Pankaj Dayama, Arpita Patra, Protik Paul*, Nitin Singh, and Dhinakaran Vinayagamurthy

How to prove any NP statement jointly? Efficient Distributed-prover Zero-Knowledge Protocols

Abstract: Traditional zero-knowledge protocols have been studied and optimized for the setting where a single prover holds the complete witness and tries to convince a verifier about a predicate on the witness, without revealing any additional information to the verifier. In this work, we study the notion of distributed-prover zero knowledge (DPZK) for arbitrary predicates where the witness is shared among multiple mutually distrusting provers and they want to convince a verifier that their shares together satisfy the predicate. We make the following contributions to the notion of distributed proof generation: (i) we propose a new MPC-style security definition to capture the adversarial settings possible for different collusion models between the provers and the verifier, (ii) we discuss new efficiency parameters for distributed proof generation such as the number of rounds of interaction and the amount of communication among the provers, and (iii) we propose a compiler that realizes distributed proof generation from the zero-knowledge protocols in the Interactive Oracle Proofs (IOP) paradigm. Our compiler can be used to obtain DPZK from arbitrary IOP protocols, but the concrete efficiency overheads are substantial in general. To this end, we contribute (iv) a new zero-knowledge IOP Graphene which can be compiled into an efficient DPZK protocol. The \( (D+1) \)-DPZK protocol D-Graphene, with \( D \) provers and one verifier, admits \( O(N^{1/C}) \) proof size with a communication complexity of \( O(D^2 \cdot (N^{1-2/C} + N_s)) \), where \( N \) is the number of gates in the arithmetic circuit representing the predicate and \( N_s \) is the number of wires that depends on inputs from two or more parties. Significantly, only the distributed proof generation in D-Graphene requires interaction among the provers. D-Graphene compares favourably with the DPZK protocols obtained from the state-of-art zero-knowledge protocols, even those not modelled as IOPs.

Keywords: Zero-Knowledge Proofs, Secure Multi-Party Computation, Distributed-Prover Zero-Knowledge

1 Introduction

A zero-knowledge protocol tries to convince a verifier about the truth of a statement without revealing any additional information. These include proving the correctness of transactions in cryptocurrencies such as [40] or validating sensitive web browser data reported during telemetry [18, 25]. Still in the dream of a decentralized world, there are multiple co-opetitive entities, i.e., collaborating but mutually distrusting entities interacting with each other to obtain insights and maximize their goals. We envisage applications of zero-knowledge proofs to enable these mutually distrusting entities to prove a claim on their joint data. In this setting, the traditional zero-knowledge protocols are restrictive since they require a single prover to have the entire witness needed to generate the proof.

In this work, we study the general setting of distributed prover zero-knowledge protocols (DPZK) where multiple co-opetitive entities, each possessing its own secret data, want to prove to a verifier that their secret data together satisfy a predicate of common interest. This is to be done without revealing any information about their sensitive data to each other or to the verifier.

Formally, we have multiple provers \( P_1, \ldots, P_D \) respectively possessing witnesses \( w_1, \ldots, w_D \). For a predicate \( C \) the provers wish to prove to a verifier that \( C(w_1, \ldots, w_D) = 1 \). A natural solution for distributed
proof generation is to start with the prover algorithm of a single prover protocol and run this algorithm between multiple provers using multi-party computation (MPC). This generic construction was discussed by Pedersen [39]. However, the generic construction is unlikely to be efficient in practice. Known constructions of efficient zero-knowledge proofs involve expensive computation (e.g. FFT) over complex mathematical structures such as fields, groups and elliptic curves, which are expensive when expressed as an arithmetic circuit. Running multiparty computation over such circuits with several parties will be prohibitive. To get around the inefficiency of a generic construction, some prior works have proposed efficient distributed proof generation for restricted class of computations. These include simple predicates involved in threshold signatures [38], some sigma protocols [31], combined range proofs [13]. Distributed proof generation for more general computation has been considered in [41], but under weaker trust model involving a trusted setup and majority of the parties being honest [41]. The goal of this paper is to enable DPZK for general computation without requiring trusted setup or honest majority. We summarize our contributions below.

Our Contributions

- We provide a formal definition of distributed prover zero-knowledge (DPZK) in the real-ideal world paradigm. Furthermore, we identify and motivate relevant efficiency parameters to measure the efficiency of a DPZK protocol.
- We present a compiler that takes any IOP-based zero-knowledge protocol and converts it to an “MPC-friendly” zero-knowledge protocol which can then be used to obtain a DPZK protocol.
- We illustrate the application of our compiler for two single-oracle IOPs, which is the preferred setting for our compiler. We obtain the protocol D-Ligero by using our compiler with the Ligero protocol from [1]. Building upon the techniques used in Ligero, we construct a new single-oracle IOP which we call Graphene. The protocol Graphene admits smaller proof sizes than Ligero while ensuring efficient verification. Moreover we show that Graphene can also be efficiently compiled to yield a DPZK protocol, which we call D-Graphene. The zero knowledge protocols are described as interactive protocols secure against honest verifiers. Using standard transforms such as [7, 26], they can be used to obtain succinct non-interactive arguments of knowledge (SNARGs), which are secure against malicious verifiers in the Random Oracle model.

Before providing a detailed overview of our work, we discuss potential real-world applications where distributed proof generation can be useful.

2 Potential Application: Multi-Wallet Anonymous Payments

One application scenario that we highlight is in the context of decentralized anonymous payment networks similar to Zcash [40]. In this example, we consider a variant of Zcash network suitably modified to work with MPC-friendly zkSNARKs discussed in this paper. The users on the network create and consume coins via following transactions: (i) Mint transaction which allows users to introduce coins to the system (after equivalent funds are deposited to a backing pool), (ii) Spend transaction which allows a user to consume his unspent coins and create new coins for other users and (iii) Redeem transaction which allowed a user to redeem his unspent coins in exchange for equivalent funds in traditional banking systems. Our application is concerned with the Spend transaction. In general an n-ary spend transaction consumes n input coins and outputs n coins with matching cumulative value. The output coins may be assigned to different users. To ensure unlinkability of input and output coins, coins are created and spent using separate identifiers, known as coin commitment (cm) and serial number (sn) respectively. Roughly, cm and sn for a coin are linked via a trapdoor τ: cm = f₁(τ) and sn = f₂(τ) for one-way functions f₁ and f₂. Knowing one of them, it is infeasible to infer the other. As part of a spend transaction, the user supplies serial numbers sn₁,...,snₙ for the n coins being consumed along with the commitments for the output coins. Additionally, the user supplies a zero knowledge proof π showing that each serial number corresponds to a valid and unspent coin and that the cumulative value of the coins is equal to the cumulative value of the output coins. By verifying the above zero knowledge proof, the participants on the network can ensure the validity of the transaction.

The above setup does not allow different users to pool in their coins as inputs to a spend transaction, for example, to jointly pay off another entity. The limitation stems from having to generate a zero knowledge
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proof, for which the user requires knowledge of all the private information associated with a coin. One way to work around the limitation is for users to transfer their respective coins (via spend transactions) to one designated user, who then initiates a spend transaction consuming all the received coins on their behalf. However, the operation is no longer atomic and the designated user may not go ahead with his transaction.

Using distributed proof generation, the set of pooling users supply the share of the witness corresponding to the coins they own, and use a distributed proof generation protocol proposed in this paper to output a proof that proves the validity of all the coins to the larger network. This results in an atomic payment between upto n senders and recipients.

Similarly, for auctions with joint bidding that use cryptocurrencies, a set of users can leverage DPZK to produce a proof that they together own coins amounting to the submitted bid.

3 Overview of Our Work

In the single-prover setting, the efficiency of a zero-knowledge protocol is usually measured in terms of:

- **prover complexity**, denoted by \( t_{pr} \), which represents the time complexity of the prover algorithm,
- **proof/argument size**, denoted by \( c_{zk} \) that refers to the amount of communication from the prover to the verifier,
- **verifier complexity**, denoted by \( t_{v} \), which represents the time complexity of the verifier algorithm, and
- **round complexity**, denoted as \( r_{zk} \), which represents rounds of interaction between the prover and the verifier.

However, these parameters do not capture the core bottleneck in the setting of multiple provers. As a first step in our work, we identify additional parameters with significant impact in a distributed proof generation. A lower value of each parameter enhances the practicality of the distributed protocol.

**Proof-generation communication** (\( c_{pr} \)): This parameter quantifies the amount of communication between the provers during the distributed proof generation. This is meant to capture additional MPC communication that provers would incur while computing the messages to the verifier. Using secret-sharing based MPC protocols, \([4, 19, 28]\), this depends on the number of multiplications between inputs from different parties (cross-

**Proof generation rounds** (\( r_{pr} \)): This indicates the number of MPC executions between the provers during the distributed proof generation. This is orthogonal to \( r_{zk} \) and may not have any correlation with it. The parameter \( r_{pr} \) is also of cryptographic interest. If there are more than one round of prover message generation that requires MPC, care has to be taken to ensure a secure composition of the individual MPCs to prove the complete protocol is secure.

**Shared circuit complexity**: We will now elaborate a bit more on the number of cross-multiplications in the circuit that needs to be evaluated distributedly for proof generation since that is of practical relevance and influences prover communication (\( c_{pr} \)) and proof generation rounds (\( r_{pr} \)). In applications where the initial witness is canonically partitioned among the provers, that is the witness \( w = w_1|...|w_D \), the term shared circuit denotes a sub-circuit consisting of wires, whose values are functions of inputs from more than one prover.

