



Feta: Efficient Threshold Designated-Verifier Zero-Knowledge Proofs

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ABSTRACT

Zero-Knowledge protocols have increasingly become both popular and practical in recent years due to their applicability in many areas such as blockchain systems. Unfortunately, public verifiability and small proof sizes of zero-knowledge protocols currently come at the price of strong assumptions, large prover time, or both, when considering statements with millions of gates. In this regime, the most prover-efficient protocols are in the designated verifier setting, where proofs are only valid to a single party that must keep a secret state.

In this work, we bridge this gap between designated-verifier proofs and public verifiability by *distributing the verifier* efficiently. Here, a set of verifiers can then verify a proof and, if a given threshold t of the n verifiers is honest and trusted, can act as guarantors for the validity of a statement. We achieve this while keeping the concrete efficiency of current designated-verifier proofs, and present constructions that have small concrete computation and communication cost. We present practical protocols in the setting of threshold verifiers with $t < n/4$ and $t < n/3$, for which we give performance figures, showcasing the efficiency of our approach.

CCS CONCEPTS

• **Security and privacy** → *Mathematical foundations of cryptography*; • **Theory of computation** → **Cryptographic protocols**; *Cryptographic primitives*.

KEYWORDS

Zero-Knowledge Proofs, Multi-Party Computation, Threshold Cryptography

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1 INTRODUCTION

A zero-knowledge proof of knowledge (ZKPoK) is an interactive protocol which allows a prover to convince a verifier, given a statement x , that the prover knows a witness w such that the pair (x, w) lies in some NP language \mathcal{L} . This is done in such a way that the verifier learns nothing but the validity of the statement, i.e. they learn nothing about the witness w , only that the prover knows the it. ZKPoKs have a wide range of applications, especially in the burgeoning area of blockchain [17], but also as building blocks of highly efficient signature schemes [13] or to increase the security level of existing cryptographic protocols from passive to active security in a black-box manner [16].

There are various parameters that influence which ZKPoK scheme is suitable for a certain application. For example, when using ZKPoKs for blockchains one needs proofs that are *publicly verifiable* and *non-interactive*; namely the proof is sent in a single message from the prover such that any verifier can verify it. Another common requirement is that they are *succinct*, namely that the proof has size and verification time that is sublinear in the size of the statement.

Therefore, most ZKPoKs such as SNARKs [10] and STARKs [9] that are considered for practical applications within blockchains for instance, are mainly optimized for small proof size and verification time (and are also publicly verifiable and non-interactive). Their drawback is that prover running time can be prohibitive for large statements, i.e. statements expressed by arithmetic circuits with billions of gates. This is because the prover runtime for all current practical succinct schemes has an inherent $\text{polylog}(|x|)$ overhead over the optimal $O(|x|)$ proof time and because prover memory access is not local¹, which leads to inherent slowdowns for increasing $|x|$.

Modern MPC-in-the-Head ZKPoKs such as KKW [21] or Limbo [15] have a proof size that is at least linear in $|x|$, with the unique exception of Ligerio [2] which achieves sub-linear proof for large enough statements. In addition, they usually use a “light” inner proof (which

¹There are theoretical works that achieve linear prover time such as e.g. [23], but to the best of our knowledge they are not concretely efficient.



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is a passively-secure MPC scheme) that requires $O(|x|)$ computation, but must be repeated $s/\log(s)$ times to achieve negligible soundness error where s is the security parameter.

Alternative ZKPoKs for large statements, which also have a practically efficient prover due to small concrete constants, are either based on garbled circuits ([19] and follow-ups) or vOLE-commitments [6, 26, 28]). All of these prover-efficient schemes have the disadvantage that they require the verifier to keep a secret state, i.e. they are designated-verifier ZKPoKs. This means that the proof can only be verified by a single party, who must be identified before the proof is produced. This makes the application in blockchains, where a proof may need to be verified by a set of validator nodes, impossible.

One can mitigate the problem of a designated verifier by distributing the verification among a larger set of parties. Here, each such verifier comes from a pre-defined, possibly large set, leading to a form of distributed designated verifier proof system. Now, if a majority of these verifiers is trusted, the statement of the prover can be accepted as validated by a majority of third parties.

Distributing Verification. This distribution of verification has an impact on the question of what a proof actually is, and also changes how protocols for such a setting can be designed.

- If the verifier is distributed, an adversary may corrupt multiple verifiers, in addition to the prover, in order to convince honest verifiers of the validity of a false statement. This means that soundness must be redefined to take this into consideration.
- When a proof is rejected, this might happen either if a prover does not have a proof or if it is honest, but verifiers may prevent successful verification of a proof. Hence, honest verifiers may want to distinguish these cases in order to not blame an honest prover or verifier as corrupt. So in the case of dishonest behaviour a security definition may require that honest verifiers do not just abort, but they also identify one (or more) of the cheating parties. This enables a form of cheater elimination.
- The distributed nature of the verifier may allow to obtain more efficient protocols: while in standard zero-knowledge the verifier must always be considered as fully corrupted, we may now be ok with only maintaining zero-knowledge if a strict subset of the verifiers does not collude.

1.1 Related Work

Thresholdizing in zero-knowledge proofs has a long history. The earliest works are those of [12] and [7], both from 1991. In the work of [12] the verifiers do not need to agree on the validity of the proof, and in addition do not communicate directly. Our work is closer in spirit to that of [7], although with a modern security definition and practical, concrete efficiency. In particular our security notion is UC-based, and captures issues related to a dishonest prover and dishonest verifiers colluding, as well as (by definition) providing a proof-of-knowledge. We also require that cheaters are identified which we feel is important in applications (and is missing in all prior work). The construction in [7] is based, unsurprisingly for its time, on Verifiable Secret Sharing (VSS), thus the protocol is highly inefficient compared to our more modern approach. Whilst VSS

enables identifiable abort, it is unclear in [7] how (or even if) this can be used to identify if a verifier and prover collaborate to cheat.

In the 2000's interests continued in this problem, but focused on proofs related to languages based on discrete logarithms (for example proving that certain discrete logarithm-based commitments satisfied some given properties). Work in this vein included [1], which focused on statements related to relations between discrete logarithms. Their application are statements tailored for systems using VSS in MPC. We essentially lift the definitions of [1] to a more general UC setting for arbitrary adversary structures, as well as extend the definitions to general languages (and not just those related to discrete logarithms).

Conceptually, our setting bears resemblance to the one considered in the MPC-in-the-head paradigm [18] where the proof is verified by a set of simulated verifiers. Compared to [18] we require that an adversarial prover can only cooperate with a small set of corrupt verifiers, as we assume a majority of verifiers to be honest.

There are other related works, which are similar but distinct from our own work. For example, one related notion is the concept of distributed zero-knowledge from [11], which looks at the case where the *statement* x is unknown to any given verifier, and is instead secret shared. The protocols in that work only support a limited class of languages, and do not consider identifiable abort, and so are vulnerable to denial-of-service attacks from a malicious verifier. Our notion can be seen as orthogonal to Multi-Prover Interactive Proofs [8], where multiple provers act independently to convince a verifier. Our notion is also complementary to the setting considered in [27] where the witness w is shared amongst a set of provers. Instead, we only have one prover and w is shared among the verifiers.

A relatively recent paper [4] focuses on reducing the total amount of entropy needed by a set of verifiers, if all verifiers are to verify the proof. This is orthogonal to our work, as we require a joint/distributed verification where some verifiers can be dishonest. However, the idea of reducing the entropy requirement would be an interesting aspect to consider in the future. As would extending the ideas of [4] to more general problem statements, since [4] focuses on languages based on discrete logarithms.

Another interesting orthogonal direction to our work is that of “Fair-Zero Knowledge” introduced in [24]. In this work a distributed-verifier notion is presented, where a prover might leak the secret to a dishonest verifiers via a subliminal channel. Nevertheless, since our “online” proof stage only requires broadcast interaction from the prover to the verifiers, fairness as in [24] for our type of proof systems might be interesting line for future work.

The renewed interest in the distributed verifier setting is shown by two recent papers by Yang et al. [29] and Applebaum et al. [3]. Both works consider the case where a majority of verifiers are honest. Applebaum et al. focus more on the theoretical side and study the minimal assumptions needed to achieve round-optimal distributed verifier protocols; the work of Yang et al. is similar to our approach and oriented to real-world efficiency, however does not present an implementation and does not consider cheater identification, thus only achieving security with selective abort.

1.2 Our Contribution

In this work, we formalize the notion of Distributed Verifier ZKPoKs (DV-ZKPoKs) in the UC framework. We provide multiple constructions of such protocols, all with cheater identification, that are secure against different thresholds of corrupted verifiers².

New definitions. We first present a formal definition of what it means for a DV-ZKPoK to be secure in the UC framework. Let us first redefine the three standard properties of ZKPoKs to be applicable to the threshold setting:

Distributed Correctness: If the prover has a witness, then the honest parties either accept the proof or identify the same corrupted verifiers that interfered with the proof.

Distributed Soundness: If the prover does not have a witness then honest verifiers only accept with negligible probability, given not too many other verifiers are corrupted. In addition the honest verifiers either agree that the prover does not have a witness, or will identify a set of corrupted verifiers.

Distributed Zero-Knowledge: The corrupted verifiers learn no new information beyond the fact that the statement is true.

Our definition will allow different adversarial structures for all of these properties. This means that our definition also encapsulates protocols where e.g. soundness breaks down if just one verifier is corrupted, but which are zero-knowledge even if all verifiers are corrupted.

There are a number of “naive” protocols which enable such distributed verifier zero-knowledge proofs using existing techniques. We will describe some of these protocols, showing the applicability of our framework.

New protocols. We then present two efficient DV-ZKPoK protocols together with necessary preprocessing protocols. These protocols are optimized for $t < n/4$ and $t < n/3$ corruptions, respectively, where n is the number of verifiers and t is the number of corrupted verifiers. Our protocols are plausibly post-quantum secure, and require as setup assumptions a PKI as well as a broadcast channel. The latter can easily be implemented if $t < n/3$ information theoretically.

