

# A Survey on Distributed Randomness

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# 1 Introduction

## 1.1 Perfect Synchrony

Suppose  $n$  participants attempt to source a common random number in a distributed yet agreeable manner. In an ideal world where the communication model is perfectly synchronous such that all participants are able to successfully send and receive their random shares  $s_i$  (which will make up the common random number) to and from all other participants at the exact same time, each participant can simply add all shares involved and call  $s = \sum s_i$  to be the randomness produced in that round. Reminiscent of rock-paper-scissors (which can facilitate quick decision-making in real life), such protocol would be not only simple, but also agreeable by all participants, as there is no room to cheat (e.g. predict the randomness in advance).

While the problem of distributed randomness is trivial in this setting, situations can change dramatically in practical settings where participants can go offline (perhaps temporarily) due to network failure, messages can be delayed either non-significantly or significantly, and Byzantine attackers can try to predict or bias the randomness to their benefit. Namely, consider the following simple scenario without perfect synchrony: three participants ( $P_1, P_2, P_3$ ) coordinate to produce a common random number  $s = s_1 + s_2 + s_3$  where each  $P_i$  sends  $s_i$ , and suppose  $P_3$  already obtains the knowledge of  $s_1$  and  $s_2$  before sending  $s_3$  to  $P_1$  and  $P_2$  as the last step of the protocol. Then  $P_3$  is able to set  $s$  to be whichever value he desires, as he can choose his  $s_3$  depending on  $s_1$  and  $s_2$ . Effectively, this protocol becomes centralized by  $P_3$  as a result.

## 1.2 Commit-Reveal

A strawman solution to the above issue, the classical commit-reveal provides an intuitive way to source a random number from a group of nodes by first allowing each node to commit (in the cryptographic sense) to a secret share and then waiting until all shares are committed before revealing them and summing them to compute the final randomness of a round. Due to the additional commit step, it becomes impossible for one participant to centralize the process and set the final randomness to be whichever value he desires. Nonetheless, note that the problem of biasing still exists, as the last person to reveal his share can in fact check the round's output faster than others and hence can decide not to reveal his number if he doesn't like the round's output. This is called the *last revealer attack*.

## 1.3 Desired Properties of Distributed Randomness

Clearly, we should prevent anyone from biasing the distributed randomness in any way. Assuming a distributed randomness beacon (DRB) setting in which a distributed randomness protocol is conducted in successive rounds in a continuous

manner, we can define overall security of a DRB by requiring the following properties.

**Definition 1.1** (*d-unpredictability*). A DRB protocol is said to be *unpredictable* with absolute bound  $d$  for  $d \geq 1$  if the probability of an adversary  $\mathcal{A}$  predicting the honest output for round  $r + d$  (where  $r$  denotes the current round) is a negligible function  $\text{negl}(\lambda)$ .

**Definition 1.2** (Secure distributed randomness beacon). A DRB protocol is said to be *d-secure* if it satisfies the following conditions:

1. Bias Resistance. Let  $\mathcal{O}$  be the output of the beacon for some round  $r$ . No computationally bounded adversary  $\mathcal{A}$  can bias the output of the beacon, i.e. fix  $c$  bits of  $\mathcal{O}$  for any round  $r > 1$  with probability greater than  $\frac{1}{2^c} + \text{negl}(\lambda)$ .
2. Unpredictability. The protocol satisfies  $d$ -unpredictability.
3. Guaranteed Output Delivery. For every round  $r \geq 1$ , the protocol outputs a value.
4. Public Verifiability. Any third party should be able to verify the beacon values even if not partaking in the generation of those values.

## 2 Building Blocks

### 2.1 Verifiable Secret Sharing

The issue with the classical Shamir's secret sharing scheme is that either the dealer or other participants could in fact be acting maliciously, e.g. Alice (a participant) needs to trust that she has received her share correctly from the dealer while she also needs to trust that other participants' revealed shares are correct.

This issue can be fixed by the notion of verifiable secret sharing (VSS). The idea is that we add an additional verification process to the usual Shamir's secret sharing scheme. Here, we take note of two commonly used VSS schemes: Feldman-VSS and Pedersen-VSS.

The mathematical setup is as follows. We choose primes  $p$  and  $q$  such that  $q \mid p - 1$  and let  $g$  be a generator of  $G_q$ , a cyclic subgroup of  $\mathbb{Z}_p^*$ . This setup has the effect of achieving the following:  $a \equiv b \pmod{q} \iff g^a \equiv g^b \pmod{p}$ . As a result, it should be understood that modular arithmetics are done in modulo  $q$  whenever the numbers involved concern the exponents while in modulo  $p$  otherwise. For convenience, we may omit  $\text{mod } p$  such that one can aptly assume arithmetics are done in modulo  $p$  given an equation unless stated otherwise.

### 2.1.1 Feldman-VSS

The following summarizes a simple VSS scheme (where  $t$  among  $n$  participants can reconstruct the group secret) proposed by Paul Feldman.

- $f(x) = \sum_{i=0}^{t-1} a_i x^i$  is randomly selected by the dealer, where  $a_i \in \mathbb{Z}_q$  and  $f(0) = a_0$  is the secret
- The shares are  $f(1), f(2), \dots, f(n)$  in mod  $q$  and are distributed to  $n$  participants, respectively
- Also distributed from the dealer are commitments to coefficients of  $f$ , i.e.  $c_j = g^{a_j}$  for  $j = 0, \dots, t-1$
- Given her share  $f(k)$  and the polynomial coefficient commitments, Alice (a participant) can verify her share by checking:

$$g^{f(k)} = g^{\sum_{i=0}^{t-1} a_i k^i} = \prod_{j=0}^{t-1} c_j^{k^j} = c_0 c_1^{k^1} c_2^{k^2} \dots c_{t-1}^{k^{t-1}}$$

- Any  $t$  number of participants (say)  $i = 1, 2, \dots, t$  can recover the secret  $a_0$  by performing Lagrange interpolation involving Lagrange coefficients  $\lambda_i = \prod_{j \neq i} \frac{j}{j-i}$  in mod  $q$ :

$$a_0 = f(0) = \sum_{i=1}^t f(i) \lambda_i$$

What is new here (compared to Shamir's secret sharing scheme) is the inclusion of commitments to polynomial coefficients in the scheme. These commitments enable participants to verify the validity of their corresponding shares.

### 2.1.2 Pedersen-VSS

Reminiscent of Pedersen commitment, Pedersen-VSS is a variation that involves two random polynomials generated by the dealer as opposed to one. Namely, the scheme runs as follows.