Consider the circuit for verifying the validity of the Spend transaction in Section 2. Let \( rt \) denote the Merkle root over the list of coins on the ledger. Thus, to show that a coin commitment \( cm \) corresponds to a valid coin, one provides an authentication path \( p \) from \( cm \) to \( rt \). Hence, the witness \( w_i \) involves the coin commitment \( cm_i \), the trapdoor \( \tau_i \) for the coin and authentication path \( p_i \) from \( cm_i \) to the root \( rt \). This part of the witness is completely known to the owner of the \( i^{th} \) coin. Thus the witness \( w \) authenticating the coins against the serial numbers is canonically partitioned into \( w_1, ... , w_n \) and requires no interaction to compute. On the other hand, secure computation is required to compute shares of witness wires checking the equality \( u_1 + ... + u_n = v_1 + ... + v_n \) where \( u_i \) is the value of the \( i^{th} \) output coin and \( v_i \) denotes the value of the \( i^{th} \) input coin. Clearly, this “shared circuit” constitutes only a fraction of the entire witness. It would be desirable, though not obvious if the secure computation for computing the proof also depends on the size of shared circuit instead of the that of the entire circuit. Since verifying merkle authentication paths using standard hash functions (like SHA2) incur upwards of \( 100K \) gates, the practicality of distributed proof generation in this case will be greatly improved if its parameters (like \( c_{pr} \) and \( r_{pr} \)) are linear in the size of the shared circuit \( N_s \) and not the total circuit size \( N \).

In summary, the efficiency of a DPZK in the public-verifiable and non-interactive setting (which is our con-
cern) will be measured via $c_{pr}$, $r_{pr}$, in addition to the parameters for the single prover protocol.

3.1 On the Formal Definition of DPZK

Just like the efficiency considerations, the security definition for a DPZK protocol needs to account for additional interaction. In particular, the security definition needs to capture the fact that interaction among the provers to generate the proof does not leak knowledge about their respective witnesses to other provers. We come up with an MPC-style definition based on real-world ideal world paradigm [14, 17, 27, 35] that takes the above issues into account. In the ideal-world, the provers deliver their respective part of the witnesses, and the functionality (that is parametrized with a language) combines them and check the assertion of a statement. In the real protocol, the provers participate in instances of MPC for ‘proof-generating functions’ to generate messages for the verifier. To keep the proof-size independent of the number of provers, one of the provers enacts in a special role called aggregator that prepares the message for the verifier, taking into account communication from all its fellow provers and communicates the same to the verifier on behalf of all the provers. We say our protocol is secure if whatever an adversary (corrupting various subsets of provers and verifier) can do in real execution can be done in the ideal execution.

We formalize the security of a DPZK protocol and state the precise trust assumptions under which we realize it in Section 4. Here we foreshadow the important aspects: (i) Witness Confidentiality, i.e, a DPZK protocol ensures that other provers do not learn private inputs of a prover during distributed proof generation involving semi-honest provers, (ii) Zero Knowledge, i.e, an honest verifier learns nothing beyond the truth of the statement in a DPZK protocol involving semi-honest provers and (iii) Soundness With Witness Extraction, i.e, an honest verifier rejects a false statement even if the provers act maliciously. In practice, the restriction of honest verifier is overcome by using standard transformations to obtain non-interactive argument from the interactive proof. Realizing a DPZK protocol for a malicious set of provers might be measured via $c_{pr}$, $r_{pr}$, in addition to the parameters for the single prover protocol.

3.2 Compiler for IOP-based Proof Systems

Several recent constructions of efficient SNARKs [6, 7] are modeled in terms of Interactive Oracle Proofs (IOPs). In this work, we present a compiler that compiles an existing IOP, into an IOP that admits efficient proof generation by a distributed set of provers. This requires navigating several technical challenges: (i) IOPs use the abstraction of oracles, wherein the verifier does not receive the messages from the prover entirely, and only query a small number of positions and (ii) transforming IOPs to Non-interactive Proof of Knowledge (SNARKs) requires the use of collision-resistant hash functions to realize the oracles. The major challenge that we address is providing the abstraction of oracle by a distributed set of provers (with shares of the message), which is indistinguishable from the one provided by a single prover (with the complete message).

We use a common aggregator $A$ to interact with the verifier on behalf of all the provers. Naively, to provide oracle access to a message, $A$ itself needs to have access to the complete message. But this violates our privacy constraints: IOPs ensure privacy only when a “small” portion of the message is accessible. We resolve this conflict by using linear sharing and homomorphic commitments. In all rounds, provers maintain a linear sharing of the IOP message. They share commitments of their shares with $A$, which then has access to the commitment of complete IOP message. To the external verifier, $A$ presents the commitment as the message and provides query access to it. While answering queries on the “committed oracle”, $A$ additionally opens the commitments that are queried. We present the above construction as a two steps: the first step involves transforming an existing IOP into an IOP with “homomorphic” oracles. In the second step, a $(D + 1)$-DPZK protocol is obtained where $D$ provers run the prover algorithm of the homomorphic IOP protocol $(D + 1)$ indicates that the protocol involves $D$ provers and one verifier. These provers jointly compute the proof where the provers start with a linear sharing of the witness. We elaborate more below and defer the details to the later section (Section 5).

Let $(\mathcal{P}, \mathcal{V})$ be an $r$ round IOP-based proof system. $\mathcal{P}$ sends $f_i = (m_i, \pi_i)$ as the $i$th round message and $\mathcal{V}$ has oracle access to $f_i$ where $m_i$ is given to $\mathcal{V}$ in the clear and $\mathcal{V}$ makes bounded number of queries to $\pi_i$. In the compiled protocol, say $(\mathcal{P}', \mathcal{V}')$, $\mathcal{P}'$ sends $f'_i = (m'_i, \pi'_i)$ at the $i$th round where $\pi'_i$ is the commitment of $\pi_i$. In this step a homomorphic commitment is used. If $\mathcal{V}'$ queries some location to the oracle, oracle sends the committed value, and $\mathcal{P}'$ provides the corresponding opening. $\mathcal{V}'$ checks if the opening of $\pi'_i$ on the queried locations are correct. If all the openings are correct then $\mathcal{V}'$ runs the verification algorithm of $\mathcal{V}$. Completeness and zero-knowledge of the newly obtained protocol follow directly from the under-
lying protocol, and soundness depends on the soundness property of the base protocol and the binding property of the commitment scheme.

To obtain the DPZK from the compiled protocol, we start with D copies of $\mathcal{P}'$. Each of these provers computes a linear sharing of $(m_i, \pi_i)$. If the $m_i$ and $\pi_i$ are linear functions of the secret, then no interaction among the provers is required. That is, they locally compute linear functions of the secret, then no interaction among these shares. If not, they perform secure evaluations of the provers is required. That is, they locally compute linear functions of the secret, then no interaction among these shares. If not, they perform secure evaluations of

The verification algorithm is the same as in the single prover protocol.

This compiler preserves the proof size and the number of the rounds. However, the compiled protocol has an overhead of proof generation and verification time. This overhead depends on the oracle size, the number of oracles and the number of rounds.

### 3.3 Instantiations of Distributed Prover Zero-Knowledge

We instantiate a few distributed proof generation protocols. As discussed earlier, a protocol obtained from the above compiler is more likely to perform better in a distributed proof generation if the base protocol has less number of rounds and oracles. Thus we start with the compiled version of Ligero [1] since it has a constant number of rounds and only one oracle. Further, we provide a protocol Graphene by optimizing this newly obtained protocol from Ligero.

Additionally, we discuss the cost of the distributed protocol obtained from Aurora [6]. This gives a perspective of the efficiency of a compiled protocol where the base protocol is a multi-oracle IOP. We study the distributed proof generation for non-IOP protocols such as Bulletproofs [13] and Spartan [42]. Bulletproofs achieve the distributed proof generation naturally without requiring any additional primitives excluding secure multiplication (which is inherent in all the instantiations). In the distributed variant of Bulletproofs, provers securely evaluate multiplication of 2 vectors. The size of these vectors is $O(N_s)$, where $N_s$ is the size of the shared circuit. Furthermore, each prover sends $O(N)$ field elements towards the aggregator. In the distributed version of Spartan, $O(N^2)$ multiplications are required among the provers. However, this construction does not ensure privacy among the provers. This shows the non-triviality of the distributed proof generation.

### 3.4 Graphene: an MPC-friendly Zero-Knowledge Protocol

To construct Graphene, we adjoin an additional dimension in the Ligero protocol and modify the encoding, the linear check, and the quadratic check accordingly. With this optimization, we break the $\sqrt{N}$ (N is the size of the circuit) barrier of Ligero, following a similar idea of the concurrent work of Ligero++ [8] where succinct inner product argument is used. Ligero++ uses inner product argument from Virgo [46] whereas we use Bulletproofs’ [13] inner product argument. Furthermore, for the soundness of Graphene, we provide novel results in coding theory. By adjoining an additional dimension, our protocol gets better flexibility to trade-off between proof size and verification time. Furthermore, we organize the witness so that if the shared circuit is small, then the communication among the provers is required for $N^{1-2/c}$ multiplications. In contrast, Ligero’s compiled protocol would require $N^{1/2}$ multiplications. Also in distributed version of Ligero and Graphene, each prover sends $O(\sqrt{N})$ and $O(N^{1-2/c})$ field elements towards the aggregator respectively. Note that the 3-D encoding, obtained by adjoining an additional dimension, helps in reducing the proof size while keeping the verification time low. Also, if the size of the shared circuit is small, this additional dimension aids in reducing the communication among the provers as well. The details of Graphene are given in Appendix B.

