq$ v1.2.0 prior to v1.6.6	CVE-2020-13250
hashicorp/consul/api	v1.3.0	prior to v1.6.2	CVE-2020-7219
nats-io/nats-server/v2	v2.1.2	prior to v2.2.0	CVE-2020-28466
nats-io/nats-server/v2	v2.1.2	prior to v2.1.9	CVE-2020-26521
nats-io/nats-server/v2	v2.1.2	prior to v2.1.9	CVE-2020-26892
nats-io/nats-server/v2	v2.1.2	prior to v2.2.0	CVE-2021-3127
nats-io/jwt	v0.3.2	prior to v2.0.1	CVE-2021-3127

Table 4: Overview of CVEs found in Prysm dependencies.

Teku (Java). As of 20210727, Teku had 48 direct dependencies, counting only the components with the `configuration implementation`. In total, 230 dependencies are used in the Teku development, of which 18 included known vulnerabilities, as collected from the Snyk database:

- *org.webjars:swagger-ui:3.25.2* is affected by SNYK-JAVA-ORGWEBJARS-575003
- *org.web3j:rlp:4.6.2* is affected by SNYK-JAVA-ORGWEB3J-598385
- *org.mozilla:rhino:1.7R4* is affected by SNYK-JAVA-ORGMOZILLA-1314295
- *org.java-websocket:Java-WebSocket:1.3.8* is affected by CVE-2020-11050
- *org.eclipse.jetty:jetty-webapp:9.4.31.v20200723* is affected by CVE-2020-27216
- *org.eclipse.jetty:jetty-servlet:9.4.31.v20200723* is affected by CVE-2021-28169
- *org.eclipse.jetty:jetty-server:9.4.31.v20200723* is affected by CVE-2021-34428, CVE-2020-27218 and CVE-2020-27223
- *org.eclipse.jetty:jetty-io:9.4.31.v20200723* is affected by CVE-2021-28165
- *org.bouncycastle:bcprov-jdk15on:1.66* is affected by CVE-2020-28052
- *org.apache.commons:commons-compress:1.20* is affected by CVE-2021-35516, CVE-2021-35517, CVE-2021-36090 and CVE-2021-35515
- *io.vertx:vertx-core:3.9.1* is affected by CVE-2019-17640
- *io.netty:netty-transport:4.1.56.Final* is affected by CVE-2021-21290
- *io.netty:netty-handler:4.1.51.Final* is affected by CVE-2021-21290 and an SNYK-JAVA-IONETTY-1042268
- *io.netty:netty-common:4.1.56.Final* is affected by CVE-2021-21290
- *io.netty:netty-codec-http:4.1.51.Final* is affected by CVE-2021-21290, CVE-2021-21295 and an SNYK-JAVA-IONETTY-1020439
- *io.netty:netty-codec-http2:4.1.51.Final* is affected by CVE-2021-21295 and CVE-2021-21409
- *commons-io:commons-io:2.6* is affected by CVE-2021-29425
- *com.google.guava:guava:29.0-jre* is affected by CVE-2020-8908

Nimbus (Nim)). As of 20210802, Nimbus had 43 direct dependencies, as included in the *vendor* folder. In total, the project used 56 dependencies. After a manual investigation in the NVD and the Snyk databases, no known vulnerability was found to affect the dependencies. Moreover, no dependency was found to be outdated. As of 20210902, one month later, the results were the same. Having neither vulnerable nor outdated dependencies seems ideal for the security of a project. The max dependency degree was only three.

This lower "vulnerability surface" seems encouraging and a positive aspect of Nimbus. However, the Nim language is much less established than Go, Java, or Rust, and the security of the language and its runtime is arguably underanalyzed.

7.5 Discussion and Recommendations

The two main beacon client projects, Lighthouse and Prysm, each depend on hundreds of third-party projects (cf. Table 3). These projects appear to pay attention to security in their dependencies, as only 5 out of hundreds had known vulnerabilities. Lighthouse seems to be more diligent, with CI checks and more regular updates.

All projects, as all successful open-source projects, are flooded with issues in their GitHub Issues tracker, and Prysm seems to be the more effective at processing and closing issues. For an attacker, open issues and the associated discussions can be goldmines of information, especially when projects don't document how to properly report security issues: Lighthouse and Prysm provide a dedicated contact and a PGP key; Teku provides a dedicated but no PGP key; Nimbus does not describe any process.