- $f(x) = \sum_{i=0}^{t-1} a_i x^i$  and  $f'(x) = \sum_{i=0}^{t-1} b_i x^i$  are randomly selected by the dealer, where  $a_i, b_i \in \mathbb{Z}_q$  and  $f(0) = a_0$  is the secret (as before)
- The shares are  $(f(1), f'(1)), \dots, (f(n), f'(n))$  in mod  $q$  and are distributed to  $n$  participants, respectively
- Also distributed from the dealer are commitments to coefficients of  $f$  and  $f'$ , i.e.  $c_j = g^{a_j} h^{b_j}$  for  $j = 0, \dots, t-1$

- Given her share  $(f(k), f'(k))$  and the polynomial coefficient commitments, Alice (a participant) can verify her share by checking:

$$g^{f(k)} h^{f'(k)} = \prod_{j=0}^{t-1} c_j^{k^j}$$

- Any  $t$  number of participants (say)  $i = 1, 2, \dots, t$  can recover the secret  $a_0$  by performing Lagrange interpolation involving Lagrange coefficients  $\lambda_i = \prod_{j \neq i} \frac{j}{j-i}$  in mod  $q$ :

$$a_0 = f(0) = \sum_{i=1}^t f(i) \lambda_i$$

Effectively, what Pedersen-VSS is able to achieve is the decoupling of  $g^{a_0}$  (as the public key corresponding to the secret key  $a_0$ ) and  $g^{a_0} h^{b_0}$  (as the published commitment for verification purposes). In other words, the verification process in which the participants verify their shares does not (even information-theoretically) leak any information regarding the initial secret  $a_0$ , a fact that is not true with Feldman-VSS.

## 2.2 Distributed Key Generation

The motivation for distributed key generation (DKG), which basically comprises  $n$  parallel instances of a VSS (run by each participant), is to achieve and utilize a group secret in a leaderless manner such that any threshold  $t$  number of participants should be able to recover the same group secret. The basic idea is that every participant becomes a leader for a VSS (hence achieving the leaderless property), in which case the protocol deals with  $n$  random polynomials  $\{f_i\}_{i=1, \dots, n} \bmod q$  as opposed to one. Though not computed explicitly, the implicit group polynomial  $f = \sum f_i$  then embeds the group secret in the form of  $f(0)$  (denoted by  $x$ ) as well as the corresponding public key  $g^{f(0)}$  (denoted by  $y$ ) via commitments to coefficients of  $f_i$  as per each VSS. Notably, this facet is the one that allows a leaderless configuration where there does not exist a leader for  $f$  even if each participant  $P_i$  remains a leader for  $f_i$  with the knowledge of  $f_i(0)$ . As a result, it is only collectively (i.e. with the collaboration of at least  $t$  number of nodes in a group) that the group can make use of  $x$  and  $y$  in the typical sense of asymmetric cryptography (e.g. signing a message) after performing a DKG.

Before delineating the process of a DKG, we include what it means for a DKG to be uniformly secure. Namely, a uniformly secure DKG should satisfy the following three correctness properties and one secrecy property.

**Definition 2.1.** In the setting where at most  $t - 1$  nodes can be controlled by an attacker without compromising the protocol, a DKG is *uniformly secure* if the following properties are satisfied.

### Correctness

1. Any subset of shares of size  $t$  can be used to recover the same group secret key  $x$ .
2. All honest parties have access to the same public key  $y = g^x$ .
3.  $x$  is uniformly distributed in  $\mathbb{Z}_q$ , and thus  $y$  is uniformly distributed in  $G_q$  (subgroup of  $\mathbb{Z}_p^*$  generated by  $g$ ).

### Secrecy

1. Other than from the fact that  $y = g^x$ , no information on  $x$  is leaked. Equivalently, this can be stated using a simulator *SIM*: for every probabilistic polynomial-time adversary  $\mathcal{A}$ , there exists a probabilistic polynomial-time simulator *SIM* that, given  $y \in G_q$  as input, produces an output distribution which is polynomially indistinguishable from  $\mathcal{A}$ 's view of a DKG protocol that ends with  $y$  as its public key output while  $\mathcal{A}$  is allowed to corrupt up to  $t - 1$  participants.

Without the third correctness property, we call a DKG *secure*. The reason behind this minor distinction is that Joint-Feldman DKG, which is most commonly used in practice, is secure but not uniformly secure while Joint-Pedersen offers uniform security. Simultaneously, however, it has been shown that a DKG protocol that is secure but not uniformly secure in fact suffices in the context of using DKG as a subprotocol for distributed randomness, even if the lack of uniform security does seem insufficient a priori in the context of DKG itself.

#### 2.2.1 Joint-Feldman

1. Each participant  $P_i$  runs a Feldman-VSS by choosing a random polynomial  $f_i(z) = \sum_{j=0}^{t-1} a_{ij} z^j$  and sending a “subshare”  $f_i(j)$  to player  $P_j$  for all  $j$
2. To satisfy the verifiability portion of the VSS,  $P_i$  broadcasts  $A_{ik} = g^{a_{ik}}$
3. Upon receiving the subshares and the corresponding commitments (e.g. in the form of a verification vector),  $P_j$  can use the verification mechanism per VSS to verify the subshares. If a verification fails,  $P_j$  can broadcast a complaint against  $P_i$ .
4. If  $P_i$  receives at least  $t$  complaints, then  $P_i$  is disqualified. Otherwise,  $P_i$  needs to reveal the subshare  $f_i(j)$  per  $P_j$  that has broadcasted a complaint. We call *QUAL* the set of non-disqualified players.
5. Once *QUAL* is set, we define  $f(z) = \sum_{i \in \text{QUAL}} f_i(z) = \sum_{i=0}^{t-1} a_i z^i$  such that each participant  $P_j$  in *QUAL* can compute the group public key  $y = g^{f(0)} =$

$\prod_{i \in QUAL} A_{i0}$ , commitments to  $f$ 's coefficients  $A_k = g^{a_k} = \prod_{i \in QUAL} A_{ik}$ , and  $P_j$ 's share (of the group secret) from subshares  $f(j) = \sum_{i \in QUAL} f_i(j)$ . Though not computed explicitly, the group secret key  $x$  is then equal to both  $\sum_{i \in QUAL} a_{i0}$  and the Lagrange interpolation involving the shares  $\{f(j)\}_{j \in QUAL}$ .