Implementations. We have implemented our protocols in C++, showing concretely efficiency both in terms of prover and verifier time. For example, for the case of $t < n/4$, the combined pre-processing and prover time for proving knowledge of the pre-image of a single SHA-256 evaluation with $n = 5$ verifiers is about 10 milliseconds, with a proof time of around 7 milliseconds. The verification time is under 15 milliseconds. A circuit with a million AND gates requires a total proof time of 96 milliseconds pre-processing and 30 milliseconds for the proof generation. The verification time is 90 milliseconds. For $n = 100$ verifiers and $t = 20$ the million AND gate circuit times become 431 milliseconds for pre-processing, 176 milliseconds to generate a proof and 219 milliseconds for the 100 verifiers to verify it. This is with a single threaded implementation of our protocols.

²In our construction, the single (cheesy) verifier of the Mac-and-Cheese protocol [6] has been crumbled into a large set of smaller verifiers. Thus, our protocol name *Feta*.

As remarked above the prior works on distributed verifier zero-knowledge have all been for discrete logarithm based languages, as opposed to the general languages considered in our paper. In addition, they have considered different and often less general security requirements, as we outlined above. Thus to compare our implementation we are left, with the admittedly unsatisfactory situation of, comparison against either publicly verifiable or designated verifier proof systems.

Our run times are all significantly smaller than the single instance publicly-verifiable proofs of similar SHA-256 pre-images, using a system such as Ligerio [2]. Using machines less powerful than the ones we used in our experiments, [2] give prover and verification times for a single pre-image of a SHA-256 evaluation of over 100 milliseconds. Our proof size, excluding pre-processing, is also significantly smaller (8 KBytes vs 100's of KBytes for Ligerio). Note, Ligerio provides a publicly verifiable proof as opposed to our distributed designated verifier proofs.

The Limbo system [15], which again provides publicly verifiable proofs, reports single threaded prover and verifier times for the same circuit of 50 milliseconds, using machines comparable to the ones in our experiments, with their proof sizes being 42 KBytes.

The Mac-n-Cheese [26] and Quicksilver protocols [6], which provide designated verifier proofs using a single threaded implementation can achieve around 7 million AND gates per second in terms of prover/verification time. Translating this to the 22.573 AND gate SHA-256 circuit would equate to a prover/verification time of 3 milliseconds.

Thus, we see our prover/verification time of 6.5/10 milliseconds, for the SHA-256 circuit in the distributed verifier case, provides a compromise between slower publicly verifiable proofs and faster designated verifier proofs.

The protocol for the case of $t < n/3$ is slightly less efficient, but still provides a highly efficient methodology for performing distributed verifier zero-knowledge proofs. Also in this case both prover and verification time are significantly smaller than in publicly verifiable schemes like Ligerio and Limbo.

Hence, we see that our notion of distributed designated verifier proofs can enable more efficient practical zero-knowledge proofs when compared to publicly verifiable proofs.

1.3 Applications

Protocols with distributed verification have a number of applications, mainly in blockchains.

- For *permissioned blockchains*, which are popular for use in companies, the validators (usually) authenticate the next block via majority voting. Such validators could act as the distributed verifiers for a proof. In such a situation the total number of validators is a handful, and thus the techniques of this paper could be used to validate a proof *before* the next block is authenticated by the chosen validator.
- In *permissionless blockchains* with oracles (i.e. groups of parties that vouch for certain external facts), the oracle parties could serve as verifiers for our proofs. The oracles are e.g. trusted by a smart contract, and our distributed verifier means that this trust can be minimized in the case of proof

verification. Oracles are sometimes also used in Layer-2 protocols on the blockchain. For example, in commit-chains like NOCUST [22], there is an operator responsible (i.e. an oracle) for committing the latest state of user account balances to the main blockchain every epoch. In the case of optimistic rollups (as in Arbitrum [20] and Optimism³), the verification and state-progression are done off-chain by the validator (i.e. an oracle) as well, while the final states (assertions) are published on the blockchain. Our distributed verifier proofs can act as a balance between optimistic rollups and full ZK-rollups. In all cases, the number of such oracles is relatively small and so the techniques of this paper could be applied.

More generally, zero-knowledge with distributed verification can be used in all zero-knowledge applications where the verifiers are known ahead of time.

1.4 Techniques

On a high level, our protocols can be described using the following four-step paradigm:

- (1) The verifiers create consistent commitments to random values r_i such that only the prover can open these later. Here, if t or less verifiers are corrupted, then they cannot reconstruct the committed values themselves.
- (2) The verifiers and the prover check together that the commitments to the random values are indeed consistent among all verifiers, and that the prover knows the openings. If not, then cheaters are identified. If they are consistent, then the preprocessing of the DV-ZKPoK is considered as finished.
- (3) In the online phase, the prover uses the r_i to commit to w as well as auxiliary information necessary to show that $(x, w) \in R$. This commitment can ideally be done by sending one message via a broadcast channel.
- (4) Upon the prover having finished committing, the verifiers perform a proof verification step. Here we aim for a “cheap” proof verification that only requires the verifiers to communicate in $O(1)$ rounds, with a message complexity that is sublinear in $|x|$ or $|w|$ as well.

To achieve this, our “preprocessing” phase lets the verifiers create many random Shamir secret sharings as commitments, where the prover only learns the secret being shared. Given the linearity of this secret sharing, consistency can easily be established using a linear test. This test only requires communication that scales in the number of parties but not $|x|$ or $|w|$. Moreover, we show that cheater identification can be achieved by additionally signing certain messages in the preprocessing protocol.

In our online phase, our protocols let the prover commit both to w as well as the intermediate wire values for a circuit C that evaluates to 0 iff w is a valid witness for the statement x . The verifiers re-evaluate C based on the committed w using the homomorphic properties of the commitment/secret sharing and check if the intermediate wire values are consistent with w and that the output of $C(w)$ is 0. This only requires a depth-1 circuit to be evaluated by the verifiers.

³<https://community.optimism.io>

In the first protocol (for $t < n/4$) we make use of error-detecting properties of a Reed-Solomon code/Shamir sharing. The linear gates are free to evaluate as the Shamir sharing is linearly homomorphic, while the multiplication is performed by each verifier multiplying the input shares of a multiplication gate locally. The bound of $t < n/4$ comes from having to perform error detection on product codes (coming from degree $2 \cdot t$ polynomials stemming from the share multiplication), which is necessary to detect cheating during the multiplication protocol by a verifier.

Our second protocol (for $t < n/3$) is slightly more complex and avoids the verifiers having to multiply shares altogether. Instead, we let the prover commit to slightly more data and use a checking procedure for multiplications that is based on the Schwarz-Zippel Lemma, similarly to [11]. This means that multiplication checks only require linear operations.

2 PRELIMINARIES

2.1 Shamir Sharing

Our protocols are built on top of Shamir’s secret-sharing scheme [25]. We briefly recap on it here in order to fix the notation we will use in the rest of the paper.

A secret s , in a finite field \mathbb{F} , is shared amongst n parties $\mathcal{P} = \{P_1, \dots, P_n\}$ by the sharing party defining a random degree t polynomial $f_s(X)$ whose constant term is the value s . Assuming $n > |\mathbb{F}|$ and that the integers $\{1, \dots, n\}$ are mapped to distinct non-zero values $\alpha_1, \dots, \alpha_n$ in \mathbb{F} , each party P_i is given the share $s^{(i)} = f_s(\alpha_i) \in \mathbb{F}$. We denote such a sharing by $\langle s \rangle_t$.

Note that this secret sharing scheme is linear, namely given $\beta, \delta, \gamma \in \mathbb{F}$ and two sharings $\langle x \rangle_t$ and $\langle y \rangle_t$, both of degree t , parties can locally produce the sharing $\langle z \rangle_t$, where $z = \beta \cdot x + \delta \cdot y + \gamma$, by computing

$$z^{(i)} = \beta \cdot x^{(i)} + \delta \cdot y^{(i)} + \gamma.$$

Also note that one can linearly combine sharings of different degrees to produce a sharing of the maximal degree, i.e. given $\langle x \rangle_{t_1}$ and $\langle y \rangle_{t_2}$ then one can locally produce $\langle x + y \rangle_t$, where $t = \max(t_1, t_2)$, which we shall write as $\langle x \rangle_{t_1} + \langle y \rangle_{t_2}$.

Reconstruction of a secret s , shared via $\langle s \rangle_t$, requires $t+1$ correct share values from different parties. It is well known that Shamir’s secret sharing scheme defined as above is equivalent to a Reed-Solomon code $[n, t+1, n-t]$ over \mathbb{F} , where the shares $(f_s(\alpha_1), \dots, f_s(\alpha_n))$ are viewed as a codeword. In particular, when the number of dishonest parties is bounded by d and $n > t + 2 \cdot d$, the parties can robustly reconstruct a shared value $\langle s \rangle_t$, so that any party who lies about their sharings will be detected. In one of our protocols we will use the fact that, if $n > 4 \cdot t$ and $d < t$ we can robustly reconstruct a value for a sharing of degree $2 \cdot t$.

Assuming $n > t + 2 \cdot d$, we denote by $\text{RobustReconstruct}(\langle s \rangle_t, d)$ the reconstruction algorithm associated with Shamir’s scheme which outputs a pair (s, flag) , where either $\text{flag} = (\text{correct}, \emptyset)$, indicating that all the shares are consistent with a degree t sharing, or $\text{flag} = (\text{incorrect}, \mathcal{D})$ where \mathcal{D} indicates the parties who input an inconsistent shares.

2.2 Digital Signatures

Our basic protocols will make use of digital signatures, for which we use the following two standard definitions.

Definition 2.1. A digital signature scheme for message space \mathcal{M} is given by the polynomial time algorithms (KeyGen, Sign, Verify).

- **KeyGen**(1^λ): On input a security parameter λ this randomized algorithm outputs a public/private key pair $(\mathfrak{pk}, \mathfrak{sk})$.
- **Sign**(\mathfrak{sk}, m): On input of private key \mathfrak{sk} and a message $m \in \mathcal{M}$, this (potentially) randomized algorithm outputs a digital signature σ .
- **Verify**(\mathfrak{pk}, σ, m): On input of a public key \mathfrak{pk} , a message m and a purported signature σ , this algorithm outputs either true (meaning accept the signature) or false (meaning reject the signature).

A digital signature scheme is said to be correct if for each $m \leftarrow \mathcal{M}$ and $(\mathfrak{pk}, \mathfrak{sk}) \leftarrow \text{KeyGen}(1^\lambda)$, $\text{Verify}(\mathfrak{pk}, \text{Sign}(\mathfrak{sk}, m), m) = \text{true}$.