From an attacker's perspective, Prysm appears to be the most attractive target: the most widely used, the highest number of dependencies, and "lesser" secure SDLC procedures than Lighthouse. Many direct dependencies of Prysm are from more trustworthy sources (from *golang.org/x/*, *k8s.io/*, *github.com/google/*, for example), however, it also uses some wallet encryption project with 1 GitHub

star (wealdtech/go-eth2-wallet-encryptor-keystorev4) among its direct dependencies. That said, as discussed in §7.2 under "Criticality", planning sabotage of such obviously security-critical projects might not be the best approach for an attacker.

Beacon clients being critical components of the Ethereum environment, attackers may devote significant resources to compromising them. Although the larger number of clients—and thus amount of code—makes for a wider attack surface, and more bugs, we argue that from a risk management perspective some diversity of beacon clients is beneficial. As Lighthouse developers argued[92], "client diversity" prevents coordinated failure of a large part of the network, as it happened after a Prysm bug.

Therefore, rather than encouraging the use of only Lighthouse and Prysm, we would more strongly encourage 1) the deployment of nodes using all four beacon clients, and 2) all beacon clients to adopt more mature security practices to prevent counterparty risks and supply chain attacks, including:

To reduce the risk of supply chain attacks (via known or maliciously introduced vulnerabilities), beacon clients and

- Document and enforce a dependency management policy, notably setting criteria on the acceptable dependencies.
- Integrate automatic checks for dependencies versions and vulnerability as part of the CI pipeline, using language-specific tools and relevant GitHub features (Actions, dependabot[93], etc.).
- Keep track of all the dependencies (direct and indirect) in a "software bill of materials", to have visibility on the project's liabilities, and help in monitoring external projects.
- Minimize the number of third-party dependencies
- When security audits are organized, consider including the most critical external dependencies in the scope.
- Use multiple sources and databases of vulnerabilities, and don't blindly trust composition tools' results (check for false positives).
- Encourage or enforce signed commits for all contributors of the project ("hypocrite commits" may not only be in dependencies).

8 Network Fingerprinting

Although nodes and validators addresses are by definition public, it doesn't mean that all client's services are public too and can be exposed to the internet. For example, the beacon node API, as discussed in §6. Moreover, exposing metadata such as a client type and version, operating system details, could be leveraged by an attacker.

In this section, we thus analyze the visibility and discoverability of beacon clients, against internet scans, and through host the host search engines Censys, FOFA, and Shodan.

8.1 Exposure Overview

Using the methodology from [36], we investigated the resistance of the beacon clients interfaces to fingerprinting techniques. Fingerprints may for example be used by an attacker to scan the internet and look for:

- Clients running a given beacon client software (e.g., Nimbus), or a specific version (range) thereof.
- Clients with an insecure configuration (e.g., the beacon node API exposed to the internet).
- Hosts with a given operating system version.

In general, Ethereum services are not trivially discoverable via search engines or hosts databases, because Ethereum relies on non-standard protocols and APIs. However, most services will leak some metadata that will permit their identification. In particular, the Prysm's web interface, which can be identified

---

[92]https://lighthouse.sigmaprime.io/switch-to-lighthouse.html
[93]https://github.blog/2021-04-29-goodbye-dependabot-preview-hello-dependabot/

via favicon hash, HTML page title, and CSS keywords. Appendix A includes some search engine queries we determined for all the beacon clients.

We found the most fingerprinting-friendly components to be:

- /eth/v1/node/version Ethereum API endpoint: Retrieves the beacon node information about its implementation in a format similar to an HTTP User-Agent header.
- /eth/v1/node/peers Ethereum API endpoint: Retrieves data about the node's network peers, returning all peers.
- /lighthouse/peers and /lighthouse/peers/connected Lighthouse-specific API endpoints[94]: Provide agent name and internal IP addresses for each listed peer.
- libp2p agent version: a free-form characteristic string, identifying the implementation of the peer[95].