### 2.2.2 Joint-Pedersen

1. Each participant  $P_i$  runs a Pedersen-VSS by choosing two random polynomials  $f_i(z) = \sum_{j=0}^{t-1} a_{ij}z^j$  and  $f'_i(z) = \sum_{j=0}^{t-1} b_{ij}z^j$  and sending a “subshare”  $(f_i(j), f'_i(j))$  to player  $P_j$  for all  $j$
2. To satisfy the verifiability portion of the VSS,  $P_i$  broadcasts  $C_{ik} = g^{a_{ik}} h^{b_{ik}}$
3. Upon receiving the subshares and the corresponding commitments (e.g. in the form of a verification vector),  $P_j$  can use the verification mechanism per VSS to verify the subshares. If a verification fails,  $P_j$  can broadcast a complaint against  $P_i$ .
4. If  $P_i$  receives at least  $t$  complaints, then  $P_i$  is disqualified. Otherwise,  $P_i$  needs to reveal the subshare  $(f_i(j), f'_i(j))$  per  $P_j$  that has broadcasted a complaint. We call  $QUAL$  the set of non-disqualified players.
5. Once  $QUAL$  is set, we define  $f(z) = \sum_{i \in QUAL} f_i(z) = \sum_{i=0}^{t-1} a_i z^i$  such that each participant  $P_j$  in  $QUAL$  can compute the group public key  $y = g^{f(0)} = \prod_{i \in QUAL} A_{i0}$ , commitments to  $f$ 's coefficients  $A_k = g^{a_k} = \prod_{i \in QUAL} A_{ik}$ , and  $P_j$ 's share (of the group secret) from subshares  $f(j) = \sum_{i \in QUAL} f_i(j)$ . Though not computed explicitly, the group secret key  $x$  is then equal to both  $\sum_{i \in QUAL} a_{i0}$  and the Lagrange interpolation involving the shares  $\{f(j)\}_{j \in QUAL}$ .

## 2.3 Publicly Verifiable Secret Sharing

While VSS allows verification of the involved shares, the fact of the matter is that such verification can only be done by the involved participants in the secret sharing process. In other words, the verification process of a VSS is not public. Publicly verifiable secret sharing (PVSS), on the other hand, assumes a public setup where the verification process can be achieved publicly (e.g. by bystanders) such that the messages exchanged during the protocol are modified accordingly in order to reflect the fact that some information kept private in a typical VSS can be public in a PVSS. Naturally, this added facet of public verifiability is useful and desirable in models such as the public bulletin board model (e.g. for blockchains). A PVSS can be represented by the following tuple of algorithms.

- $Setup(\lambda) \rightarrow pp$ . Generates the scheme parameters  $pp$ , an implicit input to all other algorithms.



- $KeyGen(\lambda) \rightarrow (pk, sk)$ . Generate PVSS key-pair  $(pk, sk)$  used for share encryption and decryption.
- $Enc(pk, m) \rightarrow c$  and  $Dec(sk, c) \rightarrow m$ . The encryption and decryption algorithms used to send shares to all, and obtain private share respectively. The invariant  $Pr[Dec(Enc(m)) = m] = 1$  must always hold true for all  $m$  in the message domain.
- $ShareGen(s) \rightarrow (S, E, \pi)$ . Typically, executed by the dealer with secret  $s$  to generate secret share vector  $S = (s_1, \dots, s_n)$  and encryption vector of shares  $E = (Enc(s_1), \dots, Enc(s_n))$  for all nodes  $P$ , and a cryptographic proof  $\pi$  committing to  $s$  which guarantees any node with  $\geq t$  shares reconstruct a unique  $s$ .
- $ShareVerify(E, \pi) \rightarrow \{0, 1\}$ . Verify if the sharing is correct. A successful verification guarantees that its share is correct and  $t$  nodes reconstruct a unique  $s$ . 0 indicates a failure whereas 1 indicates a success.
- $Recon(S) \rightarrow s$ . Reconstruct the shared secret  $s$  from the collection of shares  $S \subset \{s_1, \dots, s_n\}^t$ .

**Definition 2.2** (PVSS security). Let  $L \in P$  be the dealer with secret  $s$  and  $\lambda$  be the security parameter. A secure PVSS scheme must provide the following guarantees:

1. **Secrecy.** If  $L$  is honest, then the adversary's view during the sharing phase reveals no information about the dealer's secret  $s$  with probability better than  $\text{negl}(\lambda)$ .
2. **Correctness.** If  $L$  is honest, then the honest nodes output the secret  $s$  at the end of the reconstruction phase with high probability  $1 - \text{negl}(\lambda)$ .
3. **Public Verifiability.** If the check in verification algorithm returns 1, then with high probability  $1 - \text{negl}(\lambda)$ , the encryptions are valid shares of some secret.

Implementing the above interface, Schoenmakers' PVSS scheme and Scrape's variations of it are delineated in the following.

### 2.3.1 Schoenmakers

**Initialization.** The group  $G_q$  and the generators  $g, G$  are selected using an appropriate public procedure. Participant  $P_i$  generates a private key  $x_i \leftarrow \mathbb{Z}_q^*$  and registers  $y_i = G^{x_i}$  as its public key.

**Distribution.** The protocol consists of two steps:

1. *Distribution of the shares.* Suppose without loss of generality that the dealer wishes to distribute a secret among participants  $P_1, \dots, P_n$ . The dealer picks a random polynomial  $p$  of degree at most  $t - 1$  with coefficients in  $\mathbb{Z}_q$

$$p(x) = \sum_{i=0}^{t-1} a_i x^i$$

and sets  $s = a_0$ . The dealer keeps this polynomial secret but publishes the related commitments  $C_j = g^{a_j}$  for  $0 \leq j < t$ . The dealer also publishes the encrypted shares  $Y_i = y_i^{p(i)}$  for  $1 \leq i \leq n$  using the public keys of the participants. Finally, let  $X_i = \prod_{j=0}^{t-1} C_j^{i^j}$ . The dealer shows that the encrypted shares are consistent by producing a proof of knowledge of the unique  $p(i)$  for  $1 \leq i \leq n$  satisfying:

$$X_i = g^{p(i)}, \quad Y_i = y_i^{p(i)}.$$

The non-interactive proof is the  $n$ -fold parallel composition of the protocols for  $DLEQ(g, X_i, y_i, Y_i)$ . Applying Fiat-Shamir's technique, the challenge  $c$  for the protocol is computed as a cryptographic hash of  $X_i, Y_i, a_{1i}, a_{2i}, 1 \leq i \leq n$ . The proof consists of the common challenge  $c$  and the  $n$  responses  $r_i$ .

2. *Verification of the shares.* The verifier computes  $X_i = \prod_{j=0}^{t-1} C_j^{i^j}$  from the  $C_j$  values. Using  $y_i, X_i, Y_i, r_i, 1 \leq i \leq n$  and  $c$  as input, the verifier computes  $a_{1i}, a_{2i}$  as

$$a_{1i} = g^{r_i} X_i^c, \quad a_{2i} = y_i^{r_i} Y_i^c$$

and checks that the hash of  $X_i, Y_i, a_{1i}, a_{2i}, 1 \leq i \leq n$  matches  $c$ .