A digital signature scheme is said to be UF-CMA secure if the probability of any adversary \mathcal{A} winning the following game is negligible in λ

- (1) $(\mathfrak{pk}, \mathfrak{sk}) \leftarrow \text{KeyGen}(1^\lambda)$.
- (2) $(m^*, \sigma^*) \leftarrow \mathcal{A}^{\text{Sign}(\mathfrak{sk}, \cdot)}(\mathfrak{pk})$.
- (3) Output ‘win’ if and only if $\text{Verify}(\mathfrak{pk}, \sigma^*, m^*) = \text{true}$ and m^* was not queried to \mathcal{A} ’s signing oracle.

2.3 Zero-knowledge Proofs

A standard zero-knowledge proof takes a statement x and a witness w from some NP relation \mathcal{R} . The prover \mathcal{P} holds the pair $(x, w) \in \mathcal{R}$, whilst the verifier only has x . The goal of a zero-knowledge proof (of knowledge) is to convince the verifier that x is in the language $\mathcal{L}_{\mathcal{R}}$ of statements that have a witness in \mathcal{R} . This is done by asserting that the prover holds w such that $(x, w) \in \mathcal{R}$, while no information about w (bar the fact that the prover knows it) is revealed to the verifier. Informally, a zero-knowledge proof has three security properties:

- Correctness:** If $(x, w) \in \mathcal{R}$ then \mathcal{V} always accepts.
- Soundness:** If \mathcal{P} does not have w then \mathcal{V} only accepts with negligible probability.
- Zero-Knowledge:** There exists a simulator \mathcal{S} that on input x can create transcripts of protocol instances between \mathcal{P} and \mathcal{V} that make \mathcal{V} accept.

In the designated verifier setting, the soundness only holds for a verifier that has a secret state.

2.4 Schwarz-Zippel Lemma

One of our protocols will make use of the Schwarz-Zippel lemma for univariate polynomials, which we state here.

LEMMA 2.2 (SCHWARTZ-ZIPPEL LEMMA). *Let $F \in \mathbb{F}[X]$ denote a non-zero polynomial of degree d over a field \mathbb{F} . Let S denote a finite subset of elements of \mathbb{F} . If one selects $r \in S$ uniformly at random then*

$$\Pr[F(r) = 0] \leq \frac{d}{|S|}.$$

2.5 Coin Flipping

We will utilize at various points the ideal functionality $\mathcal{F}_{\text{Rand}}(\mathcal{P}, M, \mathbb{F})$, described in Fig. 1. This functionality allows a set of parties \mathcal{P} to

sample M uniformly random values from a finite field \mathbb{F} such that each party learns these. It does this in a manner which has identifiable abort, in the case that the adversary aborts the execution of the protocol. The implementation of this functionality is standard: The parties agree on a shared single seed using a non-interactive commitment via broadcast, then open via broadcast, and then the seed is expanded into the desired number of random values from \mathbb{F} using a PRG.

The Ideal $\mathcal{F}_{\text{Rand}}(\mathcal{P}, M, \mathbb{F})$ Functionality

On input (Rand, cnt) from all parties in \mathcal{P} , if the counter value is the same for all parties and has not been used before:

- (1) Sample $r_i \leftarrow \mathbb{F}$ for $i \in [M]$.
- (2) The values r_i are sent to the adversary, and the functionality waits for its input.
- (3) If the input is Deliver then the values r_i are sent to all parties. Otherwise the adversary will return a non-trivial subset C_A of the dishonest parties. The value (Abort, C_A) is returned to all parties.

Figure 1: Functionality $\mathcal{F}_{\text{Rand}}(\mathcal{P}, M)$

3 DISTRIBUTED VERIFIER ZERO-KNOWLEDGE PROOFS

Our definition of *Distributed Verifier Zero-Knowledge Proofs* (DV-ZKPoKs) aims to generalize the notion of a *Designated Verifier Zero-Knowledge Proof* to the threshold setting. Namely, we will have a set of designated verifiers $\mathcal{V}_1, \dots, \mathcal{V}_n$ who jointly verify the correctness of the proof using an interactive protocol.

3.1 Zero-Knowledge in the Threshold Setting

As mentioned in Section 1 in a distributed verifier setting there might exist multiple verifiers \mathcal{V}_i , some of whom may collaborate with a potentially corrupt prover \mathcal{P} . For a DV-ZKPoK we therefore get the following intuitive properties.

- Distributed Correctness:** If $(x, w) \in \mathcal{R}$ then either all honest verifiers \mathcal{V} always accept or all honest verifiers agree on a set of cheating verifiers C_A .
- Distributed Soundness:** If \mathcal{P} does not have w then honest verifiers only accept with negligible probability.
- Distributed Zero-Knowledge:** There exists a simulator \mathcal{S} that on input x can create transcripts of protocol instances between \mathcal{P} and verifiers $\mathcal{V}_1, \dots, \mathcal{V}_n$ that make verifiers accept.

Let $\mathcal{V} = \{\mathcal{V}_1, \dots, \mathcal{V}_n\}$ denote the set of verifiers. An *access structure* Γ on \mathcal{V} is a monotonically increasing subset of $2^{\mathcal{V}}$, i.e., if $S \in \Gamma$ then we have $T \in \Gamma$ for all T such that $S \subseteq T \subseteq \mathcal{V}$. The *adversary structure* Δ associated with Γ is the set of all sets $\mathcal{V} \setminus S$ for $S \in \Gamma$.

When dealing with a potentially dishonest prover and a subset of potentially dishonest verifiers, we can consider three different access structures related to the three different properties of ZK proofs.

We let the relevant access structures, for the potentially dishonest verifiers, be denoted by Γ_C (for Correctness), Γ_S (for Soundness) and Γ_Z (for Zero-Knowledge). With their different associated adversary structures being Δ_C , Δ_S and Δ_Z . We allow different access structures to provide better flexibility in applications, as well as more flexibility in designing protocols. To aid the reader one could initially think of the threshold case of $\Gamma_C = \Gamma_S = \Gamma_Z$ being all subsets of size greater than $n - t$, and $\Delta_C = \Delta_S = \Delta_Z$ being all subsets of the verifiers of size less than or equal to t .

We let \mathcal{V}_D denote the precise set of dishonest verifiers in a given protocol instance. We desire that at the end of the protocol, the verifiers either output Abort, Success or Fail. Here, Success or Fail imply that the proof was correct or not, respectively, while Abort means that some verifiers or the prover may have aborted. In all cases each honest party P will obtain a non-empty list of parties who aborted.

3.1.1 Distributed Correctness. We first discuss correctness; as usual this assumes an honest prover. In the case of $\mathcal{V}_D \notin \Delta_C$ then the adversary has enough power to break correctness. In this case some honest verifiers will abort, some will accept and some will fail - no common guarantees can be made. Note in the case when $\mathcal{V}_D \notin \Delta_C$, the set C that each honest verifier identifies as corrupt parties in the case of abort, can be different for each of them, and they may even identify honest parties as corrupted. In the case of failure or success the honest verifiers may in addition identify cheating verifiers. This is captured by the procedure Breakdown() in our ideal functionality \mathcal{F}_{DV-ZK} , which can be found in Fig. 2.

However, when $\mathcal{V}_D \in \Delta_C$ then the parties obtain consensus of output: either all honest verifiers output Success or they all output Abort. In the latter case, the verifiers identify a set $C_A \neq \emptyset$ of dishonest verifiers which is the same for each honest verifier. Consensus of output when $\mathcal{V}_D \in \Delta_C$ is needed to avoid denial-of-service attacks where a single dishonest verifier can make the honest verifiers reject a valid proof. This is captured by the procedure CompleteWithAbort() in our ideal functionality \mathcal{F}_{DV-ZK} .

Note that cheater identification is not necessary in the case of honest majority access structures Γ_C . This is because a simple majority vote will result in the honest verifiers accepting the proof (assuming consensus on accept). In the case of dishonest majority the ability for the honest parties to identify a single dishonest party (with consensus) will act as a deterrent to verifiers to act dishonestly. Thus even in the case of acceptance we allow the identification of dishonest verifiers so as to allow our functionality to capture the dishonest majority case.

3.1.2 Distributed Soundness. Soundness considers the case of a dishonest prover. We require that if $\mathcal{V}_D \notin \Delta_S$ then the adversary can get the honest verifiers to output anything it wants. Which is again captured by the procedure Breakdown() in Fig. 2.

As we require the prover to input a witness w , if $\mathcal{V}_D \in \Delta_S$ and if $(x, w) \in \mathcal{R}$ then the *worst* \mathcal{P} can do is get some honest verifiers to abort and identify a cheating party. This is again captured by the procedure CompleteWithAbort() in Fig. 2. On the other hand, if $(x, w) \notin \mathcal{R}$ then the *best* \mathcal{P} can achieve is to get some honest verifiers to abort and identify a cheating party (which could include the prover). Again, this is captured by the procedure FailWithAbort() in Fig. 2.

3.1.3 Distributed Zero-Knowledge. Finally in the case of a honest prover, if $\mathcal{V}_D \notin \Delta_Z$ then the adversary has enough power to break the zero-knowledge property and potentially learn information about w . But if $\mathcal{V}_D \in \Delta_Z$ then the adversary cannot learn w .

It is straightforward to change \mathcal{F}_{DV-ZK} so that it only has unanimous abort. Another interesting strengthening is to not permit identifiable aborts if $\mathcal{V}_D \in \Delta_C$. Since this setting seems to be not achievable if a majority of verifiers is corrupted for any interesting protocol⁴, we have opted for a definition that is achievable in both the honest and dishonest-majority setting.

In the full version we present some trivial (but potentially inefficient or not necessarily suitably secure) protocols which illustrate the definition captured by \mathcal{F}_{DV-ZK} .

4 PREPROCESSING FOR DISTRIBUTED PROOFS WITH HONEST MAJORITY $t < n/2$

We begin by outlining the preprocessing phase for our proof in the presence of a honest majority. This preprocessing can then be used with the actual online phases of the proof, which require $t < n/4$ (Section 5) or $t < n/3$ (Section 6) corruptions. The ideal preprocessing functionality $\mathcal{F}_{Prep}^{t,n}$ is described in Fig. 3. Both the protocols and functionality are defined over an extension field of appropriate degree to allow for Shamir secret sharing with n parties. We focus on the case of a binary field \mathbb{F}_{2^k} with $2^k > n$, but our protocols are easily adapted to \mathbb{F}_q for any $q > n$. We also use a repetition factor ρ such that $2^{k \cdot \rho} > 2^{\text{sec}}$, where sec is our security parameter.