Note that a lot of information is available directly from the nodes: Lighthouse API's endpoint /lighthouse/peers provides information about a peers' OS and client version retrieved from an agent version:

```
"client":{
    "kind":"Teku",
    "version":"v21.3.2",
    "os_version":"linux-x86_64",
    "protocol_version":"ipfs/0.1.0",
    "agent_string":"teku/teku/v21.3.2/linux-x86_64/oracle_openjdk-java-15"
}
```

All clients provide different information in that field:

- Lighthouse: client name, client version, OS version
- Teku: client name, client version, OS version
- Nimbus: client name
- Prysm: client name, client version

It is unclear whether Nimbus' information is less verbose on purpose.

Also, the /lighthouse/peers/connected endpoint discloses IP-addresses of internal networks, for example:

```
"peer_id":"26Uiu2HBmG7bMnsJPWE2t3PQNcgihtrsYr1kXtrtzEfh7QFvCwhEw",
"peer_info":{
    "_status":"Healthy",
    "client":{
        "kind":"Lighthouse",
        "version":"v1.4.0-3b600ac",
        "os_version":"x86_64-linux",
        "protocol_version":"lighthouse/libp2p",
        "agent_string":"Lighthouse/v1.4.0-3b600ac/x86_64-linux"
    },
    "listening_addresses":[
        "/ip4/54.169.172.126/tcp/9000",
        "/ip4/127.0.0.1/tcp/9000",
        "/ip4/10.0.48.248/tcp/9000",
        "/ip4/192.168.0.104/tcp/9000"
    ]
}
```

Disclosing the private IP addresses does not seem necessary, and can help an attacker, for example in SSRF-like attacks, as discussed in §6.3.

8.2 Clients Fingerprints Examples

For each client, we give an example of fingerprint:

---

[94]https://lighthouse-book.sigmaprime.io/api-lighthouse.html
[95]https://github.com/libp2p/specs/blob/master/identify/README.md#agentversion

Lighthouse. Instances can be found from endpoints served on port 5200[96], such as /eth/v1/node/version. Here's an example of a response from a Lighthouse node:

```
{"data":{"version":"Lighthouse/v1.4.0-3b600ac/x86\_64-linux"}}''
```

Nimbus. Instances may be found from enpoints served on port 5052[97], by JSON RPC ports 9190 and sometimes 9091[98], and in rare cases also by metrics on port 8008[99]. Note that we couldn't discover Nimbus nodes with a public REST API. A reason might be that Nimbus' REST API is in beta and disabled by default, accessible locally only[100].

Prysm. Instances can be found from their web interface, served by default on port 7500[101]. They can be also identified by the HTTP title "PrysmWebUi".

Teku. Instances can be found from endpoints served on port 5051[102]. Sometimes, Teku's API can be found on port 5052. Here's an example of a response from a Teku node:

```
{"data":{"version":"teku/v20.11.1/windows-x86\_64/oracle-java-15"}}
```

Moreover, some Teku instances include Prometheus metrics on port 8008, which also exposes version and other information, for example:

```
# HELP beacon_teku_version Teku version in use
# TYPE beacon_teku_version counter
beacon_teku_version{version="21.6.1+4-gca9294a",} 1.0
```

8.3 Nodes Discovery

We used the following base method to discover beacon nodes:

1. Take a list of the nodes found using the search engines

2. For each node from the list, query its API to retrieve the node's peers

3. Add the new nodes into the list

4. Scan potentially exposed network ports of the node

5. If possible, get a client name and version of the node using /eth/v1/node/version endpoint

6. Go to step 1 with a new extended list of nodes and repeat

We discovered about 12 000 nodes, using only the method described above without any P2P mechanisms and libraries. All found nodes are depicted on Figure 3. This map can be seen as an indicator of regional usage at a given point in time, but should not be seen as reliable evidence of the distribution of each client's usage, because of the obvious biases (fingerprints and scans reliability, exposure of the service).