### 3.5 Related Work

As mentioned earlier in the introduction, Pedersen [39] defines the notion of distributed proof generation and proposes a generic construction using MPC. Over the years, works have discussed distributed proof generation for a restricted class of predicates: Desmedt et al. [21] proposing proofs for graph isomorphism, various works [20, 33, 38] for proposing threshold signatures, Keller et al. [31] for a class of sigma protocols. More recently [13] presented a distributed variant of range proofs which allows several provers to compute a common proof showing their private inputs lie within an interval. However their protocol does not satisfy our stronger privacy requirements as the size of the proof depends on the number of provers.

Trinocchio [41] proposes a distributed proof generation method for Pinocchio [37] but only for honest majority setting. Moreover, it assumes a trusted setup. The work DIZK [44] provides a distributed implementation
of proof generation to reduce proving time. There is no notion of privacy among the provers in this setting.

In this work, we study how to achieve distributed proof generation from other existing works such as Ligero [1], Aurora [6], Bulletproofs [13], Spartan [42] and the corresponding challenges. To attain an efficient construction, we start with a Ligero-style protocol and use a similar approach to [11, 12], where the witness is viewed as a multi-dimensional matrix. However, we restrict to 3 dimensions since, among these dimensions, only the smallest one contributes to the proof size, while the remaining two aid in better verification time. In our setting, increasing the number of dimensions beyond three leads to more complicated and costlier proof-generation and verification protocols without improving any other parameters. [12] provides linear-time prover with polylogarithmic verification, but a significant drawback of this work is that the soundness error is $O(1)$. Furthermore, [11] obtain linear-time prover by using linear-time encodable codes. For this, they use a linear code provided by [23], whose decoding is conjectured intractable. Due to this property, [11] does not satisfy the proof of knowledge property. Moreover, constructions with higher dimensions require more rounds and oracles which incur higher overhead in the distributed proof generation. Ligero++ [8] overcomes Ligero’s $O(\sqrt{N})$ proof size bottleneck by using Virgo [46] inner product argument, which uses Aurora style proof system. Thus the distributed proof generation of Ligero++ is similar to the distributed variant of Aurora. In our construction, we use inner product argument from Bulletproofs. In Table 1, we compare the different metrics of efficiency for all the existing DPZK protocols.

Another recent line of works such as Wolverine [43], Mac’n’Cheese [2], LPZK [22], QuickSilver [45] focuses on the scalability of the zero-knowledge proofs. These works take the “gate-by-gate” paradigm by relying on Vector Oblivious Linear Evaluations (VOLEs). Wolverine provides a ZK protocol with 4 field elements per multiplication gate. Mac’n’Cheese further improves it by providing a protocol with 3 elements per multiplication gate. While QuickSilver and LPZK both achieve a ZK protocol with 1 element per multiplication gate, LPZK is computationally heavier. All these works have linear communication complexity. Additionally, if the circuit satisfies a certain condition, called “weak notion of uniformity”, QuickSilver achieves sub-linear communication. The gate-by-gate paradigm employed in these works, however, is restricted to interactive protocols. That is, it does not support non-interactivity. Furthermore, a common aggregator approach does not work for these protocols since this would either require the verifier to communicate with all the provers or the aggregator to learn the whole witness. Overcoming the problems mentioned above and obtaining distributed variants of these works is an interesting area to explore, which we leave as future work.

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4 Definition for Distributed Proof Zero-Knowledge

This discussion will formally define a zero-knowledge protocol which supports multiple provers and distributed proof generation. With the eventual goal of protocols that are non-interactive and publicly-verifiable, we keep our focus on public-coin (where the verifier only sends truly random messages) protocols in mind. Our definition can be extended to private-coin protocols. Note that, the non-interactiveness concerns the communication between the set of provers and the verifier. We may still need multiple rounds of communication just amongst the provers for proof preparation. Consider a language $L \in \text{NP}$ and the corresponding relation $R$ such that $x \in L \iff R(x, w) = 1$ for some witness $w$. Let $P_1, \ldots, P_D$ be $D$ provers and $V$ be the verifier. A public-coin DPZK protocol consists of four probabilistic polynomial time algorithms: $(\text{SetUp}, \Pi, A, V)$ as defined below.

- **SetUp** takes as input the security parameter $1^\lambda$ and optionally a trapdoor $\tau$ and outputs the public parameters of the system. The trapdoor input as well as the public parameter can possibly be empty.

- For a $R$-move DPZK, $\Pi$ is defined by a sequence of $R$ $D$-input and $D$-output functions/algorithms $\{\pi_i\}_{i \in [R]}$, where a move indicates a one-shot communication from the provers to the verifier. The $i$th function takes the states of the provers at $i$th state i.e. $\pi_i(st_1^i, \ldots, st_D^i)$. $st_j^i$ is set to $P_j$’s share of the witness $w_j$, randomness, the public parameters and is updated at the end of each move. For every, $\pi_i$ there is a corresponding aggregator algorithm $A_i$ that takes the outputs of $\pi_i$ and generates a single message $m_i$ for $V$ for the $i$th move. Therefore, $A$ for a $R$-move DPZK is defined as $\{A_i\}_{i \in [R]}$. $m_i$ can possibly be a message in response to a random challenge that $V$ outputs for $i$th move. Recall that $V$ only outputs uniform random challenge in a public-coin DPZK. Finally, the output of $V$ is either an accept (1) or a reject (0).
We note that computing $\pi_i$, without leaking the states to each other, may require interaction amongst the provers. It is important to note that the output of A alone is sent to the verifier on behalf of all the provers. In simple terms, A is an aggregator algorithm for the provers messages and is the key in making the proof-size delivered to the verifier independent of the number of provers. The task of accomplishing A can be assigned to (a) one or a constant-size subset of the provers, (b) an external entity or even (c) a hardware token. In this work, we take the route of allowing one of the provers to execute A.

Intuitively, a DPZK protocol for a language $L$ will satisfy the following properties: (a) correctness: when the provers and the verifier are good, the verifier should accept if and only if the provers hold a valid witness; (b) soundness: the corrupt provers cannot make the verifier accept without holding a valid (joint) witness; (c) zero-knowledge: a corrupt verifier does not learn any information, except the assertion of the statement; (d) witness-confidentiality: the witness of the honest provers remain hidden from a collusion of a corrupt verifier and a subset of provers. Below, we formally prove security of such protocols based on real/ideal world paradigm.

### 4.1 Real-Ideal World Definition for DPZK

We prove the security of our protocols based on the standard real/ideal world paradigm. Essentially, the security of a protocol is analyzed by comparing what an adversary can do in the real execution of the protocol to what it can do in an ideal execution, that is considered secure by definition (in the presence of an incorruptible trusted party). In an ideal execution, each party sends its input to the trusted party over a secure channel, the trusted party computes the function based on these inputs and sends to each party its respective output. Informally, a protocol is secure if whatever an adversary can do in the real protocol (where no trusted party exists) can be done in the above described ideal computation. We refer to [14, 17, 27, 35] for details regarding the security model. Extending the definition to Universal Composability (UC)[15] secure model and obtaining a secure protocol in this model is an interesting question that we leave as a future work.

The ideal execution: The “ideal” world execution of DPZK involves parties in $P$ that includes D provers $\{P_1, \ldots, P_D\}$ and a verifier $V$, an ideal adversary $S$ who may corrupt various subset of parties in $P$, and a functionality $F_{DPZK}$. The functionality is parametrized with an NP language $L$ and the corresponding relation/verification function $R$. Each prover $P_x$ sends $(x, w_x)$ to $F_{DPZK}$, where $x$ is the statement and $w_x$ is the $x$th part of the witness. The verifier $V$ sends $x$. $F_{DPZK}$ computes $w = w_1 \oplus w_2 \ldots \oplus w_p$, where $\oplus$ is the combining function of the parts of the witness held by the provers distributedly, and sends $R(x, w)$ to everyone. $F_{DPZK}$ is described below.

Let the corrupt set be denoted as $I$. We let $\text{ideal}_{DPZK, S(z)}(\bar{x})$ denote the random variable consisting of the output pair of the honest parties and $S$ controlling the corrupt parties in $I$ upon inputs $\bar{x} = (x_1, \ldots, x_D)$ for the parties and auxiliary input, such as trapdoor and additional information, $z$ for $S$.

The real execution: In the real model, the parties run $\Pi_{DPZK}$ protocol. We consider a synchronous network with private point-to-point channels amongst the provers, and an authenticated broadcast channel. This means that the computation proceeds in rounds, and in each round parties can send private messages to other parties and can broadcast a message to all other parties and the verifier communicate with a designated prover, referred as aggregator. We stress that the adversary cannot read or modify messages sent over the point-to-point channels, and that the broadcast channel is authenticated, meaning that all parties know who sent the message and the adversary cannot tamper with it in any way. Nevertheless, the adversary is assumed to be reshuffling, meaning that in every given round it can see the messages sent by the honest parties before it determines the messages sent by the corrupted parties.