In the protocol $\Pi_{Prep}^{t,n}$ that implements the preprocessing functionality, and given in Fig. 4, each of the n verifiers \mathcal{V}_i samples a random r_i and sends a share of $\langle r_i \rangle_t$ to each other verifier and r_i to the prover \mathcal{P} . These values are checked for consistency by forming a random linear combination using random values α_i . This random linear combination simultaneously guarantees the correctness of the underlying secret known to the prover and the consistency of the shares on a degree t polynomial. It can be repeated to achieve negligible soundness error. Next, let $\langle \vec{r} \rangle_t$ be the vector representing all sharings made by the verifiers, and let M_t be an $(n - t) \times n$ Vandermonde matrix. The verifiers locally compute the sharings $\langle \vec{s} \rangle_t = M_t \cdot \langle \vec{r} \rangle_t$, while the prover computes $\vec{s} = M_t \cdot \vec{r}$. This randomness extraction ensures that out of these n shares, of which t are known to the adversary, $n - t$ uniformly random shares are recovered, unknown to any other party than the prover. Several instances of this preprocessing phase are performed in parallel to obtain more than $n - t$ secret sharings, with (at least) an additional ρ sharings produced so as to verify the entire production is correct.

The protocol assumes a PKI in which each verifier \mathcal{V}_i has a public key pk_i and a signing key sk_i , which enables them to authenticate sent messages m with a digital signature $\text{Sign}(\text{sk}_i, m)$. In the case when the consistency check fails, this allows parties to reveal the shares that they obtained from each other. This means that parties can identify cheaters by either identifying incorrectly generated

⁴It is achievable if the prover broadcasts a publicly verifiable proof to all verifiers. If the verifiers need to use a secret-shared state to validate the proof, then dishonest-majority completeness implies that $< n/2$ verifiers are sufficient to perform this validation and possibly reconstruct the secret state. But then, this implies that $< n/2$ corrupted verifiers can use their knowledge to aid a dishonest prover to break soundness.

Functionality $\mathcal{F}_{\text{DV-ZK}}$

This functionality communicates with $n + 1$ parties $\mathcal{P}, \mathcal{V}_1, \dots, \mathcal{V}_n$ as well as the ideal adversary \mathcal{S} . We call \mathcal{P} the prover and $\mathcal{V} = \{\mathcal{V}_1, \dots, \mathcal{V}_n\}$ the verifiers. For simplicity, we write $\mathcal{W} = \mathcal{V} \cup \{\mathcal{P}\}$. The functionality is instantiated with descriptions of three access structures $\Gamma_C, \Gamma_S, \Gamma_Z \subseteq 2^{\mathcal{V}}$, and their associated adversary structures Δ_C, Δ_S and Δ_Z . The adversary structures denote which parties \mathcal{S} can corrupt without leading to a loss of correctness, soundness or zero-knowledge. Let `init` be a flag that is initially \perp .

Corrupt: Before any other command, \mathcal{S} sends `(Corrupt, \mathcal{D})` where $\mathcal{D} \subseteq \mathcal{W}$. Let $\mathcal{H} = \mathcal{W} \setminus \mathcal{D}$. If $\mathcal{P} \in \mathcal{D}$ then we call the prover “corrupted”, otherwise “honest”. We call $\mathcal{V}_{\mathcal{D}} = \mathcal{V} \cap \mathcal{D}$ the corrupted verifiers and $\mathcal{V}_{\mathcal{H}} = \mathcal{V} \setminus \mathcal{V}_{\mathcal{D}}$ the honest verifiers.

Init: On input `(Init)` by all parties in \mathcal{H} :

- (1) Send `(Init?)` to \mathcal{S} . If \mathcal{S} responds with `(ok)` then send `(InitOK)` to all parties in \mathcal{H} and set `init` $\leftarrow \top$. Otherwise send `(Abort)` to all parties in \mathcal{H} .

ProveHonest: On input `(Prove, x, w)` by $\mathcal{P} \in \mathcal{H}$ as well as `(Prove, x)` by all parties in $\mathcal{V}_{\mathcal{H}}$, if `init` = \top and if $(x, w) \in R_L$:

- (1) If $\mathcal{V}_{\mathcal{D}} \notin \Delta_Z$ then send `(Prove?, x, w)` to \mathcal{S} , otherwise send `(Prove?, x)`.
 - If $\mathcal{V}_{\mathcal{D}} \notin \Delta_C$ then run `Breakdown()`.
 - If $\mathcal{V}_{\mathcal{D}} \in \Delta_C$ then run `CompleteWithAbort()`.

ProveDishonest: On input `(Prove, x, w)` by \mathcal{S} if $\mathcal{P} \in \mathcal{D}$ as well as `(Prove, x)` by all parties in $\mathcal{V}_{\mathcal{H}}$ and if `init` = \top :

- If $\mathcal{V}_{\mathcal{D}} \notin \Delta_S$ or $\mathcal{V}_{\mathcal{D}} \notin \Delta_C$ then run `Breakdown()`.
- If $\mathcal{V}_{\mathcal{D}} \in \Delta_S, \mathcal{V}_{\mathcal{D}} \in \Delta_C$ and $(x, w) \in R_L$ then run `CompleteWithAbort()`.
- If $\mathcal{V}_{\mathcal{D}} \in \Delta_S, \mathcal{V}_{\mathcal{D}} \in \Delta_C$ and $(x, w) \notin R_L$ then run `FailWithAbort()`.

Method Breakdown():

- (1) Wait for a message `(Abort, A, F, S, C)` from \mathcal{S} where A, F, S are disjoint sets, $A \cup F \cup S = \mathcal{H}$, $C_A : \mathcal{H} \rightarrow 2^{\mathcal{W}}$.
- (2) Send `(Abort, $x, C_A(P)$)` to each $P \in A$, `(Fail, $x, C_A(P)$)` to each $P \in F$ and `(Success, $x, C_A(P)$)` to each $P \in S$.

Method CompleteWithAbort():

- (1) Wait for a message `(Abort, b, C_A)` from \mathcal{S} where $C_A \subseteq \mathcal{V}_{\mathcal{D}}$, $b \in \{0, 1\}$ and $C_A \neq \emptyset$ if $b = 0$.
- (2) If $b = 0$ then send `(Abort, x, C_A)` to each $P \in \mathcal{H}$, otherwise send `(Success, x, C_A)` to each $P \in \mathcal{H}$.

Method FailWithAbort():

- (1) Wait for a message `(Abort, b, C_A)` from \mathcal{S} where $C_A \subseteq \mathcal{V}_{\mathcal{D}}$, $b \in \{0, 1\}$ and $C_A \neq \emptyset$ if $b = 0$.
- (2) If $b = 0$ then send `(Abort, x, C_A)` to each $P \in \mathcal{H}$, otherwise send `(Fail, x, C_A)` to each $P \in \mathcal{H}$.

Figure 2: Functionality $\mathcal{F}_{\text{DV-ZK}}$ for Distributed-Verifier ZK

Functionality $\mathcal{F}_{\text{Prep}}^{t,n}$

This functionality communicates with $n + 1$ parties $\mathcal{P}, \mathcal{V}_1, \dots, \mathcal{V}_n$ as well as the ideal adversary \mathcal{S} , where \mathcal{P} denotes the prover and $\mathcal{V} = \{\mathcal{V}_1, \dots, \mathcal{V}_n\}$ the verifiers. Let $\mathcal{W} = \mathcal{V} \cup \{\mathcal{P}\}$ and $t < n/2$.

Corrupt: Before any other command, \mathcal{S} sends `(Corrupt, \mathcal{D})` where $\mathcal{D} \subseteq \mathcal{W}$. Let $\mathcal{H} = \mathcal{W} \setminus \mathcal{D}$. If $\mathcal{P} \in \mathcal{D}$ then we call the prover “corrupted”, otherwise “honest”. We call $\mathcal{V}_{\mathcal{D}} = \mathcal{V} \cap \mathcal{D}$ the corrupted verifiers and $\mathcal{V}_{\mathcal{H}} = \mathcal{V} \setminus \mathcal{V}_{\mathcal{D}}$ the honest verifiers.

Distribute Shares: On input `(Shares, n_S)` from all parties

- (1) Sample n_S random values $s_i \in \mathbb{F}_{2^k}$ for $i \in [n_S]$.
- (2) If \mathcal{P} is corrupted then send $\{s_i\}_{i \in [n_S]}$ to \mathcal{S} .
- (3) Wait for a message `(Abort, C_A)` from \mathcal{S} where $\emptyset \neq C_A \subseteq \mathcal{D}$ or `(Continue, $\{\hat{s}_i^{(p)}\}_{p \in \mathcal{V}_{\mathcal{D}}, i \in [n_S]}$)`.
 - If \mathcal{S} inputs `Abort` then `(Abort, C_A)` is returned to each party in \mathcal{H} and the functionality aborts.
 - If \mathcal{S} inputs `Continue` then generate a Shamir sharing of s_i of degree t for each $i \in [n_H]$, which we denote by $\langle s_i \rangle_t$. The individual Shamir shares are denoted by $s_i^{(j)} \in \mathbb{F}_{2^k}$ for $j \in [n]$. The sharing is chosen so that $s_i^{(j)} = \hat{s}_i^{(j)}$. The values s_i are passed to \mathcal{P} if $\mathcal{P} \in \mathcal{H}$, whilst the values $s_i^{(p)}$ are given to \mathcal{V}_p for $p \in \mathcal{V}_{\mathcal{H}}$.

Figure 3: Functionality $\mathcal{F}_{\text{Prep}}^{t,n}$ for preprocessing in the case when $t < n/2$

Protocol $\Pi_{\text{Prep}}^{t,n}$

We let M_t be an $(n-t) \times n$ Vandermonde matrix for randomness extraction. The protocol is parametrized by the number of verifiers n , number of corruptions $t < n/2$ and two integers n_S and ρ .

The protocol uses the hybrid functionality $\mathcal{F}_{\text{Rand}}$. If $\mathcal{F}_{\text{Rand}}$ sends (Abort, C_A) then each party in the protocol outputs (Abort, C_A) and terminates.