---

[96]https://lighthouse-book.sigmaprime.io/docker.html
[97]https://github.com/status-im/nimbus-eth2/blob/stable/beacon_chain/spec/network.nim#L33
[98]https://nimbus.guide/api.html
[99]https://github.com/status-im/nimbus-eth2/blob/stable/Jenkinsfile#L51
[100]https://nimbus.guide/rest-api.html
[101]https://github.com/prysmaticlabs/prysm-web-ui/blob/master/src/environments/environment.ts#L8
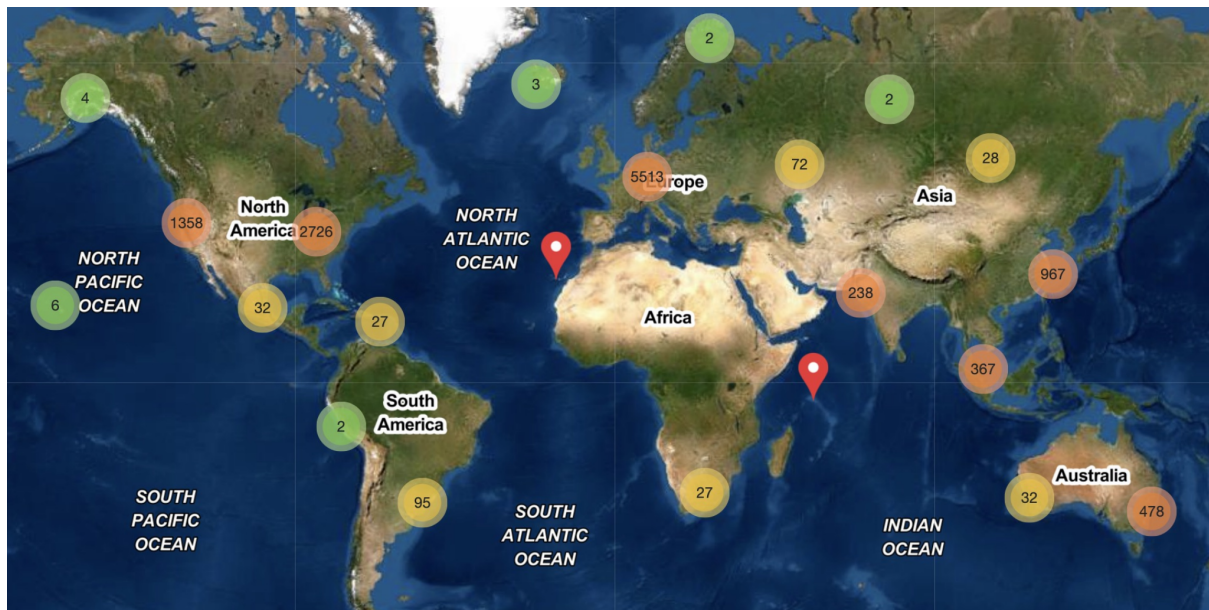[102]https://docs.teku.consensys.net/en/latest/HowTo/Get-Started/Installation-Options/Run-Docker-Image/

Figure 3: Geolocation of beacon clients identified through fingerprinting.

Acknowledgements

References

[1] BORS documentation. https://bors.tech/documentation/getting-started/.

[2] EIP-3076: Slashing protection interchange format. https://eips.ethereum.org/EIPS/eip-3076.

[3] Ethereum 2.0 networking specification. https://github.com/ethereum/eth2.0-specs/blob/dev/specs/phase0/p2p-interface.md.

[4] Ethereum 2.0 specification. https://github.com/ethereum/eth2.0-apis.

[5] Ethereum 2.0 specification. https://github.com/ethereum/eth2.0-specs.

[6] GitHub Octoverse security report 2020. https://octoverse.github.com/static/github-octoverse-2020-security-report.pdf.

[7] Introduction to libp2p. Lesson 5. https://proto.school/introduction-to-libp2p/05.

[8] Libp2p specification. https://github.com/libp2p/specs.

[9] Lighthouse fuzzing update. https://lighthouse.sigmaprime.io/fuzzing-01.html.

[10] Lighthouse security considerations. https://lighthouse.sigmaprime.io/fuzzing-lighthouse.html.

[11] Lighthouse update #26. https://lighthouse.sigmaprime.io/update-26.html.

[12] Lighthouse update #30. https://lighthouse.sigmaprime.io/update-26.html.

[13] Lighthouse Validator Client API. https://lighthouse-book.sigmaprime.io/api-vc.html.

[14] Nimbus ETH2.0 security audit request for proposal. https://our.status.im/nimbus-eth2-0-security-audit-request-for-proposal/.

[15] Nimbus update: September 11th. https://our.status.im/nimbus-update-september-11th/.

[16] Node discovery protocol version 5. https://github.com/ethereum/devp2p/blob/master/discv5/discv5.md.

[17] noise-libp2p - Secure Channel Handshake. https://github.com/libp2p/specs/tree/master/noise.

[18] Noise protocol framework. http://www.noiseprotocol.org/noise.html.