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<th>Protocols</th>
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<td>$O(\log(N))$</td>
<td>$O(\log(N))$</td>
<td>$O(N \log(N)) E + O(N \log(N)) M$</td>
<td>$O(N \log(N)) E + O(N) M$</td>
<td>$O(D \cdot \max(N, \sqrt{N}))$</td>
<td>1</td>
</tr>
<tr>
<td>D-Graphene</td>
<td>$O(N^{1/2})$</td>
<td>$O(\log(N))$</td>
<td>$O(N \log(N)) E + O(N \log(N)) M$</td>
<td>$O(N^{1/2} \log(N)) E + O(N) M$</td>
<td>1</td>
<td>$O(D \cdot \max(N, \sqrt{N}))$</td>
</tr>
</tbody>
</table>

Table 1. Comparison amongst the DPZKs. Here $N$ is the size of the circuit and, $c$ is a positive integer of our choice. $D$ is the number provers in the DPZK setting. $M$ is to indicate the amount of computation required for a single multiplication on the field elements, and $E$ is to indicate the amount of computation required for single exponentiation on the group elements, in which Dlog is assumed to be hard. And $N_s$ denotes the size of the shared circuit.
Functionality (The Distributed Prover Zero Knowledge Functionality $\mathcal{F}_{DPZK}$)

The functionality is parametrized with an NP relation $R$ of an NP language $L$.

- Upon receiving input $x_i = (x, w_i)$ from $\mathcal{P}_i \forall i \in [D]$ and $x$ from $\mathcal{V}$, do the following: if $x_i$ is an empty string or falls outside the range of the domain of $\mathcal{P}_i$’s input, reset $x_i = \text{abort}$.
- $\mathcal{F}_{DPZK}$ sends $|x_i|$ for all $\mathcal{P}_i \in [D]$ and $\{x_i\}_{i \in I}$ to the simulator $\mathcal{S}$, where for all $i \in I$, $\mathcal{P}_i$ is a corrupt prover.
- If any of the $x_i$ is abort, send abort to everyone in $\mathcal{P}$. Otherwise, compute $w = w_1 \oplus w_2 \ldots \oplus w_D$, where $\oplus$ is the combining function of the parts of the witness held by the provers distributedly and send $R(x, w)$ to $\mathcal{S}$.
- $\mathcal{S}$ sends a command abort or continue to $\mathcal{F}_{DPZK}$. If $\mathcal{F}_{DPZK}$ receives abort it sends abort to all, otherwise it sends $R(x, w)$ to everyone.

As per $\Pi_{DPZK}$, the first party produce the output of SetUp. Next, in $i$th move, the provers run a distributed protocol to compute $\pi_i$ with respective states and a single prover, runs $A_i$ on the outputs of $\pi$ received from the provers, computes $m_i$ and sends the output $m_i$ of the computation to $\mathcal{V}$. $m_i$ can possibly be a message in response to a challenge that $\mathcal{V}$ broadcasted. The protocol ends after $R$ steps.

In summary, the “real” world execution involves the PPT parties in $\mathcal{P}$, and a real world adversary $\mathcal{A}$ who may corrupt a set of parties in $I$ maliciously. Let $\text{REAL}_{\Pi, A(z), I}(\vec{x})$ denote the random variable consisting of the output pair of the honest parties and the adversary $A$ controlling the corrupt parties in $I$ in the real execution, upon inputs $\vec{x}$ (defined in the same way as the ideal world) for the parties and auxiliary input $z$ for $\mathcal{A}$.

Security via Indistinguishability of Real and Ideal World: The definition is given below

**Definition 1.** Let $\mathcal{F}_{DPZK}$ be a $(D+1)$-party functionality and let $\Pi_{DPZK}$ be a $(D+1)$-party protocol involving $\mathcal{P}$ for DPZK. We say that $\Pi_{DPZK}$ securely realizes $\mathcal{F}_{DPZK}$ if for every PPT probabilistic real-world adversary $\mathcal{A}$, there exists an PPT expected polynomial-time ideal-world adversary $\mathcal{S}$, such that for every $I \subset \mathcal{P}$, every $\vec{x} \in \{(0,1)^*\}^D$ where $|x_1| = \ldots = |x_D|$, and every $z \in \{0,1\}^*$, it holds that:

$$\text{REAL}_{\Pi_{DPZK}, A(z), I}(\vec{x}) \equiv \text{REAL}_{\Pi, A(z), I}(\vec{x})$$

Note that if the inputs of provers are not of the same length, then by padding zeros, inputs can be made of the same length. However, the verifier does not have any private input, so this requirement is exclusive to the provers.

When $I$ is $\{\mathcal{P}_1, \ldots, \mathcal{P}_D\}$, $\{\mathcal{V}\}$, a proper $t$-size subset of $\{\mathcal{P}_1, \ldots, \mathcal{P}_D\}$, a proper $t$-size subset of $\{\mathcal{P}_1, \ldots, \mathcal{P}_D\}$ plus $\mathcal{V}$, the above indistinguishability is referred as Soundness with Witness Extraction (SoWE). Zero-Knowledge (ZK), witness-confidentiality (WC), witness-confidentiality with collusion (WCwC) respectively.

**Soundness with Witness Extraction (SoWE)** Let $\mathcal{A}$ be the adversary corrupting parties in $\mathcal{P} = \{\mathcal{P}_1, \ldots, \mathcal{P}_D\}$ and $\Pi_{DPZK}$ be a secure protocol against $\mathcal{A}$. Then, by definition 1, there exists a simulator which emulates the verifier ($\mathcal{V}$) and outputs a view indistinguishable from the real-world view. If $\mathcal{A}$ interacts with $\mathcal{V}$ which causes $\mathcal{V}$ to accept, then the simulator extracts the input of $\mathcal{A}$ such that the output of the functionality is accept. We refer to this simulator as an “extractor”.

That is, a protocol $\Pi_{DPZK}$ is said to have the soundness with witness extraction property, if corresponding to an adversary $\mathcal{A}$ that corrupts $\mathcal{P} = \{\mathcal{P}_1, \ldots, \mathcal{P}_D\}$ and outputs an accepting proof for a statement $x$ and relation $R$, there exists an extractor $\mathcal{E}$ that emulates $\mathcal{V}$ and with overwhelming probability extracts a witness $w$ such that $R(x, w) = 1$.

**Zero-Knowledge (ZK)** Let $\mathcal{A}$ be the adversary corrupting the verifier $\mathcal{V}$. A protocol $\Pi_{DPZK}$ is said to have the zero-knowledge property, if there exists a simulator $\mathcal{S}$ that outputs a transcript which is indistinguishable from a real transcript. Note that a non-colluding verifier (verifier that does not collude with any of the provers) learns nothing more than the statement’s assertion, not even the number of provers in the protocol. Therefore the simulated transcript remains independent of the number of provers.

Note that if the functionality in Figure 4.1 is modified such that the witness $w$ is the input of only one prover and a protocol is secure against a verifier that learns nothing more than the assertion of the statement $x$, has the zero-knowledge property. The simulator for a corrupt verifier does not use the parameter $D$ to simulate the view. Our construction satisfies this requirement.
Witness-Confidentiality (WC) A protocol $\Pi_{\text{DPZK}}$ is said to have witness confidentiality property if an adversary $A$, corrupting $t \leq D$ out of $D$ provers, learns nothing about the honest provers’ inputs. That is, there exists a simulator $S$ acting on behalf of the honest provers and the verifier, which generates a view which is indistinguishable from the real-world view of the corrupt provers.

Witness-Confidentiality with Collusion (WCwC) A protocol $\Pi_{\text{DPZK}}$ is said to have witness confidentiality with collusion property if there exists a simulator $S$, corresponding to an adversary $A$ corrupting $t$ provers and the verifier, that plays the role of the honest provers and generates a view which is indistinguishable from the real-world view of the corrupt parties.

While we give a very strong definition as above, motivated by several practical aspects, we relax the assumption on adversarial power and will focus on a subset of the above properties for our constructions. We elaborate below on this.

### 4.2 Our Setting for DPZK

Our final goal is to produce arguments/proofs that is non-interactive and publicly-verifiable. We stress that the non-interactiveness concerns the communication between the set of provers and the verifier. We may still need multiple rounds of communication just amongst the provers for proof preparation. Most of the applications we foresee work best with these features. With these features as end-goal, we will design public-coin honest-verifier protocols that via generalized Fiat-Shamir heuristic [7, 26] can be turned into non-interactive and publicly-verifiable proofs/arguments. This setting has quite a many interesting bearing for us. First, in the honest-verifier setting, the verifier is considered to be only semi-honestly corrupt and so the ZK property needs to be proven keeping such a weaker adversary in mind. Second, non-interactiveness and publicly-verifiable make the two properties WC and WCwC equivalent, since the verifier has nothing more to add to the view of the corrupt provers in the case of collusion (in fact, the view of a corrupt aggregator itself subsamples the view of a verifier).

Our next relaxation comes in the form of imposing a semi-honest behaviour on the prover that acts as an aggregator. We justify the reason as follows. First, our aggregation function is deterministic. Having a deterministic aggregation procedure reduces the task to just combining the inputs and has a better promise to be executed through a hardware token that may not have randomness sampling capability. The deterministic also in part helps the function to be reproducible by every prover when the information sent to the aggregator is sent over a public broadcast channel. This allows an easy check on the behaviour of the aggregator and a strong deterrent for the aggregation to be carried out dishonestly, as reputation may be at stake and applications typically bind the provers to act rationally (and hence honestly or semi-honestly) for the common cause of coming up with an accepting proof.