Distribute Shares:

(1) Each party $\mathcal{V}_i \in \mathcal{V}$ executes the following protocol:

(a) For $j \in [[(n_S + \rho)/(n-t)]]$ do

(i) Sample $r_{i,j} \in \mathbb{F}_{2^k}$ and generate a sharing $\langle r_{i,j} \rangle_t$.

(ii) Send $(r_{i,j}^{(p)}, \text{Sign}(\mathfrak{s}\mathfrak{f}_i, r_{i,j}^{(p)}))$ to \mathcal{V}_p for $p \neq i$. Note this is done as a single message for all j values needed.

(iii) Send $(r_{i,j}, \text{Sign}(\mathfrak{s}\mathfrak{f}_i, r_{i,j}))$ to \mathcal{P} , again this is done as a single message for all j values needed.

(iv) On receiving $(r_{p,j}^{(i)}, \sigma_{p,j}^{(i)}) = (r_{p,j}^{(i)}, \text{Sign}(\mathfrak{s}\mathfrak{f}_p, r_{p,j}^{(i)}))$ from party \mathcal{V}_p , verify the signature. If the signature $\sigma_{p,j}^{(i)}$ does not hold or if \mathcal{V}_p did not send any message at all

(A) Broadcast (Complaint, i, \mathcal{V}_p).

(B) Upon receiving (Complaint, i, \mathcal{V}_p) party \mathcal{V}_p publicly sends $(r_{p,j}^{(i)}, \sigma)$ to all parties, who forward it to \mathcal{V}_i .

(v) Similarly, do the same for the signatures that \mathcal{P} should obtain.

(2) For $\ell \in [\rho]$ do as follows.

(a) Execute $(\alpha_{1,j,\ell}, \dots, \alpha_{n,j,\ell}) \leftarrow \mathcal{F}_{\text{Rand}}(\{\mathcal{V}_1, \dots, \mathcal{V}_n, \mathcal{P}\}, n, \mathbb{F}_{2^k})$.

(b) Compute $T_\ell^{(i)} \leftarrow \sum_j \sum_{v \in [n]} \alpha_{v,j,\ell} \cdot r_{v,j}^{(i)}$ and broadcast $T_\ell^{(i)}$.

(c) The prover \mathcal{P} computes $T_\ell \leftarrow \sum_j \sum_{v \in [n]} \alpha_{v,j,\ell} \cdot r_{v,j}$ and broadcasts T_ℓ .

(d) If the $T_\ell^{(i)}$ do not form a valid degree- t sharing of T_ℓ then go to **Abort**(ℓ).

(3) For $j \in [n_S/(n-t)]$ do

(a) $c \leftarrow (j-1) \cdot (n-t)$.

(b) The prover \mathcal{P} computes and outputs $(s_{1+c}, \dots, s_{n-t+c})^T = M_t \times (r_{1,j}, \dots, r_{n,j})^T$,

(c) $\mathcal{V}_i \in \mathcal{V}$ compute and output $(\langle s_{1+c} \rangle_t, \dots, \langle s_{n-t+c} \rangle_t)^T = M_t \times (\langle r_{1,j} \rangle_t, \dots, \langle r_{n,j} \rangle_t)^T$.

Abort(ℓ): Each \mathcal{V}_i holds $r_{v,j}^{(i)}, \sigma_{v,j}^{(i)}$ for $v \in [n]$ and $j \in [[(n_S + \rho)/(n-t)]]$, while \mathcal{P} holds $r_{v,j}, \sigma_{v,j}$ for $v \in [n]$ and $j \in [[(n_S + \rho)/(n-t)]]$ (for simplicity, each \mathcal{V}_i signs a share $r_{i,j}^{(i)}$ for itself).

(1) Each verifier \mathcal{V}_i broadcasts $\{r_{v,j}^{(i)}, \sigma_{v,j}^{(i)}\}_{v,j}$, while \mathcal{P} broadcasts $\{r_{v,j}, \sigma_{v,j}\}_{v,j}$. If any signature $\sigma_{v,j}^{(i)}$ does not hold then identify \mathcal{V}_i as a cheater and abort. If any $\sigma_{v,j}$ does not hold then identify \mathcal{P} as cheater and abort.

(2) If for some $i \in [n]$ it holds that $T_\ell^{(i)} \neq \sum_{v,j} \alpha_{v,j,\ell} \cdot r_{v,j}^{(i)}$ then identify \mathcal{V}_i as cheater and abort. If it holds that $T_\ell \neq \sum_j \sum_v \alpha_{v,j,\ell} \cdot r_{v,j}$ then identify \mathcal{P} as a cheater and abort.

(3) For any \mathcal{V}_v , if $r_{v,j}^{(1)}, \dots, r_{v,j}^{(n)}$ do not form a valid degree- t sharing of $r_{v,j}$ then identify \mathcal{V}_v as a cheater and abort.

Figure 4: Protocol for preprocessing with $t < n/2$

sharings or incorrectly formed messages. Signatures prevent dishonest parties from framing honest parties by claiming to have obtained shares that the honest party never sent.

THEOREM 4.1. *Assuming that Sign is an unforgeable signature scheme, then the protocol $\Pi_{\text{Prep}}^{t,n}$ in Fig. 4 securely implements the functionality $\mathcal{F}_{\text{Prep}}^{t,n}$ in the $\mathcal{F}_{\text{Rand}}$ -hybrid model against any static adversary corrupting at most $t < n/2$ parties except with probability $2^{-\rho \cdot k+1}$.*

The proof is based on the following three lemmas. First, we show that if a dishonest party creates an incorrect sharing, then the protocol enters **Abort** with overwhelming probability. Second, we show that if a verifier sends an incorrect share to an honest prover, then the protocol enters **Abort** with overwhelming probability.

Finally, we show that upon entering **Abort** at least one dishonest party is identified, and only dishonest parties are identified. The proofs of these Lemmas, Theorem 4.1, are given in the full version.

LEMMA 4.2. *Let $\mathcal{V}_{\mathcal{H}} = \mathcal{V} \cap \mathcal{H}$ and assume $t < n/2$. For $v \in [n]$, consider the shares $r_{v,j}^{(i)}$ for $\mathcal{V}_i \in \mathcal{V}_{\mathcal{H}}$ and let $S_{v,j}$ be the unique polynomials of smallest degree over \mathbb{F}_{2^k} such that $S_{v,j}(i) = r_{v,j}^{(i)}$. If there exist v, j such that⁵ $\deg(S_{v,j}) > t$, then the protocol enters **Abort** except with probability $2^{-k \cdot \rho}$.*

LEMMA 4.3. *Let $\mathcal{V}_{\mathcal{H}} = \mathcal{V} \cap \mathcal{H}$ and $t < n/2$ and assume $\mathcal{P} \in \mathcal{H}$. For $v \in [n]$, consider the shares $r_{v,j}^{(i)}$ of $\mathcal{V}_i \in \mathcal{V}_{\mathcal{H}}$ and let $S_{v,j}$ be*

⁵Here we use that $t < n/2$, as $S_{v,j}$ could otherwise not be of degree $> t$.

the unique polynomials of degree t over \mathbb{F}_{2^k} such that $S_{v,j}(i) = r_{v,j}^{(i)}$. Furthermore, let $r_{v,j}$ be the values received by \mathcal{P} . If there exist v, j such that $S_{v,j}(0) \neq r_{v,j}$, then the protocol enters **Abort** except with probability $2^{-k \cdot \rho}$.

LEMMA 4.4. *Assuming unforgeability of Sign, then **Abort** always terminates with at least one dishonest party being identified. Furthermore, it only terminates identifying dishonest parties.*

5 DISTRIBUTED PROOF WITH $t < n/4$ CORRUPTIONS

In this section we describe a protocol which deals with $t < n/4$ corruptions of the verifiers, i.e. Γ_C , Γ_S and Γ_Z are access structures consisting of all sets with more than $n - t$ verifiers in them. The protocol Π_{4t} , given in Fig. 5, forms the basis of our following protocol in the case of $t < n/3$, indeed it shares the same pre-processing phase from the previous section.

In the setting where we have $t < n/4$ corruptions we can rely on the Reed-Solomon decoding to robustly open secret sharings of degree up to $2t$. Thus we can efficiently verify multiplications. We assume the statement to be verified is given by a circuit C over \mathbb{F}_{2^k} which will evaluate to zero only on input of the witness w , i.e. $C(w) = 0$.

Given the values \vec{s} generated in pre-processing, the prover can trivially “commit” to the witness w as well as the outputs of all the multiplication gates of C by broadcasting the difference between \vec{s} and these values towards the verifiers. The verifiers can then evaluate the circuit as follows: to obtain the wire output values of a gate, they can either simply apply the corresponding linear operation directly on their shares, or obtain a sharing for the output wire from the prover’s broadcast for multiplications. After evaluating the entire circuit in this manner, the verifiers can robustly open $\langle C(w) \rangle_t$ and verify it correctly evaluates to zero.

The verifiers also have to check that the commitments the prover provided for the outputs of the multiplication gates are consistent. For each verifier \mathcal{V}_i , let $a_j^{(i)}$ be the share of the left input corresponding to the j th multiplication/AND gate, $j \in [n_S]$. Correspondingly, $b_j^{(i)}$ is the share for the right input and $c_j^{(i)}$ for the output. Then $c_j^{(i)} = a_j^{(i)} \cdot b_j^{(i)}$ is a degree $2 \cdot t$ sharing of the value $c_j = a_j \cdot b_j$ output by this multiplication gate. We represent this sharing by $\langle c_j \rangle_{2 \cdot t}$. The proof proceeds by verifying that the values held in $\langle c_j \rangle_{2 \cdot t}$ are identical with the values held in $\langle s_j \rangle_t - (s_j - c_j)$, and provided by the prover, therefore checking that all committed multiplication gate outputs were correct.

To achieve this, the verifiers check that a random linear combination over all products of the inputs corresponds to the same linear combination over the gate outputs. More precisely, for each multiplication gate $j \in [n_S]$, the verifiers sample a uniformly random multiplier β_j and locally compute shares $A^{(i)} = \sum_j \beta_j \cdot a_j^{(i)} \cdot b_j^{(i)}$, and $C^{(i)} = \sum_j \beta_j \cdot c_j^{(i)}$. Then, since $t < n/4$, the verifiers reliably reconstruct $\langle A \rangle_{2t}$ and $\langle C \rangle_t$. If $A = C$ then the verifiers accept the proof, otherwise they reject. Cheater identification can be achieved in a straightforward manner thanks to the error correction during the robust reconstruction. Moreover, the check is made zero-knowledge by letting \mathcal{P} share additional valid random multiplication triples.