[19] The Rust Security Advisory Database. https://rustsec.org/.

[20] The Auditors Handbook to Nimbus Beacon Chain. https://nimbus.guide/auditors-book/.

[21] A. Asgaonkar. Weak subjectivity in Eth2.0. https://notes.ethereum.org/@adiasg/weak-subjectvity-eth2.

[22] J.-P. Aumasson. Too much crypto. https://eprint.iacr.org/2019/1492.

[23] J.-P. Aumasson, Q. T. M. Nguyen, and A. Sanso. Security of BLS fast verification. https://hackmd.io/TODO.

[24] P. S. L. M. Barreto, B. Lynn, and M. Scott. Constructing elliptic curves with prescribed embedding degrees. https://eprint.iacr.org/2002/088.

[25] D. Boneh, M. Drijvers, and G. Neven. Compact multi-signatures for smaller blockchains. https://eprint.iacr.org/2018/483.

[26] D. Boneh, M. Drijvers, and G. Neven. BLS Multi-Signatures With Public-Key Aggregation, 2018. https://crypto.stanford.edu/~dabo/pubs/papers/BLSmultisig.html.

[27] D. Boneh, S. Gorbunov, R. Wahby, H. Wee, and Z. Zhang. BLS signatures. https://datatracker.ietf.org/doc/draft-irtf-cfrg-bls-signature/.

[28] D. Boneh, B. Lynn, and H. Shacham. Short Signatures from the Weil Pairing. In *ASIACRYPT*, 2001. https://www.iacr.org/archive/asiacrypt2001/22480516.pdf.

[29] S. Bowe. BLS12-381: New zk-SNARK elliptic curve construction. https://electriccoin.co/blog/new-snark-curve.

[30] V. Buterin. Proof of Stake: How i learned to love weak subjectivity. https://blog.ethereum.org/2014/11/25/proof-stake-learned-love-weak-subjectivity/.

[31] V. Buterin. Fast verification of multiple BLS signatures, 2019. https://ethresear.ch/t/fast-verification-of-multiple-bls-signatures/5407.

[32] J. Camenisch, S. Hohenberger, and M. Ø. Pedersen. Batch verification of short signatures. 2012.

[33] A. Decan, T. Mens, and E. Constantinou. On the impact of security vulnerabilities in the npm package dependency network. 2018. https://dl.acm.org/doi/10.1145/3196398.3196401.

[34] J. Drake. Pragmatic signature aggregation with BLS, 2018. https://ethresear.ch/t/pragmatic-signature-aggregation-with-bls/2105.

[35] A. Faz-Hernández, S. Scott, N. Sullivan, R. Wahby, and C. Wood. Hashing to elliptic curves. https://datatracker.ietf.org/doc/draft-irtf-cfrg-hash-to-curve/.

[36] S. Gordeychik, D. Kolegov, and A. Nikolaev. SD-WAN internet census, 2018. https://arxiv.org/pdf/1808.09027.pdf.

[37] Gradle documentation. Listing dependencies. https://docs.gradle.org/current/userguide/viewing_debugging_dependencies.html#sec:listing_dependencies.

[38] M. Kalinin. Detecting slashing conditions. https://hackmd.io/@n0ble/By897a5sH.

[39] H. Krawczyk. What are key exchange protocols? https://cyber.biu.ac.il/wp-content/uploads/2018/07/KE1_Hugo_BIU_Feb2018-online.pdf.

[40] NCC. Public report – BLST cryptographic implementation review. https://research.nccgroup.com/2021/01/20/public-report-blst-cryptographic-implementation-review/.

[41] NCC. Zcash Overwinter consensus and Sapling cryptography review. https://www.nccgroup.trust/globalassets/our-research/us/public-reports/2019/ncc_group_zcash2018_public_report_2019-01-30_v1.3.pdf.

[42] M. Ohm, H. Plate, A. Sykosch, and M. Meier. Backstabber's knife collection: A review of open source software supply chain attacks. In *DIMVA 2020*, 2020.

[43] OWASP. API security project. https://owasp.org/www-project-api-security/.

[44] OWASP. Application Security Verification Standard. https://owasp.org/www-project-application-security-verification-standard/.