**Reconstruction.** The protocol consists of two steps:

1. *Decryption of the shares.* Using its private key  $x_i$ , each participant finds the share  $S_i = G^{p(i)}$  from  $Y_i$  by computing  $S_i = Y_i^{1/x_i}$ . They publish  $S_i$  plus a proof that the value  $S_i$  is a correct decryption of  $Y_i$ . To this end, it suffices to prove knowledge of an  $\alpha$  such that  $y_i = G^\alpha$  and  $Y_i = S_i^\alpha$ , which is accomplished by the non-interactive version of the protocol  $DLEQ(G, y_i, S_i, Y_i)$ .
2. *Pooling the shares.* Suppose without loss of generality that participants  $P_i$  produce correct values for  $S_i$ , for  $i = 1, \dots, t$ . The secret  $G^s$  is obtained by Lagrange interpolation:

$$\prod_{i=1}^t S_i^{\lambda_i} = \prod_{i=1}^t \left( G^{p(i)} \right)^{\lambda_i} = G^{\sum_{i=1}^t p(i)\lambda_i} = G^{p(0)} = G^s$$

where  $\lambda_i = \prod_{j \neq i} \frac{j}{j-i}$  is a Lagrange coefficient.

Note that the participants do not need nor learn the values of the exponents  $p(i)$ . Only the related values  $S_i = G^{p(i)}$  are required to complete the reconstruction of the secret value  $S = G^s$ . Also, note that participant  $P_i$  does not expose its private key  $x_i$ ; consequently participant  $P_i$  can use its key pair in several runs of the PVSS scheme. The type of encryption used for the shares has been optimized for performance; however, if desired, it is also possible to use standard ElGamal encryption instead.

Clearly, the scheme is homomorphic. For example, given the dealer's output for secrets  $G^{s_1}$  and  $G^{s_2}$ , the combined secret  $G^{s_1+s_2}$  can be obtained by applying the reconstruction protocol to the combined encrypted shares  $Y_{i1}Y_{i2}$ .

### 2.3.2 Scrape's Variations

Scrape offers two variations of Schoenmakers' PVSS: one that relies on the DDH (decisional Diffie-Hellman) assumption in the random oracle model and one that relies on the DBS (decisional bilinear square) assumption in the plain model. Accordingly, the former utilizes the same NIZK (i.e. *DLEQ* by Chaum and Pedersen) from Schoenmakers' whereas the latter utilizes a bilinear pairing, which serves as a valid size-efficient substitute to the NIZK at the cost of pairing-related computations. Both variations make novel use of Reed-Solomon codes from coding theory in a way that the total number of exponentiations needed to verify the shares distributed by the dealer in a PVSS is decreased from  $O(nt)$  (which becomes quadratic if  $t = \frac{n}{2}$  for instance) to  $O(n)$ . In other words, the approaches optimize the verifier's computational complexity before the Reconstruction phase.

The idea is that the verifier does not have to compute  $t$  exponentiations via  $X_i = \prod_{j=0}^{t-1} C_j^{ij}$  per share, before which the dealer publishes the commitments  $C_j$  to the polynomial coefficients. Instead, the dealer publishes  $v_i = g^{p(i)}$  directly alongside the dual code  $\mathcal{C}^\perp$  of the  $[n, k, n-k+1]$  Reed-Solomon code  $\mathcal{C}$  corresponding to the shares calculated by the dealer in the form  $\mathcal{C} = \{(p(1), \dots, p(n)) \mid p(x) \in \mathbb{Z}_q[x], \deg(p(x)) \leq t-1\}$ , in which case the verifier can randomly sample a codeword  $c^\perp = (c_1^\perp, \dots, c_n^\perp)$  from  $\mathcal{C}^\perp$ , indirectly compute the inner product of  $c^\perp$  and the share vector  $(s_1, \dots, s_n)$ , and verify that  $\prod v_i^{c_i^\perp} = g^{\sum s_i c_i^\perp} = g^0 = 1$  with  $O(n)$  exponentiations.

## 2.4 Verifiable Delay Function

A verifiable delay function (VDF) is a function that takes a prescribed time to compute, even on a parallel computer. However once computed, the output can be quickly verified by anyone. Moreover, every input must have a unique valid output as per a function. A VDF can be represented by a tuple of three algorithms:

- $Setup(\lambda, T) \rightarrow pp$  is a randomized algorithm that takes a security parameter  $\lambda$  and a time bound  $T$ , and outputs public parameters  $pp$ .

- $Eval(pp, x) \rightarrow (y, \pi)$  takes an input  $x$  and outputs  $y$  and a proof  $\pi$ .
- $Verify(pp, x, y, \pi) \rightarrow \{accept, reject\}$  outputs *accept* if  $y$  is the correct evaluation of the VDF on input  $x$ .

A VDF must satisfy the following three properties:

- $\epsilon$ -evaluation time.  $Eval(pp, x)$  runs in time at most  $(1 + \epsilon)T$ , for all  $x$  and all  $pp$  output by  $Setup(\lambda, T)$ .
- Sequentiality. A parallel algorithm  $\mathcal{A}$ , using at most  $poly(\lambda)$  processors, that runs in time less than  $T$  cannot compute the function. Specifically, for a random  $x$  and  $pp$  output by  $Setup(\lambda, T)$ , if  $(y, \pi) \leftarrow Eval(pp, x)$  then  $Pr[\mathcal{A}(pp, x) = y]$  is negligible.
- Uniqueness. For an input  $x$ , exactly one  $y$  will be accepted by  $Verify$ . Specifically, let  $\mathcal{A}$  be an efficient algorithm that given  $pp$  as input, outputs  $(x, y, \pi)$  such that  $Verify(pp, x, y, \pi) = accept$ . Then  $Pr[Eval(pp, x) \neq y]$  is negligible.

Intuitively, one can understand VDF as a computational task that cannot be sped up by parallelism as a result. Exponentiation in a group of unknown order is believed to have this property and was used by Rivest, Shamir, and Wagner to construct a time-lock puzzle. The two well-regarded VDF proposals, i.e. one due to Pietrzak and the other due to Wesolowski, similarly make use of the serial nature of this task.

## 3 Protocols

### 3.1 PVSS-based

#### 3.1.1 Scrape

Scrape is run between  $n$  parties  $P_1, \dots, P_n$  who have access to a public ledger (a la public bulletin board model) where they can post information for later verification. At a high level, the protocol is an improvement over commit-reveal such that the concept of reconstruction can prevent the last revealer attack in case any committed inputs are not revealed later. A PVSS protocol is used as a subprotocol, and it is assumed that the Setup phase is already done and the public keys  $pk_i$  of each party  $P_i$  are already registered in the ledger. In detail, the protocol proceeds as follows:

1. **Commit:** For  $1 \leq j \leq n$ , party  $P_j$  executes the Distribution phase of the PVSS subprotocol as the Dealer with threshold  $t = \frac{n}{2}$ , publishing the encrypted shares and the verification information  $PROOF_D^j$  on the public ledger, and also learning the random secret  $h^{s^j}$  and  $s^j$ .  $P_j$  also publishes a commitment to the secret exponent  $Com(s^j, r_j)$  (with fresh randomness  $r_j \leftarrow \mathbb{Z}_q$ ), for  $1 \leq j \leq n$ .