THEOREM 5.1. *If $t < n/4$, then protocol Π_{4t} secure implements the functionality $\mathcal{F}_{\text{DV-ZK}}$ in the $(\mathcal{F}_{\text{Prep}}^{t,n}, \mathcal{F}_{\text{Rand}})$ -hybrid model with $\Gamma_C = \Gamma_S = \Gamma_Z$ being the set of all subsets of verifiers of size $n - t$ or more, except with probability $1/|\mathbb{F}|$.*

Proof (Sketch) The main observation is that given a correct sharing of random values $\langle s_j \rangle_t$ from the preprocessing, the verifiers can check the validity of the proof by evaluating the circuit C on input $\langle w_j \rangle_t = \langle s_j \rangle_t - (s_j - w_j)$ and using multiplicative shares $\langle c_j \rangle_t = \langle s_j \rangle_t - (s_j - c_j)$, which are consistent Shamir’s shares of the witness value and output of the multiplication gates provided by the prover. This means that all the honest shares are guaranteed to be consistent with the same t -degree and $2t$ -degree polynomials. Therefore, since $t < n/4$, the Reed-Solomon reconstruction allows honest parties to obtain the correct output of the circuit’s evaluation by running $\text{RobustReconstruct}(\langle o \rangle_t, t)$ and also to correct errors on the degree $2t$ -polynomial derived by $\text{RobustReconstruct}(\langle A \rangle_{2t} - \langle C \rangle_t, t)$. In this way honest verifiers can detect an incorrect proof, either because $o \neq 0$ or the multiplication check fails; moreover the reconstruction algorithm also allows to detect errors, i.e. incorrect shares from dishonest verifiers, and hence identify cheaters.

In the simulation, if the prover is corrupt, the adversary provides the proof to the simulator, which can extract the witness using the preprocessed values obtained by emulating the preprocessing functionality. If the proof is incorrect, \mathcal{S} rejects the proof and checks if during the verification dishonest verifiers sent inconsistent shares, identifying cheaters.

A more detailed proof of this theorem is given in the full version.

6 DISTRIBUTED PROOF WITH $t < n/3$ CORRUPTIONS

The general approach for this setting will be very similar to the case $t < n/4$ described in the previous section. The main difference is that now we can no longer robustly reconstruct a degree $2t$ polynomial, so we will instead rely on the Schwartz-Zippel lemma to check the correctness of the multiplications. More precisely, we use a checking method similar to the one used in [6, 11]. We first transform the n_S multiplication gates into an inner product triple by taking a random linear combination and updating the left inputs to the multiplications correspondingly. Given a challenge from the verifiers, this operation is entirely local.

This inner product triple is then repeatedly compressed by applying the Schwartz-Zippel lemma, until only a final, single multiplication triple remains. This final triple can be checked by the verifiers by robustly opening it. The prover adds an extra random multiplication to preserve the zero-knowledge property in this process. To avoid $\log n_S$ rounds of communication between the prover and the verifiers, we apply the Fiat-Shamir transform to make the process of proving non-interactive. We also use the Fiat-Shamir transform to compute the initial re-randomization factors. For this to work we apply a minor change to the preprocessing functionality $\mathcal{F}_{\text{Prep}}^{t,n}$, so that it additionally outputs a random string $v \in \mathbb{F}_2^\lambda$ to each parties $\mathcal{P}, \mathcal{V}_1, \dots, \mathcal{V}_n$. This is used in the random oracle to bind the statement and the proof to this value. The compression itself is performed as follows. Assume we have an inner

Protocol Π_{4t}

Let C be the circuit to be proved; the prover \mathcal{P} is assumed to know an input witness w such that $C(w) = 0$.

Let n_S denote the number of AND gates in the circuit, n_W the length of the witness w and ρ a positive integer.

Let CheckMult and OutputRec be two additional flags initially set to \top and \perp respectively.

Init: Call $\mathcal{F}_{\text{Prep}}^{t,n}$, so that \mathcal{P} obtains s_i and the verifiers $\mathcal{V}_1, \dots, \mathcal{V}_n$ obtain $\langle s_i \rangle_t$ for $i \in [n_S + n_W + 3\rho]$, i.e. \mathcal{V}_j obtains $s_i^{(j)}$, $j \in [n]$.

Set $x_j = s_{j+n_W+n_S+\rho}$ and $y_j = s_{j+n_W+n_S+2\rho}$, $j \in [\rho]$.

Prove: The prover “evaluates” the circuit as follows:

- (1) Compute the difference between the input wire values w_i and the pre-processed values s_i , i.e. $w_i - s_i$, $i \in [n_W]$.
- (2) Evaluate the circuit gate-by-gate:
 - (a) For every linear gate, simply compute the resulting wire value
 - (b) For each AND gate, compute the resulting wire value $c_j \leftarrow a_j \cdot b_j$ and $c_j - s_{j+n_W}$, $j \in [n_S]$.
 - (c) Compute ρ additional random triples as $x_j \cdot y_j = z_j$, and $z_j - s_{j+n_W+n_S}$, $j \in [\rho]$
- (3) Set the proof to be the concatenation of all the values $\{w_i - s_i\}_{i \in [n_W]}$, $\{c_j - s_{j+n_W}\}_{j \in [n_S]}$, and $\{z_j - s_{j+n_W+n_S}\}_{j \in [\rho]}$.

Verify: The verifiers $\mathcal{V}_1, \dots, \mathcal{V}_n$ jointly check the circuit evaluation:

- (1) Evaluate the circuit within the Shamir secret sharing, computing a share of the output wire $\langle o \rangle_t$:
 - (a) Shares of the input wires can be computed as $\langle w_i \rangle_t \leftarrow \langle s_i \rangle_t + (w_i - s_i)$ for $i \in [n_W]$.
 - (b) Shares of the output wire values for an AND gate can be computed as
$$\langle c_j \rangle_t \leftarrow \langle s_{j+n_W} \rangle_t + (c_j - s_{j+n_W}), \text{ for } j \in [n_S].$$
 - (c) A degree $2 \cdot t$ sharing $\langle c_j \rangle_{2,t}$ of this same value is computed by each \mathcal{V}_j as $c_j^{(i)} \leftarrow a_j^{(i)} \cdot b_j^{(i)}$.
 - (d) Linear gates can be evaluated linearly over the shares in the degree t sharing.
 - (e) Recompute $\langle x_i \rangle_t = \langle s_{i+n_W+n_S+\rho} \rangle_t$, $\langle y_i \rangle_t = \langle s_{i+n_W+n_S+2\rho} \rangle_t$ and $\langle z_i \rangle_t \leftarrow \langle s_{i+n_W+n_S} \rangle_t + (z_i - s_{i+n_W+n_S})$. Furthermore, compute a degree- $2t$ sharing of z_i by locally multiplying the shares of x_i, y_i as in Step 1c.

- (2) The verifiers call RobustReconstruct($\langle o \rangle_t, t$), to obtain (o, flag_o) .

- (3) If $o \neq 0$:

- If $\text{flag}_o = (\text{correct}, \emptyset)$ then output Fail.
- If $\text{flag}_o = (\text{incorrect}, C_o)$, then output the dishonest verifiers in C_o and Fail.

- (4) Else, set OutputRec = \top . If $\text{flag}_o = (\text{incorrect}, C_o)$, identify the dishonest verifiers in C_o .

- (5) *Multiplications check:* Verifiers repeat ρ times the following.

- (a) Call $(\beta_1, \dots, \beta_{n_S+1}) \leftarrow \mathcal{F}_{\text{Rand}}(\{\mathcal{V}_1, \dots, \mathcal{V}_n\}, n_S + 1, \mathbb{F}_{2^k})$.
- (b) Compute

$$\langle A \rangle_{2t} = \sum_{j \in [n_S]} \beta_j \cdot \langle c_j \rangle_{2t} + \beta_{n_S+1} \cdot \langle z_i \rangle_{2t} \text{ and } \langle C \rangle_t = \sum_{j \in [n_S]} \beta_j \cdot \langle c_j \rangle_t + \beta_{n_S+1} \cdot \langle z_i \rangle_t$$

- (c) Run RobustReconstruct($\langle A \rangle_{2t} - \langle C \rangle_t, t$), to obtain (T, flag_T)

- (d) If $T \neq 0$, set CheckMult = \perp . Moreover,

- If $\text{flag}_T = (\text{correct}, \emptyset)$, then output Fail.
- If $\text{flag}_T = (\text{incorrect}, C_M)$, then identify the dishonest verifiers in flag_{T_v} and output Abort

- (6) If both CheckMult = \top and OutputRec = \top , accept the proof and identify possible dishonest verifiers $C_A = C_o \cup \{C_{M_v}\}_{v \in [\rho]}$

Figure 5: Protocol Π_{4t} for $t < n/4$

product triple $((x_i)_{1 \leq i \leq N}, (y_i)_{1 \leq i \leq N}, z)$, such that $z = \sum_{i=1}^N x_i \cdot y_i$, and that N is a multiple of two (otherwise, we implicitly pad the x_j and y_j by zeroes). The prover then interpolates N polynomials of degree 1, $f_k(x)$ and $g_k(x)$, such that $f_k(j) = x_{2 \cdot k + j}$ and $g_k(j) = y_{2 \cdot k + j} = y_j$, for $j \in [2]$. Furthermore, define the polynomial of degree 2 $h(x) = \sum_{k=1}^{\frac{N}{2}} f_k(x) \cdot g_k(x) = h_1 + h_2 \cdot x + h_3 \cdot x^2$. Observe that by construction, $z = \sum_{j=1}^2 h(j) = h_2 + h_3$. The prover commits to the coefficients of $h(x)$ so that the verifiers can evaluate it with only linear operations. Given the relation between z

and those coefficients above, the verifiers can recover a commitment to h_3 from $\langle z \rangle_t$, and $\langle h_2 \rangle_t$ through only linear operations, allowing the prover to eliminate a commitment to h_3 from the proof. The compressed inner product triple can now be obtained as $((f_k(r))_{1 \leq k \leq N/2}, (g_k(r))_{1 \leq k \leq N/2}, h(r))$ for a randomly chosen value of r .