In summary, we will prove three properties for our protocols: (a) ZK assuming a semi-honest verifier, (b) SoWE tolerating malicious provers and (c) WC tolerating semi-honest provers and aggregator. Our protocol can easily be modified to achieve privacy from the maliciously corrupt provers. But we do not have a provably secure DPZK when the aggregator is maliciously corrupt. A DPZK which is provably secure when the provers and the aggregator is maliciously corrupt remains open.

As for the form of witness partition across the prover’s, we assume that the provers jointly hold an additive sharing of the witness $w$. This is general enough and well supported by secret sharing protocols.

### 4.3 Related Notions

Closely related to our notion is the work of [31] which discusses threshold proofs. This work distributes the prover’s side of interactive proofs of knowledge over multiple parties for: (i) improving the security against theft of the user’s identity, (ii) improving robustness by ensuring that only a restricted size subset of the provers may be corrupted. The work of [31] primarily captures sigma protocols without allowing interaction among the provers. Our definition captures a broader class of protocols via allowing interaction amongst the provers. In other words, threshold proofs are a sub-class of the protocols we cater to. Also, other than increasing security via a decentralization of the prover (or distributing prover’s task), our goal is to capture scenarios where multiple provers would like to jointly prove a statement. Our real-ideal world based definition is inline with MPC-style definitions and is more powerful. [39] also defines distributed proofs. [39] considers the provers’ witnesses to always be secret shares of a “global” witness, and hence the provers’ witnesses are random when the distributed proof generation begins.
But, our definition allows for any distribution on the provers’ witnesses, and this impacts some of our security proofs. In other words, any individual share of the witness used in [39] does not have any stand-alone significance. On the other hand, in our security definition, any individual share of the witness is a private input of the corresponding shareholder, and it provides privacy of such individual shares. Another notion, called multi-prover interactive proofs (MIP), was introduced by Goldwasser et al. [3]. Here, multiple provers hold a common witness corresponding to a statement and provide proofs. MIP is used to reduce the soundness error. However, the setting in MIP [3, 9] is entirely different from our notion since, in the DPZK setting, no prover holds a complete witness, and all the provers jointly provide a proof. A linking paradigm between zero-knowledge and MPC, called MPC-in-the-head, was introduced by Ishai et al. [30], where the prover runs a multiparty protocol in its head and uses the view of the emulated parties to provide a proof. This process requires opening the views/inputs of the parties performing the MPC. Therefore, this approach cannot be used to obtain a DPZK protocol since, in this setting, opening a party’s view to the verifier implies compromising that party’s privacy. Moreover, the efficiency of the zero-knowledge construction from MPC-in-the-head-paradigm depends on the MPC protocol emulated by the prover, i.e., the protocol decides the number of parties and corruption scenario (honest majority or dishonest majority/semi-honest or malicious). In an arbitrary setting, using MPC-in-the-head-paradigm can be inefficient. One might ask to run MPC to generate the trusted setup and then use a protocol with a trusted setup. However, generating a trusted setup via MPC requires the verifier to participate in the MPC, which precludes publicly verifiable non-interactive proofs.

5 DPZK Compiler

With recent advancements in zero-knowledge, protocols in IOP paradigm, such as Ligero [1], Ligero++ [8], Aurora [6] to name a few, bring efficiency in proof size, proof generation time and verification time. Most of the IOP-based protocols work with only symmetric key primitives, which leads to better efficiency. Therefore in search of efficient DPZK, we look into the IOP-based paradigm. Designing a DPZK directly from an IOP-based protocol faces the following challenges. (i) Each prover sets its oracle individually: in this case the verifier is required to communicate with each prover. It violates the zero-knowledge requirement of DPZK, specifically, the verifier learns the number of provers in the protocol. Furthermore, it increases the proof size and verification time by a factor of the number of provers. (ii) All the provers send their messages to one designated prover, called aggregator who aggregates and sets up the oracle in every round: in this case, the aggregator learns the private input of an honest prover, which defies the witness confidentiality property. In our construction, we use the second approach mentioned above where an aggregator sets up the oracle in every round. To ensure the witness confidentiality property it is now required that the aggregator be able to combine the messages from the provers without learning them in clear. Moreover, it is also required that a corrupt prover should not be able to deviate from the messages once the aggregator sets up the oracle. A homomorphic commitment scheme offers itself as a primitive which handles the above requirements. Such a scheme can be instantiated using Pedersen commitment or Pedersen vector commitment.

We encounter another roadblock as follows. In particular, it need not be the case that oracles in every round are linear functions of the witness. In cases where the oracle is a non-linear function, its construction may involve interactions among the provers. To tackle this, we use MPC in our construction. Therefore, the IOP protocols with fewer oracles/rounds are more likely to provide a better DPZK since the required number of MPC invocations would be lesser. Below we discuss a compiler that compiles a single prover ZK protocol to support distributed proof generation.

5.1 The Compiler

We give a generic construction from an IOP-based proof system to obtain another proof system that is suitable for distributed proof generation. The compiled protocol use homomorphic oracles. For this, the compiler requires a homomorphic functional commitment scheme for linear functions. A functional commitment scheme, \( FC \), over a domain \( D \) is a tuple of four probabilistic polynomial-time algorithms - (SetUp, Com, Open, Verify). SetUp generates the key \( ck \) for the commitment. Com commits to a message \( m \). Open provides a witness for a partial or complete opening of the message \( m \), and Verify on input the commitment value and the witness outputs 1 if the opening is valid, and 0 otherwise. We refer the readers to [34] for more details on functional
Interactive Oracle Proofs (IOP)

Let \(\mathcal{P}, \mathcal{V}\) be a \(r\)-round IOP-based zero-knowledge proof system. Let \(st^0 = \{x, w\}, st^1 = \{x\}\), \(s_0 = \perp\) and \(s_r, v_r\) be the randomness used by \(\mathcal{P}\) and \(\mathcal{V}\) respectively. Then for \(i = 1, \ldots, r\), in the \(i\)th round: (i) \(\mathcal{V}\) computes \((c_i, st^i) = V_{f_0, f_1, \ldots, f_{r-1}}(st^{i-1}_r, v_r)\) and sends \(c_i\) to \(\mathcal{P}\). (ii) \(\mathcal{P}\) computes \((f_i, st^i) = P(c_1, \ldots, c_i, st^i_{i-1}, \rho_p)\). The output of the protocol is \(b := V_{f_0, f_1, \ldots, f_r}(st^r_r, v_r)\), and \(b\) belongs to \(\{0, 1\}\). \(\mathcal{P}, \mathcal{V}\) has the following properties.

Completeness: For every \((x, w) \in R\), \(\mathcal{P}(x, w), \mathcal{V}(x)\) outputs \(b = 1\) with probability 1.

Proof of knowledge: \(\mathcal{P}, \mathcal{V}\) has proof of knowledge property if there exists a probabilistic polynomial-time algorithm \(E\) (extractor) and a negligible function \(\mu\) such that, for every \((x, \mathcal{P}^*)\), \(Pr[(x, E_{\mathcal{P}^*}(x)) \in R] \geq Pr[(\mathcal{P}, \mathcal{V}(x)) = 1] - \mu(|x|)\).

Zero knowledge: \(\mathcal{P}, \mathcal{V}\) has zero knowledge property if there exists a probabilistic polynomial-time algorithm \(S\) (simulator) such that for every \((x, w) \in R\), it generates a transcript \(\tau\) which is indistinguishable from a transcript of \(\mathcal{P}(x, w), \mathcal{V}(x)\) to any PPT distinguisher.

Homomorphic IOP

Let \(\mathcal{P}, \mathcal{V}\) be an IOP-based zero-knowledge proof system with proof of knowledge property. In general, the prover in an IOP protocol provides oracle access to its messages in each round, while the verifier makes bounded number of queries to these oracles. Without loss of generality, we will write messages from the prover as \(f_i = (m_i, \pi_i)\) for the \(i\)th round, where \(m_i\) denotes the part of message read in entirety by the verifier while \(\pi_i\) is the message to which the verifier has (bounded) query access.

The compiler takes an IOP-based zero knowledge protocol \(\mathcal{P}, \mathcal{V}\) and a homomorphic functional commitment scheme \(\text{Com}(\cdot)\). It outputs a protocol \(\mathcal{P}', \mathcal{V}'\), where \(\mathcal{P}', \mathcal{V}'\) is obtained in the following way: \(\mathcal{P}'\) and \(\mathcal{V}'\) run \(\mathcal{P}\) and \(\mathcal{V}\) algorithms respectively, in a state preserving manner. That is, \(\mathcal{P}'\) runs \(\mathcal{P}\)'s first round and stores the state of \(\mathcal{P}\). Upon receiving the challenge from \(\mathcal{V}'\), \(\mathcal{P}'\) runs the next round of \(\mathcal{P}\) with the prior round’s state and updates the state. \(\mathcal{P}'\) follows this for all rounds. \(\mathcal{V}'\) does the same for \(\mathcal{V}\).

At \(i\)th round, \(\mathcal{P}'\) sets \(\pi^i = \text{Com}(ck, \pi_i)\).