2. **Reveal:** For every set of encrypted shares and the verification information  $PROOF_D^j$  published in the public ledger, all parties run the Verification phase of the PVSS subprotocol. Let  $\mathcal{C}$  be the set of all parties who published commitments and valid shares. Once  $\frac{n}{2}$  parties have posted their commitments and valid shares on the ledger, party  $P_j$  opens its commitment, posting  $\text{Open}(s^j, r_j)$  on the ledger, for  $j \in \mathcal{C}$ .
3. **Recovery:** For every party  $P_a \in \mathcal{C}$  that does not publish  $\text{Open}(s^a, r_a)$  in the Reveal phase, party  $P_j$  runs the Reconstruction phase of the PVSS protocol posting  $\tilde{s}_j^a$  and  $PROOF_j^a$  to the public ledger, for  $1 \leq j \leq n$ . Once  $\frac{n}{2}$  valid decrypted shares are published, every party reconstructs  $h^{s^a}$ .

The final randomness is computed as  $\rho = \prod_{j \in \mathcal{C}} h^{s^j}$ .

### 3.1.2 HydRand

HydRand can be interpreted as an improvement over Scrape, where at most one operation of PVSS distribution or reconstruction is conducted every round such that we are able to reduce the protocol's communication complexity by a factor of  $n$ , i.e. from  $O(n^3)$  to  $O(n^2)$ . Basically, this is made possible by introducing the concept of a round leader (which is nonexistent in the case of Scrape) such that one of the following two scenarios is to happen every round: the round leader reveals his secret committed in his previous round (i.e. the last time he was the round leader as per some predefined, deterministic leader selection mechanism) and commits to a new secret to be utilized in a future round by distributing the corresponding PVSS shares via a message of size  $O(n)$  (hence at most one PVSS distribution), or the leader fails to reveal his secret committed in his previous round in a timely manner, in which case the non-leader nodes are able to reconstruct the secret by aggregating the shares that are received previously (hence at most one PVSS reconstruction). This indeed contrasts with Scrape, where there are  $O(n)$  fresh operations of PVSS distribution and reconstruction every round due to the fact that each node has to perform one each round.

Again, the difference is that PVSS shares distributed by a leader in HydRand are used not in the current round (which is the case for Scrape), but the next time the same leader is selected in some future round. Combined with the fact that HydRand's randomness each round is defined as the hash of the previous round's randomness as well as the round leader's secret corresponding to the current round (but committed previously), this can potentially cause the beacon's unpredictability property to fail without any remedy, as the leader selection mechanism can theoretically select only the adversarial nodes as the round leaders such that it becomes possible for the adversarial nodes to predict the entire randomness chain in advance.

To remedy this, HydRand takes the approach that a round leader is not allowed to be selected again for the next  $f$  rounds (where  $f$  denotes the number of Byzantine

nodes). As a result, the protocol guarantees that there exists at least one honest node in  $f + 1$  consecutive rounds such that it is impossible to achieve predictability for up to  $f + 1$  rounds. Nonetheless, it remains possible to achieve predictability for up to  $f$  rounds with a low probability whenever  $f$  Byzantine nodes are consecutively selected as leaders, and this remains a tradeoff incurred by HydRand.

Employing Scrape’s PVSS as a subprotocol, HydRand’s rounds are implemented in three distinct phases: propose, acknowledge, and vote.

**I. Propose.** During this phase, the round leader  $\ell$  reveals his previously committed value  $s_\ell$  and provides a new commitment  $Com(s_\ell^*)$ . For this purpose, it is the leader’s task to propose a new dataset  $D_r$  for the current round  $r$ . As a performance optimization, we split a dataset into two parts: a header and a body. For certain operations, we only require sending the header of the dataset. The header  $header(D_r)$  of dataset  $D_r$  contains:

- the hash of the dataset’s body  $H(body(D_r))$
- the current round index  $r$
- the round’s random beacon value  $R_r$
- the revealed secret value  $s_\ell$
- the round index  $\tilde{r}$  of the previous dataset  $D_{\tilde{r}}$
- the hash  $H(D_{\tilde{r}})$  of the previous dataset  $D_{\tilde{r}}$  if  $\tilde{r} > 0$
- a list of random beacon values  $\{R_k, R_{k+1}, \dots\}$  for all recovered rounds between  $\tilde{r}$  and  $r$  (if any)
- the Merkle tree root hash  $M_r$  over all encrypted shares in the new commitment  $Com(s_\ell^*)$

Then the body  $body(D_r)$  of dataset  $D_r$  contains:

- a confirmation certificate  $CC(D_{\tilde{r}})$  which confirms that  $D_{\tilde{r}}$  was previously accepted as a valid dataset
- a recovery certificate  $RC(k)$  for all rounds  $k \in \{\tilde{r} + 1, \tilde{r} + 2, \dots, r - 1\}$  which confirms that there exists a recovery for all rounds between  $\tilde{r}$  and  $r$
- the commitment  $Com(s_\ell^*)$  to a new randomly chosen secret  $s_\ell^*$

Note that the leader selects  $\tilde{r} < r$  as the most recent regular round, for which the leader is not aware of any successful recovery.

After the construction of the above dataset, a correct leader  $\ell$  broadcasts a signed *propose* message to all nodes. Each node  $i$ , which receives such a message from the

leader before the end of the propose phase, checks the validity of the dataset  $D_r$ . For this purpose  $i$  verifies that  $D_r$  is constructed as previously defined and properly signed. This includes a check that the revealed secret  $s_\ell$  corresponds to the previous commitment of the current leader. Additionally, the validity of the confirmation and recovery certificates is checked. A *confirmation certificate* for dataset  $D_r$  is valid iff it consists of  $f + 1$  signed messages from  $f + 1$  different senders. Similarly, a *recovery certificate* for some round  $k$  is a collection of  $f + 1$  signed messages from  $f + 1$  different senders.

**II. Acknowledge.** If a node  $i$  receives a valid dataset  $D_r$  from the round's leader  $\ell$  during the propose phase, it constructs and broadcasts a signed acknowledge message thereby also forwarding the revealed secret value  $s_\ell$  as part of the header. Further, each node  $i$  collects and validates acknowledge messages from other nodes.

**III. Vote.** Each node  $i$  checks the following conditions:

- During the current propose phase a valid dataset  $D_r$  was received.
- During the current acknowledge phase at least  $2f + 1$  valid acknowledge messages from different senders have been received.
- All acknowledge messages received refer to the dataset's hash  $H(D_r)$ . Valid acknowledge messages for more than one value of  $H(D_r)$  form a cryptographic proof of leader equivocation.