To verify the proof, the verifiers check that the circuit output reconstructs to 0 and that the final multiplication triple is correct. The interpolation of $f_k(x)$ and $g_k(x)$ is linear, so the verifiers can perform the operation locally over the secret sharing, and with the

Protocol- Π_{3t}

Let C be the circuit to be proved; the prover \mathcal{P} is assumed to know an input witness w such that $C(w) = 0$.

Let n_S denote the number of AND gates in the circuit, n_W the length of the witness w , and $\sigma = \lceil \log_2 n_S \rceil$. Let $K = \mathbb{F}_{2^k}$ and $L = \mathbb{F}_{2^{\rho \cdot k}}$, with $\phi : K \rightarrow L$ the field homomorphism that embeds K in L . The protocol uses a hash function modelled as a random oracle. For secret sharings in L , let the evaluation points of verifier \mathcal{V}_i be $\phi(i \in K)$.

Init: Call $\mathcal{F}_{\text{Prep}}^{t,n}$ in K , so that \mathcal{P} obtains s_i and the verifiers $\mathcal{V}_1, \dots, \mathcal{V}_n$ obtain $\langle s_i \rangle_t$ for $i \in [n_S + n_W]$, i.e. \mathcal{V}_j obtains $s_i^{(j)}$, $j \in [n]$.

Call $\mathcal{F}_{\text{Prep}}^{t,n}$ in L , so that \mathcal{P} obtains S_i and the verifiers obtain $\langle S_i \rangle_t$ for $i \in [3 + 2 \cdot \sigma]$. All parties obtain a random string $v \in \mathbb{F}_2^\lambda$.

Prove: The prover “evaluates” the circuit as follows:

- (1) Compute the difference between the input wire values w_i and the pre-processed values s_i , i.e. $w_i - s_i$, $i \in [n_W]$.
- (2) Evaluate the circuit gate-by-gate:
 - (a) For every linear gate, simply compute the resulting wire value
 - (b) For each AND gate, compute $c_j \leftarrow a_j \cdot b_j$ and $c_j - s_{j+n_W}$, $j \in [n_S]$. Let $A_j = \phi(a_j)$, $B_j = \phi(b_j)$ and $C_j = \phi(c_j)$.
- (3) Compute an additional random multiplication triple $(A, B, C) \in L^3$, and compute $A - S_1$, $B - S_2$, $C - S_3$.
- (4) Set π to be the concatenation of all committed values so far: $\{w_i - s_i\}_{i \in [n_W]}$, $\{c_j - s_{j+n_W}\}_{j \in [n_S]}$, $A - S_1$, $B - S_2$, $C - S_3$.
- (5) Randomize the multiplication triples $(A_j, B_j, C_j = A_j \cdot B_j)_j$ into an inner product triple $((R_j \cdot A_j)_j, (B_j)_j, \sum_j R_j \cdot C_j)$, where $n_S + 1$ random value R_j are sampled, seeded with a hash of (π, x, v) .
- (6) Compress the inner product triple σ times until a single multiplication triple remains. For $j \in [\sigma]$:
 - (a) Parse the current inner product triple as $((X_k)_k, (Y_k)_k, Z)$, $k \in [n_S/2^j]$
 - (b) Interpolate the polynomials $f_k(x)$ and $g_k(x)$ such that $f_k(0) = X_{2 \cdot k - 1}$, $f_k(1) = X_{2 \cdot k}$, $g_k(0) = Y_{2 \cdot k - 1}$ and $g_k(1) = Y_{2 \cdot k}$.
 - (c) Define $h(x) = \sum_k f_k(x) \cdot g_k(x) = h_1 + h_2 \cdot x + h_3 \cdot x^2$.
 - (d) Append commitments to the coefficients h_1, h_2 of the polynomial $h(x)$ to π : $\{h_i - X_{3+2 \cdot j+i}\}_{i \in [2]}$.
 - (e) Obtain a random field element $T_j \in L$, seeded with a hash of the current value of π .
 - (f) The inner product triple now becomes $((f_k(T_j))_k, (g_k(T_j))_k, h(T_j))$.

The proof consists of the final value of π .

Verify: The verifiers $\mathcal{V}_1, \dots, \mathcal{V}_n$ jointly check the circuit evaluation:

- (1) Evaluate the circuit within the Shamir secret sharing on K , computing a share of the output wire $\langle o \rangle_t$:
 - (a) Shares of the input wires can be computed as $\langle w_i \rangle_t \leftarrow \langle s_i \rangle_t + (w_i - s_i)$ for $i \in [n_W]$.
 - (b) Shares of the output wire values for an AND gate $c_j = a_j \cdot b_j$ can be computed as
$$\langle c_j \rangle_t \leftarrow \langle s_{j+n_W} \rangle_t + (c_j - s_{j+n_W}), \text{ for } j \in [n_S].$$
- (c) Let $\langle A_j \rangle_t = \phi(\langle a_j \rangle_t)$, $\langle B_j \rangle_t = \phi(\langle b_j \rangle_t)$ and $\langle C_j \rangle_t = \phi(\langle c_j \rangle_t)$.
- (c) Linear gates can be evaluated linearly over the shares in the degree t sharing.
- (2) The verifiers obtain A, B and C by similarly adding the commitment to the preprocessing shares.
- (3) The verifiers call $(o, \text{flag}_o) \leftarrow \text{RobustReconstruct}(\langle o \rangle_t)$.
 - (a) If $o \neq 0$:
 - If $\text{flag}_o = (\text{correct}, \emptyset)$ then output Fail.
 - If $\text{flag}_o = (\text{incorrect}, C_o)$, then output the dishonest verifiers in C_o and Fail.
 - (b) If $\text{flag}_o = (\text{incorrect}, C_o)$, identify the dishonest verifiers in C_o .
- (4) Obtain the same – secret-shared – randomization to an inner product triple as the prover, using the same random value R .
- (5) Perform the analog of the prover’s compressions, for $j \in [\sigma]$:
 - (a) Interpolate $\langle f_k(x) \rangle_t$ and $\langle g_k(x) \rangle_t$ similar to the prover.
 - (b) The polynomial $\langle h(x) \rangle_t$ can be recovered from the commitment to its coefficients, together with $\langle h_2 \rangle_t = \langle Z \rangle_t - \langle h_2 \rangle_t$.
 - (c) Update the inner product triple to be the compressed version with the same random T_j as the prover.
- (6) Let the final remaining multiplication triple be $(\langle X \rangle_t, \langle Y \rangle_t, \langle Z \rangle_t)$.
- (7) Call $(w, \text{flag}_w) \leftarrow \text{RobustReconstruct}(\langle w \rangle_t, t)$ for $w \in \{X, Y, Z\}$. If $\text{flag}_w = (\text{incorrect}, C_w)$, identify the cheaters in C_w .
- (8) If $X \cdot Y \neq Z$, Fail. Otherwise accept the proof.

Figure 6: Protocol Π_{3t} for $t < n/3$

shares of the coefficients of $h(x)$ the evaluation of all polynomials in r can also be performed locally.

Fig. 6 describes the protocol in detail. To ensure the soundness of this protocol, the multiplication check and compression must be performed over a large enough finite field. It is however possible to

keep the proof size small by performing the circuit evaluation over a smaller finite field \mathbb{F}_{2^k} such that $2^k > n$ to allow for the secret sharing. The (shares of the) inputs and outputs of the multiplication gates are then lifted to an extension field $\mathbb{F}_{2^{\rho \cdot k}}$ to perform the multiplication check with sufficient soundness.

THEOREM 6.1. *Let \mathcal{H} be a random oracle that maps into $\mathbb{F}_{2^{\rho \cdot k}}$. If $t < n/3$ then protocol Π_{3t} described in Fig. 6 securely implements the functionality $\mathcal{F}_{\text{DV-ZK}}$ against a static adversary in the $(\mathcal{F}_{\text{Prep}}^{t,n}, \mathcal{F}_{\text{Rand}})$ -hybrid model with $\Gamma_C = \Gamma_S = \Gamma_Z$ being the set of all subsets of verifiers of size $n - t$ or more, except with probability*

$$\epsilon \cdot \log_2(n_S) + q(\epsilon + 2/|\mathcal{D}| + 2^{-\lambda})$$

where q is the number of random oracle queries made by a malicious prover, $\epsilon = 2^{-\rho \cdot k + 2}$ and $|\mathcal{D}| = 2^{-\rho \cdot k}$.

The main idea of the proof is similar to that of Theorem 5.1 and the main difference is the multiplication check as described above. A detailed proof of this theorem is given in the full version.

7 EXPERIMENTS

We implemented our protocols in C++ and tested with different circuits and number of verifiers.

For experiments with less than 10 parties, our tests were run on a cluster of computers running Ubuntu 20.04.2 with a ping time of roughly 0.6 ms, and a total bandwidth of 9.41Gbit/s per machine. The machines had either Intel i7-770K CPUs running at 4.2 GHz with 32 GB of RAM, or Intel i9-9900 CPUs running at 3.1 GHz with 128 GB of RAM. For the other experiments ($n > 10$), we utilized $n + 1$ machines on Amazon AWS. Each of these was an individual *c5.large* instance in the *eu-central-1* region, with a measured ping of roughly 0.5 ms, and 4.17Gbit/s bandwidth. Each configuration was run a total of 200 times and the median was taken to obtain the presented running times.

We present experimental validation of the efficiency of our protocols for small circuits by presenting prover and verification times for proving knowledge of an AES-128 key corresponding to a public plaintext-ciphertext pair and a boolean circuit proving the knowledge of a pre-image for the SHA-256 compression function. These functions were chosen as the boolean circuits for these are readily available, and well-studied. The AES-128 circuit has 6400 AND gates, while the SHA-256 circuit has 22573 AND gates. We also present results for a SHA-256 pre-image consisting of 10 512-bit blocks, which gives a circuit of 1,317,424 total gates and 220,369 AND gates, and a circuit consisting solely of one million AND gates, with 128 inputs. For all circuits and protocols we present results for a system tolerating a single corrupted verifier ($t = 1$) and a total of $n = 5$ verifiers in Table 1. For the protocol for $t < n/3$, we also provide numbers for $t = 2$ corruptions with $n = 7$ parties in total.