\(\mathcal{P}'\) sends \(f^i = (m_i, \pi^i)\). \(\mathcal{V}'\) has oracle access to \(f^i\) such that it gets \(m_i\) in clear and queries limited number of locations of \(\pi^i\). According to the queried locations, \(\mathcal{P}'\) provides opening of those locations. That is, if \(\mathcal{V}'\) queries \(j\) then \(\mathcal{P}'\) sends \(\text{Open}(ck, \pi^i[j], aux)\) to \(\mathcal{V}'\), where \(aux\) denotes auxiliary information.

\(\mathcal{V}'\) sets the challenge \(c^i = c_i\). When \(c_i\) consists of oracle query \(j\), \(\mathcal{P}'\) receives \(\pi^i[j]\) from the oracle and \(W_i,j = \text{Open}(ck, \pi^i[j], aux)\) from \(\mathcal{P}'\). Further \(\mathcal{V}'\) receives \(m_i\), \(\mathcal{V}'\) checks if \(\text{Verify}(ck, \pi^i[j], W_{i,j}, \pi_i[j]) = 1\), followed by the verification algorithm of \(\mathcal{V}\).
lar to \( V \), \( V' \) receives \( m_i \). In \( \langle P, V \rangle \), \( V \) receives \( \pi_i[j] \) depending on the \( V \)'s choice of \( j \). However, in \( \langle P', V' \rangle \), \( V' \) receives \( \pi'_i[j] \) corresponding to its choice, where \( \pi'_i[j] \) is the commitment of \( \pi_i[j] \) and gets the corresponding opening from \( P', V' \) performs Verify to check if the above opening is correct or not, and for an honest prover, the opening is always correct. Now, \( V \) and \( V' \) hold the same data and perform the same verification. If \( V \) outputs \( b = 1 \), then \( V' \) also outputs \( b = 1 \). Therefore completeness holds for \( \langle P', V' \rangle \).

**Proof of knowledge** of \( \langle P', V' \rangle \) holds due to the proof of knowledge property of \( \langle P, V \rangle \) and the binding property of the commitment scheme.

Let \( P'^* \) be a prover such that \( \langle P'^*, V'(x) \rangle = 1 \). We claim that there is an PPT extractor \( E' \) that extracts a witness \( w \) corresponding to the statement \( x \) with very high probability.

\( E' \) rewinds \( P'^* \) sufficiently many times to extract \( \pi_i \). Thereafter we consider following cases on how \( P'^* \) answers oracle queries for the remainder of the transcript.

**Case I:** \( P'^* \) opens \( \pi_i[j] \) to \( \pi_i[j] \) for all \( i, j \). Then consider a prover \( P^* \) sends \( f_i = (m_i, \pi_i) \) where \( P'^* \) sends \( f'_i = (m_i, \pi'_i) \) and \( \pi_i = \text{Open}(\pi'_i) \). \( V' \) in \( \langle P'^*, V' \rangle \) and \( V \) in \( \langle P^*, V \rangle \) performs the same verification. Since \( \langle P'^*, V'(x) \rangle = 1 \), therefore \( \langle P^*, V(x) \rangle = 1 \). By the proof of knowledge property of \( \langle P, V \rangle \), there is an PPT extractor \( E \) that extracts a witness \( w \) with very high probability. \( E' \) runs the same algorithm and outputs \( w \) with the same probability.

**Case II:** \( P'^* \) opens at least one \( \pi'_i[j] \) for some \( i, j \) to some value \( \pi'_i[j] \) such that \( \pi'_i[j] \neq \pi_i[j] \). This breaks the binding property of the commitment scheme.

Therefore, \( \Pr[(x, \epsilon^{P'^*}(x)) \in R] = \Pr[(x, \epsilon^{P^*}(x)) \in R] - O(|x|)\epsilon_c \), where \( \epsilon_c \) is the probability that any PPT algorithm can break the binding property of Com.

\( \Pr[(P'^*, V'(x)) = 1] = \Pr[(P^*, V(x)) = 1] \). Due to the proof of knowledge property of \( \langle P, V \rangle \), we have \( \Pr[(x, \epsilon^{P'^*}(x)) \in R] \geq \Pr[(P^*, V(x)) = 1] - O(|x|)\epsilon_c \). Hence, \( \Pr[(x, \epsilon^{P'^*}(x)) \in R] \geq \Pr[(P^*, V(x)) = 1] - O(|x|)\epsilon_c - \mu(|x|) \). Set \( \mu'(x) = O(|x|)\epsilon_c + \mu(|x|) \). Since \( \mu' \) is a negligible function, therefore \( \langle P', V' \rangle \) has the proof of knowledge property.

**Zero-knowledge** of \( \langle P', V' \rangle \) holds directly from the zero-knowledge property of \( \langle P, V \rangle \).

Since \( \langle P, V \rangle \) has zero-knowledge property, therefore \( \exists \) a simulator \( S \) that generates a transcript that is indistinguishable from a real transcript. Using \( S \), we will construct a new simulator \( S' \).

\( S' \) executes \( S \). If \( \tau \) is the transcript generated by \( S \), let \( \pi_i[j] \) be the parts of the transcript \( \tau \) corresponding to the \( i \)th round’s oracle response when queried at the \( j \)th location. Then \( S' \) commits to \( \pi_i \) and gets \( \pi'_i \). Finally the simulated transcript, \( \tau' \), generated by \( S' \) by replacing \( \pi_i[j] \) with \( \pi'_i[j] \) and adding corresponding opening of \( \pi'_i[j] \) is indistinguishable from a real execution of \( \langle P', V' \rangle \). This ensures the zero-knowledge property. \( \square \)

**Distributed Proof Generation**

Let \( \langle P, V \rangle \) be an IOP-based zero-knowledge proof system. We define a \((D + 1)\) party protocol \((\text{Dist}(P, D), V)\) with one verifier \( V \) and \( D \) identical copies of \( P \) algorithm, say \( P = \{P_1, \ldots, P_D\} \). In this protocol \( V \) receives messages from one designated party, \( A \), from \( P \) and parties in \( P \) can interact among themselves. In \( \text{Dist}(P, D), V \), \( P_x \) has input \( x, w_x \) for all \( \xi \in D \) and \( V \) has input \( x \). Since \( (f_i, st^\rho_p) = P(c_1, \ldots, c_i, st^\rho_p_{i-1}, \rho_p) \), parties in \( P \) jointly compute \( P(\cdot) \) with public inputs \( c_1, \ldots, c_i \) and \( P_x \)’s private input \( \{st^\rho_p_{i-1}, \rho_p\} \). To obtain a linear sharing of \( (f_i, st^\rho_p) \), parties in \( P \) perform a \( t \)-secure MPC, where at most \( t(\leq D) \) parties can be corrupted. For \( \xi \in [D] \), each \( P_x \) obtains \( ((f_i), (st^\rho_p)) \) where \( \langle \cdot \rangle \) is a \( t \)-out of \( n \) sharing. If \( P(\cdot) \) is a linear function then no interaction is required among the provers. But \( P(\cdot) \) need not be a linear function, in which case communication among the parties in \( P \) is required.

\[ \langle \text{Dist}(P, D), V \rangle \text{ from } \langle P, V \rangle: \]

1. Initiate \((D+1)\)-party protocol with \( D \) copies of \( P \), say \( P = \{P_1, \ldots, P_D\} \) and one \( V \). \( P_1 \) in \( P \) starts the protocol with inputs \( (x, w_\xi) \) and \( V \)'s input is \( x \).
2. \( P_\xi \) sets \( st_\xi = \{x, w_\xi\} \). \( A \) sends \( f_0 = \perp \) and \( V \) sets \( st_0^\xi = \{x\} \).
3. Let \( r \) be number of rounds of \( \langle P, V \rangle \). For \( i = 1 \) to \( r \), parties do the following:
   a. \( V \) computes \((c_i, st^\rho_p) = V^{f_0, f_1, \ldots, f_{i-1}}(st^\rho_p_{i-1}, \rho_c) \) and sends \( c_i \) to all parties in \( P \).
   b. Parties in \( P \) jointly perform \( (f_i, st^\rho_p) = P(c_1, \ldots, c_i, \{st^\rho_p_{i-1}, \rho_p\}_{\xi \in [D]}) \). \( P_x \) obtains a linear sharing of \( (f_i, st^\rho_p) \), say \((f_i), (st^\rho_p)\) \).
   c. \( P_x \) sends \((f_i), (st^\rho_p)\) to \( A \), a chosen party from \( P \).
   d. \( A \) combines \((f_i)\) to obtain \( f_i \). \( A \) sends messages \( f_i = (m_i, \pi_i) \).
4. \( V \) outputs \( b = V^{f_0, f_1, \ldots, f_r}(st^\rho_p, \rho_c) \).
**Lemma 5.2.** Let \( \langle P', V' \rangle \) be an homomorphic IOP-based protocol obtained by using the above mentioned compiler. If the witness, \( w \), is shared among \( D \) provers \( P = \{ P_1, \ldots, P_D \} \) additively, then \( \text{Dist}(P', D, V') \) realizes \( F_{DPZK} \) functionality securely.