[45] I. Pashchenko, H. Plate, S. E. Ponta, A. Sabetta, and F. Massacci. Vulnerable open source dependencies: Counting those that matter. In *ACM/IEEE International Symposium on Empirical Software Engineering and Measurement*, 2018.

[46] N. T. M. Quan. 0. https://eprint.iacr.org/2021/323.

[47] Quantstamp. Prysm security assessment certificate. https://docs.prylabs.network/assets/files/Quantstamp_Prysm_Phase_0_Final_Report-d70b22fbd999b05e34346a2505782619.pdf.

[48] Quantstamp. Teku security assessment certificate. https://certificate.quantstamp.com/full/teku.

[49] T. Ristenpart and S. Yilek. The power of Proofs-of-Possession: Securing multiparty signatures against rogue-key attacks. https://eprint.iacr.org/2007/264.

[50] Y. Sakemi, T. Kobayashi, T. Saito, and R. Wahby. Pairing-friendly curves. https://datatracker.ietf.org/doc/draft-irtf-cfrg-pairing-friendly-curves/.

[51] M. Scott, N. Benger, M. Charlemagne, L. J. D. Perez, and E. J. Kachisa. Fast hashing to G2 on pairing friendly curves. https://eprint.iacr.org/2008/530.

[52] Synopsys. Open source security and risk analysis report 2021. https://www.synopsys.com/software-integrity/resources/analyst-reports/open-source-security-risk-analysis.html.

[53] M. Taylor, R. K. Vaidya, D. Davidson, L. D. Carli, and V. Rastogi. Defending against package typosquatting. In *NSS*, 2020.

[54] Trails of Bits. Prysm security assessment. https://docs.prylabs.network/assets/files/Trail_of_Bits_Prysm_Phase_0_Final_Report-ff2b2307a648f6b23dea9ed119b1516f.pdf.

[55] D. L. Vu, I. Pashchenko, F. Massacci, H. Plate, and A. Sabetta. Towards using source code repositories to identify software supply chain attacks. In *CCS '20*, 2020. https://doi.org/10.1145/3372297.3420015.

[56] D.-L. Vu, I. Pashchenko, F. Massacci, H. Plate, and A. Sabetta. Typosquatting and combosquatting attacks on the Python ecosystem. In *IEEE European Symposium on Security and Privacy Workshops (EuroS PW)*, 2020. https://ieeexplore.ieee.org/document/9229803.

[57] D. Vyzovitis, Y. Napora, D. McCormick, D. Dias, and Y. Psaras. GossipSub: Attack-resilient message propagation in the Filecoin and ETH2.0 networks. 2020. https://arxiv.org/abs/2007.02754.

[58] R. S. Wahby and D. Boneh. Fast and simple constant-time hashing to the BLS12-381 elliptic curve. https://eprint.iacr.org/2019/403.

[59] Q. Wu and K. Lu. On the feasibility of stealthily introducing vulnerabilities in open-source software via hypocrite commits. https://linuxreviews.org/images/d/d9/OpenSourceInsecurity.pdf.

A Fingerprinting Queries

The target Ethereum consensus clients can be enumerated using popular search engines (Censys, FOFA, Shodan) and the queries listed below. The employed methodology can be defined as follows:

- Research the network interfaces of the clients and identify the unique patterns that can be used for their recognition at scale.
- Define and express the patterns within search engines query languages.
- Discover and enumerate nodes using search engines.
- Analyze the effectiveness of this approach for each client.

The full methodology used for fingerprinting can be found in [36]. For each query, we provide our estimate of the level of confidence that an identified host is a target host (as opposed to false positives). This reflects the reliability of the fingerprints and queries used to identify the host and a number of possible false positives. Note that fingerprints of some clients can't be expressed in all search engines query language, or can be quite ineffective due to high number of false positive hosts. In that case, we didn't provide the queries below.

A.1 Lighthouse

Confidence level: medium.

Censys.

- 443.https.get.headers.server:"Lighthouse/v1.3.0-3a24ca5/x86_64-linux"
- 443.https.get.body_sha256:"3179d38cb95e71e83a9fd64d57257c74c52c27a35c7d515f7fa256221c308b3b"

Shodan.

- http.html:"code" http.html:"405" http.html:"METHOD_NOT_ALLOWED" http.html:"stacktraces"
- "server: Lighthouse" "http/1.1" 405 http.html:"METHOD_NOT_ALLOWED"
- "server: Lighthouse/v1.3.0-3a24ca5/x86_64-linux"

A.2 Nimbus

Confidence level: medium.