If all conditions are met, node  $i$  broadcasts a signed confirmation message. Otherwise, node  $i$  broadcasts a recover message. Note that a Merkle tree root hash is required to enable nodes which are not in possession of  $Com(s_\ell)$  to verify the share decryption proof.  $R_{r-1}$  is included for efficient external verification.

At the end of this phase, each node  $i$  can obtain the round's random beacon value  $R_r$ . We distinguish between the following two cases: (i) node  $i$  already knows the secret value  $s_\ell$ , because it received the dataset  $D_r$  or an acknowledge message for  $D_r$ , and (ii) node  $i$  has received at least  $f + 1$  valid recover messages which include at least  $f + 1$  decrypted secret shares for  $s_\ell$ . In the latter case, the reconstruction procedure of Scrape's PVSS can be executed to produce the value  $h^{s_\ell}$ . In both cases,  $R_r$  is then obtained by computing:

$$R_r \leftarrow H(R_{r-1} || h^{s_\ell})$$

### 3.1.3 RandPiper

RandPiper offers two protocols: GRandPiper (Good Pipelined Random beacon) and BRandPiper (Better Pipelined Random beacon). While GRandPiper roughly follows HydRand's protocol, it improves upon it via its idiosyncratic use of BFT

SMR (state machine replication) protocol, which uses erasure coding and cryptographic accumulators (either of the bilinear type incurring a trusted setup tradeoff or of the Merkle tree type) to implement the public bulletin board model in a Byzantine broadcast fashion such that HydRand’s worst-case communication complexity of  $O(n^3)$  is improved to  $O(n^2)$  in GRandPiper.

The key idea is that RandPiper’s SMR protocol allows a round leader to Byzantine broadcast a message of size  $O(n)$  within a total communication complexity of  $O(n^2)$  rather than  $O(n^3)$ . While this improvement benefits the side of communication complexity indeed, the same issue of predictability present in HydRand still remains in GRandPiper, where an adversary can predict up to  $f$  number of rounds (albeit with low probability that becomes trivial when  $n$  is large). The trusted setup assumption due to the initial  $q$ -SDH parameters is also a tradeoff. While using Merkle trees as accumulators as opposed to bilinear ones would eliminate the trusted setup assumption, Merkle trees increase the total communication complexity from  $O(n^2)$  to  $O(n^2 \log n)$ .

The following delineates RandPiper’s SMR protocol, which happens largely in 4 steps (preceded by an epoch advancement) per epoch (i.e. round): propose, vote, vote certificate, and commit.

**0. Epoch advancement.** When  $\text{epoch-timer}_{e-1}$  expires, node  $p_i$  enters epoch  $e$ . After entering epoch  $e$ , node  $p_i$  sends its highest ranked certificate to leader  $L_e$ . In addition, it also sets  $\text{epoch-timer}_e$  to  $11\Delta$  and starts counting down.

**1. Propose.** After entering epoch  $e$ , leader  $L_e$  waits for  $2\Delta$  to collect highest ranked certificates from all honest nodes. The  $2\Delta$  wait before a proposal ensures that leader  $L_e$  can collect highest ranked certificates from all honest nodes when leader  $L_e$  enters epoch  $e$   $\Delta$  time before other honest nodes. After the  $2\Delta$  wait, leader  $L_e$  proposes a block  $B_h$  by extending the highest ranked block certificate known to  $L_e$ . The proposal for  $B_h$ , conceptually, has the form  $\langle \text{propose}, B_h, e, \mathcal{C}, z_{pe} \rangle_{L_e}$  where  $z_{pe}$  is the accumulation value for the pair  $(B_h, \mathcal{C})$ . In order to facilitate efficient equivocation checks, the leader signs the tuple  $\langle \text{propose}, H(B_h, \mathcal{C}), e, z_{pe} \rangle_{L_e}$  and sends  $B_h$  and  $\mathcal{C}$  separately. This size of the signed message is  $O(k)$  and hence can be broadcast during equivocation or while delivering  $p_e$  without incurring cubic communication overhead.

**2. Vote.** If a node receives the first valid proposal  $p_e$  when  $\text{epoch-timer}_e \geq 7\Delta$  and block  $B_h$  extends the highest ranked certificate known to the node, it invokes  $\text{Deliver}(\text{propose}, p_e, z_{pe}, e)$ . In addition, the node sets its  $\text{vote-timer}_e$  to  $2\Delta$  and starts counting down. When  $\text{vote-timer}_e$  reaches 0 and detects no epoch  $e$  equivocation, the node sends vote to  $L_e$ . If block  $B_h$  does not extend the highest ranked certificate known to the node or receives proposal  $p_e$  when its  $\text{epoch-timer}_e < 7\Delta$ , the node simply ignores the proposal and does not vote for  $B_h$ .



**3. Vote certificate.** When leader  $L_e$  receives  $t + 1$  vote messages for the proposed block,  $L_e$  broadcasts **vote-cert** to all nodes. Similar to the proposal, the hash of the certificate is signed to allow for efficient equivocation checks. It is important to note that two different certificates for the same value is still considered an equivocation in this step.

**4. Commit.** When node  $p_i$  receives the block certificate  $v_e$  when epoch timer is large enough ( $3\Delta$ ), it invokes **Deliver**(vote-cert) and sets **commit-timer<sub>e</sub>** to  $2\Delta$ . When **commit-timer<sub>e</sub>** reaches 0, if no equivocation for epoch  $e$  has been detected, node  $p_i$  commits  $B_h$  and all its ancestors. The **Deliver**() message ensures that all honest nodes have received  $\mathcal{C}$  before quitting epoch  $e$ . We note that it is not necessary for node  $p_i$  to vote for  $B_h$  to commit it. A block certificate on  $B_h$  implies that at least one honest node voted for  $B_h$  and if node  $p_i$  had a different highest ranked certificate due to which it did not vote, then the corresponding block was not committed.

**A. Equivocation.** At any time in epoch  $e$ , if a node  $p_i$  detects an equivocation, it broadcasts equivocating message signed by  $L_e$ . As mentioned earlier, the message signed by  $L_e$  are  $O(1)$  sized and does not incur large communication. Node  $p_i$  also stops participating in epoch  $e$  at that time.

**B. Deliver function.** The **Deliver**() function implements efficient broadcast of long messages using erasure coding techniques and cryptographic accumulators. When the function is invoked using the input parameters, the message  $b$  is first divided into  $n$  coded shares  $(s_1, \dots, s_n)$  using Reed-Solomon codes and a cryptographic witness  $w_j$  is computed for each value  $s_j$ . Then, the share  $(s_j, w_j)$  is sent to the node  $p_j \in P$  along with the accumulation value  $z_e$ , keyword **key**, and  $L_e$ 's signature on the message. When a node  $p_j$  receives the first valid shares for an accumulation value  $z_e$  such that the witness  $w_j$  verifies the share  $s_j$ , it forwards the share  $(s_j, w_j)$  to all nodes. When a node  $p_i$  receives  $n - t$  valid shares corresponding to the first accumulation value  $z_e$  it receives, it reconstructs the object  $b$ . Note that node  $p_i$  reconstructs object  $b$  for the first valid share even though it detects equivocation in an epoch.