**Proof.** In \( \text{Dist}(P', D, V') \), \( P'_\xi \) obtains \( \langle f_i \rangle_\xi = \langle (m_i)_{\xi}, (\pi_i)_{\xi} \rangle \). \( P'_\xi \) commits to \( \langle \pi_i \rangle_\xi \) and obtains \( \langle \pi'_i \rangle \). \( P'_\xi \) sends \( f'_i = (m_i, \pi'_i) \). Let \( J \) be the set of indices queried by \( V' \), where \( |J| \) is bounded by the query complexity \( q \) of \( \langle P, V \rangle \). In response to these queries, \( P'_\xi \) sends the corresponding openings. That is, \( P'_\xi \) sends \( \text{Open}(\langle \pi'_i \rangle) = \langle \pi_i \rangle \) to \( A \), for all \( j \in J \). \( A \) sends \( \pi_i[j] = \sum_{\xi \in D} \langle \pi_i \rangle_\xi \) to \( V' \).

**Soundness with Witness Extraction:** Claim: The above construction of \( \text{Dist}(P', D, V') \) has Soundness with Witness Extraction (SoWE) property if \( \langle P', V' \rangle \) has proof of knowledge property.

Let \( P^* \) be a set of \( D \) provers such that 
\[
\text{Dist}(P^**, D, V') = 1.
\]
Let \( P^* \) be a prover that sends \( f'_i = (m_i, \pi_i) \), where \( A \) in \( \text{Dist}(P^**, D, V') \) sends the same \( f'_i \). \( P^* \) is the same since the verification in both \( \text{Dist}(P', D, V') \) and \( \langle P', V' \rangle \) is the same. Due to the proof of knowledge property of \( \langle P', V' \rangle \), there is an PPT extractor \( \mathcal{E} \) which outputs \( w \) with high probability. \( \mathcal{E}_{DP} \) is the extractor that has oracle access to \( P^* \) and runs \( \mathcal{E} \) algorithm which has oracle access to the \( P^* \) where \( P^* \) sends the same message as the \( A \) in \( \text{Dist}(P^**, D, V') \).

If \( \mathcal{E} \) outputs \( w \) with probability \( p \), \( \mathcal{E}_{DP} \) outputs \( w \) with the same probability \( p \).

Therefore, \( \text{Pr}[(x, \mathcal{E}_{DP}(x)) \in R] = \text{Pr}[(x, \mathcal{E}^P(x)) \in R] \). Since \( \langle P^*, V' \rangle \) has proof of knowledge property, therefore \( \text{Pr}[(x, \mathcal{E}^P(x)) \in R] \geq \text{Pr}[(P^*, V')(x) = 1] - \mu'(|x|) \). Hence, \( \text{Pr}[(x, \mathcal{E}_{DP}(x)) \in R] \geq \text{Pr}[(P^*, D), V'(x)] = 1 \). This is possible since the number of opened values are bounded by query complexity and that ensures it does not leak any information about the underlying message. Then the simulator commits to \( \langle \pi_i \rangle \) and obtains \( \langle \pi'_i \rangle \). This simulated view is indistinguishable from a real world A's view.

**Zero-Knowledge:** Since in \( \text{Dist}(P', D, V') \), the verifier’s view does not change, therefore the same simulator works for the distributed prover setting also. Hence the zero-knowledge property is obvious.

**Witness Confidentiality:** Let at the \( i \)-th round, provers run \( t \)-secure MPC, \( \Pi_P \), to obtain \( \langle f_i \rangle \) and \( \langle st_i \rangle \) such that \( \sum_{\xi} \langle m_i \rangle_{\xi} = m_i \) and \( \sum_{\xi} \langle \pi_i \rangle_{\xi} = \pi_i \), where \( f_i = (m_i, \pi_i) \).

Corresponding to a corrupted set \( C \) of \( t \) provers, \( S \) does the following:
- \( S \) calls the zero-knowledge simulator, \( S_{ZK} \) and obtains a transcript \( \tau \).
- On behalf of the verifier, \( S \) sets the challenge \( c_i \) obtained from the transcript \( \tau \), and corresponding response \( m_i \) and \( \{ \pi_{ij} \}_{j \in J} \), where \( J \) be the set of queried locations. \( S \) picks a \( \pi_i \) that is consistent with \( \{ \pi_{ij} \}_{j \in J} \). This is possible due to the bounded independence property, that is. \( \pi_i \) remains random (independent of the witness \( w \)) even after revealing \( |J| \) locations of \( \pi_i \).
- If provers run MPC, \( \Pi_P \) to obtain \( \langle f_i \rangle \) and \( \langle st_i \rangle \), and \( S_P \) be the simulator. Consider \( \{ st_{ij} \}_{j \in C} \) be the inputs of the corrupted parties to the protocols \( \Pi_P \). Then \( S \) executes \( S_P \) with inputs \( \{ st_{ij} \}_{j \in C}, \langle f_i \rangle \) and \( \{ st_i \} \) correspondingly.
- Finally, \( S \) sends \( \{ m_i \}_{j \notin C} \) and \( \{ \pi_i \} \}_{j \notin C} \) to \( A \).

Here note that the view generated by \( S \) is indistinguishable from a real execution of the protocol. We establish this by the following argument.

\[
\text{SView}_1 \| \cdots \| \text{SView}_r \| \text{RView}_1 \| \cdots \| \text{RView}_r \\
\approx \text{SView}_1 \| \cdots \| \text{RView}_r \| \text{RView}_{i+1} \| \cdots \| \text{RView}_r
\]

Where \( \text{SView}_i \) represents the simulated view of the \( i \)-th round and analogously \( \text{RView}_i \) represents the real view of the \( i \)-th round. Now using hybrid argument we get simulated view \( \approx \) real view.

Privacy against \( A \) holds due to the hiding property of the commitment scheme and the zero-knowledge property of the underlying protocol. A’s view consists of \( \langle (m_i), (\pi_i') \rangle \) and \( \text{Open}(\langle \pi_i' \rangle) = \langle \pi_i \rangle \) for all \( j \in J \), where \( |J| \) is bounded by the query complexity. The simulator runs the zero knowledge simulator internally and obtains \( m_i \) and \( \pi_i[j] \). It creates additive sharing of \( m_i \) and \( \pi_i[j] \), that is, \( (m_i) \) and \( (\pi_i)[j] \). The simulator picks \( \langle \pi_i \rangle \) such that the obtained values are consistent. This is possible since the number of opened values are bounded by query complexity and that ensures it does not leak any information about the underlying message. Then the simulator commits to \( \langle \pi_i \rangle \) and obtains \( \langle \pi'_i \rangle \). This simulated view is indistinguishable from a real world A’s view.

The compiler preserves the proof size and round complexity of the underlying protocol. The overhead of the computational complexity depends on the oracle size and round complexity of the protocol. If \( \langle P, V \rangle \) has an oracle of size \( |\pi_i| \) in the \( i \)-th round, then the prover’s complexity in \( \langle P', V' \rangle \) incurs an additional \( |\pi_i| \) group exponentiations in the \( i \)-th round. Similarly, if the verifier in \( \langle P, V \rangle \) makes \( q \) many queries to the oracle \( \pi_i \), that adds \( q \) group exponentiations in the verifier’s complexity in \( \langle P', V' \rangle \). In general, \( \text{Dist}(P', D, V') \) may require \( O(N) \)
multiplication in each round for most of the protocols. Note that our construction uses public key cryptography heavily. Reducing the usage of it will improve the efficiency significantly and will lead to a more practical solution. We believe that obtaining a practical solution of this problem is an interesting problem and will lead to further research.

6 DPZK Instantiation

In this section, we present the distributed proof generation from various protocols. We call the distributed variant of a protocol “X” as “D-X”. We start with Ligero [1], where we discuss the efficiency of the distributed prover variant, D-Ligero. We optimize D-Ligero and provide a zero-knowledge protocol, named Graphene, that achieves better proof size, reduced verification time as well as communication among the provers. We explain the high-level idea of Graphene in this section and provide the details in Appendix B. The distributed version of Graphene is given in Appendix C. We then move on to the state-of-the-art IOP-based zero-knowledge protocol Aurora [6]. We discuss the efficiency of the compiled version of Aurora that enables distributed proof generation. This multi-oracle IOP shows the overhead of the compilation. We also discuss distributed proof generation from non-IOP protocols such as Bulletproofs [13] and Spartan [42]. We study the efficiency and challenges of the distributed prover variants of these protocols.

6.1 Protocols with Single Oracle

D-Ligero:

We compile the Ligero protocol, and instantiate the functional commitment scheme FC by Pedersen vector commitment scheme. Note that this FC has homomorphic property and the Open algorithm outputs the committed value m as the witness. The Verify algorithm can be replaced by an inner product argument where m is the witness.

The proof for an R1CS instance in Ligero constitutes of the check that verifies if the witness w satisfies the following condition: \( x = Aw \land y = Bw \land z = Cw \land x \circ y = z \), where is A, B, C matrices are dependent on the R1CS instance. The above check is segmented into three checks: (i) Interleaved check, (ii) Linear check, and (iii) Quadratic check.

In Ligero, \( \mathcal{P} \) rewrites the vectors \( w, x, y, z \) as matrices in a canonical way, that is, the first \( \ell \) entries are set as the first row of the matrix, next \( \ell \) entries form the second row and so on. This way a matrix is formed which has, say \( m \) rows and \( \ell \) columns, where \( m = \ell = O(\sqrt{N}) \). This is referred to as the canonical matrix form. The prover encodes these matrices using Reed–Solomon (RS)-encoding to encode each row of the matrices. In the compiled Ligero protocol, \( \mathcal{P} \) computes commitment of each column of these matrices. The commitment scheme takes \( m \) length messages. In the original Ligero protocol, \( t \) (depends on the query complexity) many columns and a linear combination of the rows are opened to the verifier. This enforces a bound on the proof size in Ligero. We circumvent this bound by replacing the openings with inner product checks.