In Fig. 7, we present results for $n \in \{20, 40, 60, 80, 100\}$ with the maximum value for t allowed by the protocols. Table 2 contains more detailed results of our experiments with $n = 100$ verifiers.

7.1 Results

Our experimental results are presented in Table 1 and Fig. 7. We can immediately see that Π_{4t} is a small factor more efficient than Π_{3t} . Both protocols have runtimes that allow for practical deployment.

Given that a threshold of $t < n/4$ may be enough in a number of practical situations, one can see that the more efficient Π_{4t} can be preferred.

We have already made some comparisons with other systems in Section 1. Notice that [5, 14, 15] report comparable prover and verification times for AES, however these papers use a more compact description of the AES circuit over \mathbb{F}_{2^8} with S-boxes instead of AND gates. We could utilize the same approach, obtaining better runtimes. However, our goal is different from the one in these papers as they specifically aim to obtain efficient post-quantum signature schemes based on AES, while we support general circuits, only using AES and SHA-256 as examples.

For protocol Π_{4t} from Fig. 5, targeting $t < n/4$, we selected the finite field \mathbb{F}_{2^3} to accommodate the secret sharing, when $n < 7$ and \mathbb{F}_{2^7} for the other cases. We performed $\rho = 14$ (resp. $\rho = 6$) parallel repetitions of the protocol to boost the statistical security to 2^{-42} . When looking at the trade-off between the field size of \mathbb{F}_{2^k} and the number of repetitions ρ for this protocol, notice that the security level will always be $2^{-k \cdot \rho}$, regardless of how we distribute the load across the two parameters. Similarly, the communication cost among the verifiers does not depend on either ρ or k individually, but only on the product $\rho \cdot k$. Using a larger field size, however, does increase the proof size and the communication cost of the preprocessing phase, as those only depend on the field size, and not on ρ . Hence it should be preferred to use a smaller field with more parallel repetitions, rather than increasing the field size to target a security level for this protocol. The communication cost (in terms of amount of bytes sent by each verifier) in the verification protocol is $O(n)$ in the case of protocol Π_{4t} .

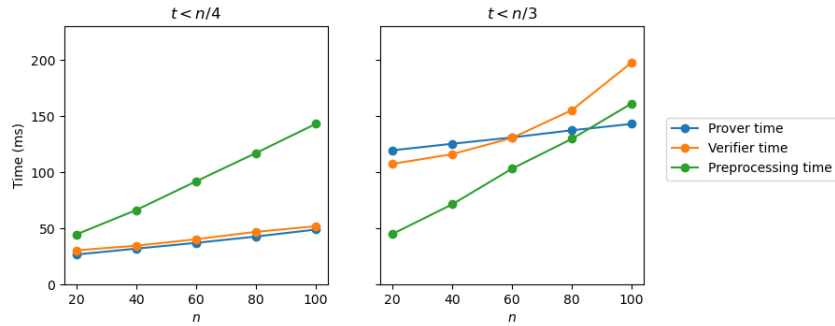
For Π_{3t} in Fig. 6, targeting $t < n/3$, we again choose to aim for a security level of $\text{sec} = 40$ and let the maximum number of queries the prover can make to \mathcal{H} be $q = 2^{40}$. Similar to the above case, we choose $\mathbb{F}_{2^k} = \mathbb{F}_{2^3}$ as the minimal field to accommodate for the secret sharing for $n \leq 7$ and \mathbb{F}_{2^7} for the other cases; we let $\mathbb{F}_{2^{\rho \cdot k}} = \mathbb{F}_{2^{87}}$ be the extension field, when $n \leq 7$, and $\mathbb{F}_{2^{\rho \cdot k}} = \mathbb{F}_{2^{91}}$ for the other cases, to ensure soundness for all our evaluation circuits.

Large number of verifiers. Table 2 and Fig. 7 show that increasing the number of parties has a small impact on proof and verification time for protocol Π_{4t} , while the change is a little more evident in Π_{3t} . There is only a small difference in the pre-processing execution between our two protocols. Our Π_{4t} protocol can prove circuits of 1 million AND gates in less than 176/220ms for proof and verification, respectively, with 100 verifiers; while our Π_{3t} requires proof/verification time of 563/892ms for the same circuit and number of verifiers. In both protocols the proof size is $\approx 0.8\text{MB}$.

Communication cost. The communication cost is $O(n)$ in the case of protocol Π_{3t} ; which scales linearly with the number of verifiers, however, importantly it is sublinear in the total circuit size. Note, the threshold t has no effect on the round or total communication cost, it only increases the computational cost to perform a robust opening. Also note, for small n , the computation time mostly dominates for the prover, and we see only little impact of a growing number of verifiers on the prover time. When the number of verifiers grows larger, the communication starts to dominate. For the

| Protocol | Circuit | n | t | Field | Parameters | Number of preproc. element | Proof size (bytes) | Preprocessing Time (ms) | Prover Time (ms) | Verifier Time (ms) |
|------------|---------|---|---|--------------------|-----------------------|----------------------------|--------------------|-------------------------|------------------|--------------------|
| Π_{4t} | AES | 5 | 1 | \mathbb{F}_{2^3} | $\rho = 14$ | 7000 | 2496 | 1.67 | 4.07 | 6.83 |
| Π_{4t} | SHA-256 | 5 | 1 | \mathbb{F}_{2^3} | $\rho = 14$ | 23000 | 8449 | 3.45 | 7.06 | 14.02 |
| Π_{4t} | SHA x10 | 5 | 1 | \mathbb{F}_{2^3} | $\rho = 14$ | 230000 | 84655 | 28.52 | 33.64 | 43.87 |
| Π_{4t} | 1M AND | 5 | 1 | \mathbb{F}_{2^3} | $\rho = 14$ | 1100000 | 375048 | 95.64 | 30.03 | 89.81 |
| Π_{3t} | AES | 4 | 1 | \mathbb{F}_{2^3} | $\mathbb{F}_{2^{87}}$ | 6655 + 50 | 2811 | 2.01 | 7.81 | 8.43 |
| Π_{3t} | SHA-256 | 4 | 1 | \mathbb{F}_{2^3} | $\mathbb{F}_{2^{87}}$ | 22530 + 35 | 8808 | 3.41 | 22.83 | 24.24 |
| Π_{3t} | SHA x10 | 4 | 1 | \mathbb{F}_{2^3} | $\mathbb{F}_{2^{87}}$ | 225745 + 50 | 85079 | 24.46 | 50.32 | 50.94 |
| Π_{3t} | 1M AND | 4 | 1 | \mathbb{F}_{2^3} | $\mathbb{F}_{2^{87}}$ | 1000128 + 50 | 375516 | 98.89 | 180.07 | 200.27 |
| Π_{3t} | AES | 7 | 2 | \mathbb{F}_{2^3} | $\mathbb{F}_{2^{87}}$ | 6655 + 50 | 2811 | 2.98 | 7.86 | 8.93 |
| Π_{3t} | SHA-256 | 7 | 2 | \mathbb{F}_{2^3} | $\mathbb{F}_{2^{87}}$ | 22530 + 35 | 8808 | 4.52 | 21.88 | 24.16 |
| Π_{3t} | SHA x10 | 7 | 2 | \mathbb{F}_{2^3} | $\mathbb{F}_{2^{87}}$ | 225745 + 50 | 85079 | 25.16 | 54.23 | 80.28 |
| Π_{3t} | 1M AND | 7 | 2 | \mathbb{F}_{2^3} | $\mathbb{F}_{2^{87}}$ | 1000128 + 50 | 375516 | 113.79 | 187.56 | 212.69 |

Table 1: Experimental results for running the protocols in Fig. 5 and Fig. 6 on our evaluation circuits

Figure 7: Timing on the 10-block SHA256 circuit with $t = \lfloor (n-1)/4 \rfloor$ and $t = \lfloor (n-1)/3 \rfloor$ respectively. The base field is \mathbb{F}_{2^7} and for $t < n/3$ the extension field is $\mathbb{F}_{2^{91}}$.

| Protocol | Circuit | n | t | Field | Parameters | Proof size (bytes) | Preprocessing Time (ms) | Prover Time (ms) | Verifier Time (ms) |
|------------|---------|-----|----|--------------------|-----------------------|--------------------|-------------------------|------------------|--------------------|
| Π_{4t} | AES | 100 | 20 | \mathbb{F}_{2^7} | $\rho = 6$ | 5,824 | 33.26 | 2.36 | 10.60 |
| Π_{4t} | SHA-256 | 100 | 20 | \mathbb{F}_{2^7} | $\rho = 6$ | 19,714 | 42.09 | 5.47 | 13.39 |
| Π_{4t} | SHA x10 | 100 | 20 | \mathbb{F}_{2^7} | $\rho = 6$ | 197,527 | 166.35 | 46.63 | 51.28 |
| Π_{4t} | 1M AND | 100 | 20 | \mathbb{F}_{2^7} | $\rho = 6$ | 875,112 | 432.21 | 175.92 | 218.51 |
| Π_{3t} | AES | 100 | 30 | \mathbb{F}_{2^7} | $\mathbb{F}_{2^{91}}$ | 6,153 | 71.55 | 5.56 | 68.06 |
| Π_{3t} | SHA-256 | 100 | 30 | \mathbb{F}_{2^7} | $\mathbb{F}_{2^{91}}$ | 20,090 | 70.20 | 15.34 | 80.52 |
| Π_{3t} | SHA x10 | 100 | 30 | \mathbb{F}_{2^7} | $\mathbb{F}_{2^{91}}$ | 197,971 | 181.13 | 135.09 | 215.65 |
| Π_{3t} | 1M AND | 100 | 30 | \mathbb{F}_{2^7} | $\mathbb{F}_{2^{91}}$ | 875,602 | 595.44 | 562.45 | 891.46 |

Table 2: Experimental results for $n = 100$ verifiers on our evaluation circuits

verifiers, similarly the increased amount of communication partners takes its toll, along with an increased computational cost for robust reconstruction when t starts to grow.

For our preprocessing protocol for any $t < n/2$, the dominant cost is each verifier sending $n_S/(n-t)$ shares to every other verifier, and the prover. Therefore, if t is a constant fraction of n , the communication per verifier is linear in the circuit size but essentially independent of n . For instance, with $t = n/3$ it is roughly $\frac{3}{2} \cdot n_S$ field elements, and for $t = n/4$ this becomes $\frac{4}{3} \cdot n_S$.

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