Shodan.

- "HTTP/1.1 411 Length Required" "Content-Length: 0" "Date" -"server" -"expires" -"cache" port:8545
- "HTTP/1.1 411 Length Required" "Content-Length: 0" "Date" -"server" -"expires" -"cache" port:9190

A.3 Prysm

Confidence level: high.

Censys.

- 443.https.get.title:"PrysmWebUi"

FOFA.

- "prysmwebui"

Shodan.

- http.favicon.hash:1426715472
- http.title:"PrysmWebUi"
- http.component:"tailwindcss" http.component:"google font api" all:"prysmwebui"
- "Content-Length: 917" all:"eth"

A.4 Teku

Confidence level: medium.

FOFA.

- header="Content-Length: 131" && header="Server: Javalin" && port="5051"

Shodan.

- "HTTP/1.1 404 Not Found" "Server: Javalin" "Content-Length: 131" "Content-Type: application/json" "Date"

B Scripts

This section lists the scripts we used to find information about the beacon clients projects and their dependencies. A large part of these scripts is generally applicable to any project in the same language.

B.1 Lighthouse (Rust)

```bash
#!/bin/bash

##### Calculating max degree of dependencies
# on macOS, make sure to use GNU sed (gsed)
# the --prefix option prints the depth value before each line
cargo tree --prefix depth | grep -v '^\s*$' | sed -e 's/[0-9]\+/ & /g' -e 's/^ \| $//'
| cut -d " " -f 1 | sort -u > depth.txt
echo -e "Dependencies max degree: $(cat depth.txt | wc -l)";
```

```bash
##### Count all dependencies
cargo tree --prefix none | grep -v '^\s*$' | grep  -v "(*)" | sort -u > all_dependencies.txt
sed -E 's/v[0-9]+\.[0-9]+.*$/ /g' all_dependencies.txt | sort -u > unversioned_all.txt
echo -e "Total dependencies: $(cat all_dependencies.txt | wc -l)";
echo -e "Total dependencies without version:
$(cat unversioned_all.txt | wc -l)";

##### Count direct dependencies
rm all.txt > /dev/null 2>&1
find . -name Cargo.toml -exec cat {} + >> all.txt
for file in all.txt
do
        sed ':a;N;/\n\[.*\]/!s/\n/,/;ta;P;D' $file
        | grep '\[dependencies]' | sed 's/,/\n/g'
        | tail -n +2 >> direct
done
cat direct | sed '/dependencies]/d' | grep -v "path =" | cut -d " " -f 1 | awk 'NF' | grep -v '"'
| sort -u > direct_dependencies.txt
rm direct
echo -e "Direct dependencies: $(cat direct_dependencies.txt | wc -l)";

##### Generate dependency graph
cargo depgraph > graph.dot
cat graph.dot | dot -Tpng > graph.png
echo -e "Dependency graph of the project was created at the ./graph.png file";
```

B.2   Prysm (Go)

This script uses the https://github.com/KyleBanks/depth tool to help in visualizing the depth of dependencies while printing a tree with alignments depending on the degree. We could not run the tool against the Prysm, so we ran it for each of its dependencies that were GitHub projects. By leveraging the different alignments of the outputs, we found the max degree. Although it does not include all the projects, it is a good estimation as the majority of modules are GitHub projects.

```bash
#!/bin/bash

##### Count total dependencies
go list -m -u all | sed '1d' > all_dependencies.txt;
echo -e "Total dependencies: $(cat all_dependencies.txt | wc -l)";

##### Count direct dependencies
awk "/require/{y=1;next}y" go.mod | grep -v "indirect" | sed -n '/)/q;p' > direct_dependencies.txt;
echo -e "Direct dependencies: $(cat direct_dependencies.txt | wc -l)";

##### Count outdated dependencies
go list -m -u -json all | go-mod-outdated -update -style markdown | sed '1,2d'> outdated.txt
echo -e "Total outdated dependencies: $(cat outdated.txt | wc -l)";

##### Count outdated direct dependencies
go list -m -u -json all | go-mod-outdated -update -direct -style markdown | sed '1,2d'> dir_outdated.txt
echo -e "Direct outdated dependencies: $(cat dir_outdated.txt | wc -l)";

##### Calculating max degree of dependencies
cat all_dependencies.txt | grep github | cut -d " " -f 1 > all_edit.txt
cat all_edit.txt | while read line
do
        go run ~/go/pkg/mod/github.com/\!kyle\!banks/depth@v1.2.1/cmd/depth/depth.go $line >> tem
done

awk -F'[^ ]' '{print length($1),NR}' tem > tem2
var1=$(cat tem2 | sort  -nr | head -1 | cut -d " " -f 1)
# max degree is equal to the max  gap spaces /2 because there are 2 gaps for each gap,
#+1 because I run the script against the dependencies and not the lighthouse project
var2=$(expr $var1 / 2 + 1)
# estimation because I can run it only for some GitHub dependencies and not everything
```

```
echo -e "Best estimation for dependencies max degree:";
echo $var2
```