While GRandomPiper is essentially an improvement over Hydrand employing the above SMR protocol, BRandomPiper offers a slightly different approach to distributed randomness, motivated to provide a guarantee of absolute unpredictability rather than probabilistic unpredictability. The key difference is that BRandomPiper makes use of  $n$  secrets (one from each node) per round as opposed to one (from the round leader) like GRandomPiper or Hydrand. Similar to Scrape, this in fact requires  $n^2$  secret shares ( $n$  shares per secret) per round. To perform better than Scrape's

quartic worst-case communication complexity, however, BRandPiper fine-tunes its public bulletin board during the protocol such that the number of messages posted on the public bulletin board (realized by the BFT SMR protocol) is minimized.

The main idea is that a leader commits to  $n$  secrets (corresponding to the next  $n$  rounds) in one round at once as opposed to committing to one secret on a per-round basis. It is in this way that each node (leader or non-leader) should have access to  $n$  secret shares (each corresponding to a different secret, one from each node) per round such that a homomorphic sum of those shares followed by a reconstruction phase with other nodes should yield the randomness shared by the entire group in that round a la DKG. Nonetheless, the tradeoff is an additional multiplicative factor of  $O(f)$  in total communication complexity, i.e.  $O(fn^2)$ , which becomes cubic in the worst case when  $f = O(n)$  but remains quadratic in the best case when  $f = O(1)$ .

### 3.1.4 SPURT

While similar to BRandPiper in achieving absolute unpredictability (rather than probabilistic) by utilizing  $n$  secrets (whose sum becomes the group secret) per round, SPURT takes a different approach where those  $n$  secrets every round are taken not from a leader (from any rounds including previous rounds), but from all the non-leader nodes in a round. A leader, on the other hand, effectively functions to facilitate the overall communication among nodes, lowering the total communication complexity from that in Scrape where all nodes need to broadcast messages of size  $O(n)$  every round.

Given a round leader selected in a round-robin fashion, SPURT proceeds in four phases: commitment, aggregation, agreement, and reconstruction.

**1. Commitment.** During the commitment phase, each node chooses a uniformly random secret and computes shares for the chosen secret using PVSS. Each node then sends all these shares to the leader  $L_r$ . Here on, we can denote the messages sent by nodes to  $L_r$  by PVSS tuples of round  $r$ . Despite having access to PVSS messages from all nodes,  $L_r$  cannot break unpredictability of SPURT. Intuitively, this is because each share is encrypted using the public key of the recipient node, and a zero-knowledge scheme is used for proving consistency.

**2. Aggregation.** In the aggregation phase,  $L_r$  upon receiving PVSS tuples from a node, validates them. Upon receiving and validating PVSS messages from  $t+1$  nodes,  $L_r$  aggregates them using the additive homomorphic property of the underlying polynomial commitment and encryption schemes. If  $p_1, p_2, \dots, p_{t+1}$  are the underlying polynomials from the  $t+1$  valid polynomial commitments,  $L_r$  aggregates them to obtain the commitment to the aggregated polynomial  $\tilde{p}(x) = \sum_{j=1}^{t+1} p_j(x)$ . Moreover,  $L_r$  aggregates the  $t+1$  encrypted shares to obtain encrypted shares corresponding to the aggregated polynomial  $\tilde{p}(x)$ .

**3. Agreement.** After aggregation,  $L_r$  computes a cryptographic digest of the commitment of the aggregated polynomial  $\tilde{p}(x)$ , the identities (or indices) of nodes whose polynomial are aggregated into  $\tilde{p}(x)$ , and the encrypted shares of the secret embedded in  $\tilde{p}(x)$ .  $L_r$  then sends this cryptographic digest to all of the nodes via a broadcast channel. Note that this theoretical concept of a broadcast channel is realized by some SMR protocol.

Additionally, to each node  $i$ ,  $L_r$  sends node  $i$  the entire commitment to the aggregated polynomial  $\tilde{p}(x)$ , and the encrypted shares corresponding to  $\tilde{p}(x)$  using the pair-wise channel between  $i$  and  $L_r$ . Moreover,  $L_r$  also sends the encrypted shares for  $i$  of the original  $t + 1$  polynomials aggregated into  $\tilde{p}(x)$ , and the corresponding NIZK proofs. Note that these shares are encrypted under the public key of  $i$ . In total, during the agreement phase,  $L_r$  sends  $O(\lambda)$  bits of data via the broadcast channel and  $O(\lambda n)$  bits of data to each node using pair-wise private channels.

Each node  $i$ , upon receiving the cryptographic digest over the broadcast channel and private messages from  $L_r$ , validates them to ensure that  $L_r$  did the aggregation phase correctly. For this step, node  $i$  relies on the properties of linear error-correcting code and NIZK proofs forwarded by  $L_r$ . Upon successful validation, node  $i$  starts the reconstruction phase. Else, node  $i$  moves to the next round with the next leader and the cycle continues.

**4. Reconstruction.** When the agreement phase terminates, i.e. all honest nodes agree on the cryptographic digest broadcast by  $L_r$ , every honest node who received the valid shares from  $L_r$  multicasts its aggregated share along with the NIZK proof of its correctness. If the agreement phase terminates successfully, then at least  $t + 1$  honest nodes hold valid shares of the aggregated polynomial  $\tilde{p}(x)$ . Also, all nodes will be able to prove the correctness of their aggregated shares. Moreover, all these nodes start the reconstruction phase within three messages transmission delays. Hence, during the reconstruction phase, every honest node will receive at least  $t + 1$  valid shares of  $\tilde{p}(x)$ , along with their correctness proofs. As a result, every honest node will be able to successfully reconstruct the polynomial via  $h^{\tilde{p}(x)}$ , and hence the output of the randomness beacon for this round.

Besides the fact that SPURT takes a different approach (secrets are received from non-leader nodes rather than leader nodes) to achieve the same goal (absolute unpredictability via  $n$  secrets per round) as BRandPiper, it is noteworthy that bits of data that are broadcasted (as opposed to sent privately) are minimized ( $O(\lambda)$  instead of  $O(\lambda n)$ ) in SPURT. As a result, the total communication complexity is  $O(\lambda n^2)$  in the best case. In the worst case, the additional cost in communication complexity can be incurred during the reconstruction phase, e.g. when some honest nodes might not receive the correct messages from the round leader, in which case other non-leader nodes might have to be queried for a Merkle path of size  $O(\log n)$  and the list of signers of size  $O(n)$ . Thus, the worst-case communication complexity

is  $O(\lambda n^2 \log n + n^3)$ .