B.3   Nimbus (Nim)

The following one-liner lists all the dependencies of a `.nimble` file, the name of which is given as an argument:

```sh
#!/bin/sh

perl -p -e 's/,\n/,/' $1 | grep requires | cut -d' ' -f2- | sed 's/ //g' | sed 's/,/\n/g'
```

B.4   Teku (Java)

The following script is suitable for projects using Gradle as a package manager, and extracts dependencies with the configuration `implementation` from all the `build.gradle` files included in the project.

```bash
#!/bin/bash

##### Count direct dependencies
find . -name "build.gradle" -exec cat {} \; | grep "implementation" | grep -v "project(" | tr -s ' ' >output
sort -u output > direct_dependencies.txt;
rm output
echo -e "Direct dependencies:  $(cat direct_dependencies.txt | wc -l)";

##### Count all dependencies
gradle -q dependencies | grep "\---" | grep -v "project " | cut -d "-" -f 4-7 | grep -v "(*)" | sed 's/->.*$/ /p'
        | sed -E 's/:[0-9]+\.[0-9]+.*$/ /g' | sort -u > all_dependencies.txt
echo -e "All dependencies:  $(cat all_dependencies.txt | wc -l)";

##### Calculating max degree of dependencies
gradle -q dependencies | sed 's/|/ /g' testfile | awk -F'[^ ]' '{print length($1),NR}' > depth.txt
# max degree is equal to the max  gap spaces /5 (because there are 5 gaps for each degree)
# + 1 (as the 1st degree there is no gap)
echo -e "Dependencies max degree: $(expr $(cat depth.txt | sort  -nr | head -1 | cut -d " " -f 1) / 5 + 1)";
```

B.5   GitHub

This Python script uses the GitHub REST API to extract useful project metadata: language, number of stars, number of open issues, and date of hte last commit.

```python
import sys
import requests
import argparse
import json
from termcolor import colored, cprint

parser = argparse.ArgumentParser(description='Beacon Client Dependencies scanner')
parser.add_argument('client', metavar='repo/project_name', type=str,
                    help='a beacon client GitHub repository for scanning')
parser.add_argument('file', metavar='filename', type=str,
                    help='output json file')
args = parser.parse_args()
client = args.client
fi = args.file
print(colored("Scanning... " + client, 'blue'))
try:
        response = requests.get("https://api.github.com/repos/"+client, timeout=5)
        response.raise_for_status()

        date = response.headers["date"]
        print(colored("Results, as of date: " + date, "magenta"))

        dictionary = response.json()
```

```python
        name = dictionary['name']
        print(colored("Beacon client: " + name, "blue"))

        language = dictionary['language']
        print(colored("Written in " + language, "magenta"))

        stars = dictionary['stargazers_count']
        print(colored("It has " + str(stars) + " stars", "magenta"))

        open_issues = dictionary['open_issues_count']
        print(colored("It has " + str(open_issues) + "open issues", "magenta"))

        last_update = dictionary['updated_at']
        print(colored("Last commit at " + last_update, "magenta" ))

        f = open(fi+".json", "w")
        f.write(json.dumps(response.json(), indent=4))
        f.close()
        print("Response written in the " + fi + ".json file")

except requests.exceptions.HTTPError as httperror:
        print(httperror)
except requests.exceptions.ConnectionError as connection:
        print(connection)
except requests.exceptions.Timeout as timeout:
        print(timeout)
except requests.exceptions.RequestException as requestexception:
        print(requestexception)
```