### **3.2 DVRF-based**

Distributed verifiable random function (DVRF) is quite naturally a distributed version of VRF, where the VRF's secret key is distributed among a group of participants.

Hash of VUF  $\rightarrow$  VRF

Threshold signature can be interpreted under this bucket

#### **3.2.1 RandHerd**

Involves threshold Schnorr + CoSi (collective signing = multisig aggregation + communication tree) in a fairly complicated way

#### **3.2.2 Dfinity**

League of Entropy's drand

Stalling the network? 100% eventual liveness assumption?

#### **3.2.3 DDH-DVRF**

Does not use pairings

### **3.3 VDF-based**

#### **3.3.1 Extending Commit-Reveal**

Unicorn: pre-VDF

RANDAO + VDF

#### **3.3.2 Extending Public Randomness**

Taking some closing stock price or a block hash + VDF

#### **3.3.3 RandRunner**

A VDF chain involving a group of trapdoor VDFs

## References

- [1] Feldman, Paul. “A practical scheme for non-interactive verifiable secret sharing.” 28th Annual Symposium on Foundations of Computer Science (sfcs 1987). IEEE, 1987.
- [2] Pedersen, Torben Pryds. “A threshold cryptosystem without a trusted party.” Workshop on the Theory and Application of Cryptographic Techniques. Springer, Berlin, Heidelberg, 1991.
- [3] Gennaro, Rosario, et al. “Secure distributed key generation for discrete-log based cryptosystems.” International Conference on the Theory and Applications of Cryptographic Techniques. Springer, Berlin, Heidelberg, 1999.
- [4] Gennaro, Rosario, et al. “Revisiting the distributed key generation for discrete-log based cryptosystems.” RSA Security’03.
- [5] Dodis, Yevgeniy, and Aleksandr Yampolskiy. “A verifiable random function with short proofs and keys.” International Workshop on Public Key Cryptography. Springer, Berlin, Heidelberg, 2005.
- [6] Hanke, Timo, Mahnush Movahedi, and Dominic Williams. “Dfinity technology overview series, consensus system.” arXiv preprint arXiv:1805.04548 (2018).
- [7] Schindler, Philipp, et al. “ETHDKG: Distributed Key Generation with Ethereum Smart Contracts.” IACR Cryptol. ePrint Arch. 2019 (2019): 985.
- [8] Schoenmakers, Berry. “A simple publicly verifiable secret sharing scheme and its application to electronic voting.” Annual International Cryptology Conference. Springer, Berlin, Heidelberg, 1999.
- [9] Syta, Ewa, et al. “Scalable bias-resistant distributed randomness.” 2017 IEEE Symposium on Security and Privacy (SP). Ieee, 2017.
- [10] Cascudo, Ignacio, and Bernardo David. “SCRAPE: Scalable randomness attested by public entities.” International Conference on Applied Cryptography and Network Security. Springer, Cham, 2017.
- [11] Schindler, Philipp, et al. “HydRand: Efficient continuous distributed randomness.” 2020 IEEE Symposium on Security and Privacy (SP). IEEE, 2020.
- [12] Kate, Aniket, Gregory M. Zaverucha, and Ian Goldberg. “Constant-size commitments to polynomials and their applications.” International conference on the theory and application of cryptology and information security. Springer, Berlin, Heidelberg, 2010.

- [13] Galindo, David, et al. “Fully Distributed Verifiable Random Functions and their Application to Decentralised Random Beacons.” IACR Cryptol. ePrint Arch. 2020 (2020): 96.
- [14] Boneh, Dan, and Moni Naor. “Timed commitments.” Annual international cryptology conference. Springer, Berlin, Heidelberg, 2000.
- [15] Schindler, Philipp, et al. “RandRunner: Distributed randomness from trapdoor vdfs with strong uniqueness.” Cryptology ePrint Archive, Report 2020/942.
- [16] Bhat, Adithya, et al. “RandPiper: Reconfiguration-Friendly Random Beacons with Quadratic Communication.” Cryptology ePrint Archive, Report 2020/1590.
- [17] Bonneau, Joseph, Jeremy Clark, and Steven Goldfeder. “On Bitcoin as a public randomness source.” IACR Cryptol. ePrint Arch. 2015 (2015): 1015.
- [18] Cherniaeva, Alisa, Ilia Shirobokov, and Omer Shlomovits. “Homomorphic Encryption Random Beacon.” IACR Cryptol. ePrint Arch. 2019 (2019): 1320.
- [19] Das, Sourav, et al. “SPURT: Scalable Distributed Randomness Beacon with Transparent Setup.” Cryptology ePrint Archive, Report 2021/100. <https://eprint.iacr.org/2021/100>, 2021.
- [20] Cachin, Christian, Klaus Kursawe, and Victor Shoup. “Random oracles in Constantinople: Practical asynchronous Byzantine agreement using cryptography.” Journal of Cryptology 18.3 (2005): 219-246.
- [21] Han, Runchao, et al. “RandChain: Decentralised Randomness Beacon from Sequential Proof-of-Work.” Cryptology ePrint Archive, Report 2020/1033, 2020. <https://eprint.iacr.org/2020/1033>.
- [22] Lindell, Yehuda. “Secure Multiparty Computation (MPC).” IACR Cryptol. ePrint Arch. 2020 (2020): 300.
- [23] Chen, Jing, and Silvio Micali. “Algorand.” arXiv preprint arXiv:1607.01341 (2016).
- [24] Azouvi, Sarah, Patrick McCorry, and Sarah Meiklejohn. “Winning the caucus race: Continuous leader election via public randomness.” arXiv preprint arXiv:1801.07965 (2018).
- [25] Kiayias, Aggelos, et al. “Ouroboros: A provably secure proof-of-stake blockchain protocol.” Annual International Cryptology Conference. Springer, Cham, 2017.

- [26] David, Bernardo, et al. “Ouroboros praos: An adaptively-secure, semi-synchronous proof-of-stake blockchain.” Annual International Conference on the Theory and Applications of Cryptographic Techniques. Springer, Cham, 2018.
- [27] Nakamoto, Satoshi. “A peer-to-peer electronic cash system.” <https://bitcoin.org/bitcoin.pdf> (2008).
- [28] Gagol, Adam, et al. “Aleph: Efficient atomic broadcast in asynchronous networks with byzantine nodes.” Proceedings of the 1st ACM Conference on Advances in Financial Technologies. 2019.
- [29] Bünz, Benedikt, Steven Goldfeder, and Joseph Bonneau. “Proofs-of-delay and randomness beacons in ethereum.” IEEE Security and Privacy on the blockchain (IEEE S&B) (2017).