In the interleaved check, \( \mathcal{P} \) proves that the rows of the oracle matrices are codewords. \( \mathcal{P} \) proves the claim probabilistically by showing that a random linear combination of the rows is a code word. \( \mathcal{V} \) uniformly picks the coefficients for the linear combination. Therefore, if one or more rows in the matrices are not correct codewords, then the linear combination is not a codeword with high probability. Furthermore, \( \mathcal{V} \) queries the oracle with few indices (the number of queries is bounded by the security parameter \( t \) for zero-knowledge) and receives the corresponding columns. Upon receiving the columns, \( \mathcal{V} \) performs the same linear combination and checks that it is consistent with the row received from \( \mathcal{P} \). In the linear check, \( \mathcal{P} \) proves the knowledge of a vector \( x \) such that \( Ax = b \) holds for public matrix \( A \) and vector \( b \). This check is reduced to a probabilistic check \( r^T Ax = r^T b \), where \( r \) is a random vector picked by \( \mathcal{V} \). \( \mathcal{P} \) computes a polynomial \( p(x) \) such that the sum of the evaluations on publicly known points is equal to \( r^T b \), and sends this \( p(x) \) to \( \mathcal{V} \). \( \mathcal{V} \) checks if the above condition holds, and it further checks if \( p(x) \) is constructed correctly from \( r, A, \) and \( w \). \( \mathcal{V} \) validates this by querying some locations of the oracle. In the quadratic check, \( \mathcal{P} \) proves that \( x \circ y = z \) (\( \circ \) denotes the Hadamard product of two vectors), where the corresponding encoded values are set as oracles. \( \mathcal{V} \) gives a randomly sampled challenge vector \( r \) to \( \mathcal{P} \). \( \mathcal{P} \) constructs a polynomial \( p(x) \) using \( r \) and the encoding polynomials of \( x, y, z \). This polynomial should evaluate to 0 on publicly known points. \( \mathcal{P} \) sends the polynomial \( p(x) \) to \( \mathcal{V} \). Upon receiving \( p(x) \), \( \mathcal{V} \) checks if the above condition is true or not. Furthermore, it checks whether \( p(x) \) is correctly constructed. For this, it queries some locations of the oracles.

In the compiled protocol, \( \mathcal{V} \) obtains commitments corresponding to the queried columns, and instead of
sending the openings of those columns, we perform the inner product argument. Since the opening of the columns is not sent, we can elongate the size of the columns without increasing the proof size. The inner product argument requires communication of \(O(\log N)\) elements, where \(N\) is the size of the witness vector.

Therefore the newly obtained protocol has proof size \(O(\ell + \log(m))\), where \(\ell\) is the size of the row, and \(m\) is the size of the column. However, verifying these inner products requires \(O(N)\) exponentiations for a witness vector of dimension \(N\). Thus increasing the column size unreasonably may result in a better proof size but increases the verification time, which is undesirable. Furthermore, for the quadratic check protocol, the polynomial \(p(x)\) depends non-linearly on the witness since it requires multiplication of the polynomials used for encoding \(x, y\).

Therefore, provers in \(\mathcal{P}\) engage in a secure computation protocol where they obtain an additive sharing of \(p(x)\). In general, this incurs communication for computing a circuit of depth \(1\) with \(O(N)\) multiplications. Nevertheless, if the size of the shared circuit is sufficiently low (smaller than the row size in the canonical matrix), then it is possible to embed the shared circuit in a row. In this case, MPC is required only for the row that contains the shared circuit.

**Distributed-prover Zero-Knowledge Protocols**

**Graphene and D-Graphene:**

In Graphene, we follow the same approach as in Ligero. We start with the extended witness \(w\), consider it as a 3 dimensional matrix of size \(p \times m \times s\) where \(p\) 2 dimensional matrices of size \(m \times s\) called a slice, are stacked one after another. In contrast to Ligero, where each row is encoded separately, we encode each two-dimensional slice separately. Let \(\ell = s + b\), \(h > 2m\), \(n > 2\ell\) where \(b\) is the bounded independence parameter depending on the query complexity. Let \(\zeta = \{\zeta_1, \ldots, \zeta_l\}\), \(\eta = \{\eta_1, \ldots, \eta_n\}\) and \(\alpha = \{\alpha_1, \ldots, \alpha_h\}\) be public set of points in \(\mathbb{F}\). We define \(G = \{\{\alpha_j, \zeta_k\} : j \in [m], k \in [f]\}\) and \(H = \{\{\alpha_j, \eta_k\} : j \in [h], k \in [n]\}\) to be the interpolation domain and evaluation domain respectively. To encode the \(ith\) slice, we construct a bivariate polynomial \(Q^t(x, y)\) such that \(Q^t(\alpha_j, \zeta_k) = w[i, j, k]\) and \(\text{deg}_x(Q^t) < m\) and \(\text{deg}_y(Q^t) < \ell\). The encoded witness \(U\) is such that \(U[i, j, k] = Q^t(\alpha_j, \eta_k)\) for \(i \in [p], j \in [h], k \in [n]\). Then each column of each slice is committed using Pedersen vector commitment. Here we instantiate the homomorphic FC with the Pedersen commitment scheme with message length \(h\). Finally, \(V\) is provided oracle access to the committed matrix. We design interleaved check protocol over committed values which is performed together with the linear check and quadratic check. The details are presented in Appendix B.2. The linear check is similar to Ligero, where a probabilistic reduction is performed. \(V\) sends a random \(r\) followed by both \(\mathcal{P}\) and \(V\) locally computing \(R = rT A\). Using \(\alpha, \eta \mathcal{P}, V\) interpolate \(p\) polynomials \(R^i(x, y)\) such that \(R^i(\alpha_j, \zeta_k) = R^i[i, j, k]\) for \(i \in [p], j \in [m], k \in [s]\) and \(\text{deg}_x(R^i) < m\), \(\text{deg}_y(R^i) < s\) for all \(i \in \mathcal{P}\). \(V\) computes polynomial \(p_j(y) = \sum_{i \in [p]} R^i(\alpha_j, y)Q^t(\alpha_j, y)\). If the witness is correct then \(v^T A w = rT b \Rightarrow \langle R, w \rangle = rT b \Rightarrow \sum_{j \in [m], k \in [s]} p_j(\zeta_k) = rT b\). Furthermore, \(p_j(\eta_k) = \sum_{i \in [p]} R^i(\alpha_j, \eta)U[i, j, k]\) due to the encoding. \(\mathcal{P}\) constructs a matrix \(P\) of size \(h \times n\) such that \(P[j, k] = p_j(\eta)\) and commits to \(P\). By providing partial opening using inner product arguments from Bulletproofs, \(\mathcal{P}\) proves that the polynomials \(p_j(y)\) satisfies the following conditions:

- \(p_j(\eta_k) = \sum_{i \in [p]} R^i(\alpha_j, \eta)U[i, j, k]\) for all \(j \in [h], k \in [n]\)
- \(\sum_{j \in [m], k \in [s]} p_j(\zeta_k) = rT b\)

Similar to the linear check, in the quadratic check, \(\mathcal{P}\) encodes \(x, y, z\) to obtain \(U_x, U_y, U_z\) and lets \(Q_x^i, Q_y^i, Q_z^i\) be the respective polynomials. \(\mathcal{P}\) constructs polynomials \(Q^t\) such that \(Q^t = Q_x^i \cdot Q_y^i - Q_z^i\).

Since \(x \cdot y = z\), we have \(Q^t(\alpha_j, \zeta_k) = 0\) for all \(i \in [p], j \in [m], k \in [s]\). To check this, \(V\) sends a random vector \(r \in \mathbb{F}\) as a challenge. \(\mathcal{P}\) locally computes \(p_j(\cdot) = \sum_{i \in [p]} R^i(\alpha_j, \eta_i)\). Analogous to the linear check, \(\mathcal{P}\) forms \(P\) matrix and commits to it, and further proves that \(P\) satisfies the following:

- \(p_j(\eta_k) = \sum_{i \in [p]} r^i [U_x[i, j, k] \cdot U_y[i, j, k] - U_z[i, j, k]]\)
- \(p_j(\zeta_k) = 0\) for all \(j \in [m], k \in [s]\)

To obtain D-Graphene, parties in \(\mathcal{P}\) execute secure multiplication to get an additive sharing of \(U_x[i, j, k], U_y[i, j, k]\). The remaining steps in both linear and quadratic check do not require any interaction among the provers. Therefore, the provers interact to evaluate a circuit with \(O(N)\) many multiplications with depth \(1\). However, with smaller shared circuit, where the shared circuit can be embedded into a column of a slice such that multiplication is required only for that column. The details of the protocol are given in Appendix B.

### 6.2 Multiple Oracle IOP

**D-Aurora:**

In Aurora [6], the size of the oracle is \(O(N)\), the proof size is \(O(\log^2 N)\), and number of rounds is \(O(\log N)\). Aurora is an IOP-based proof system where almost all
the messages from $P$ to $V$ are set as oracles, and $V$ makes oracle-queries to complete the verification. We can convert Aurora using our compiler, where we instantiate FC using Pedersen commitment, such that it supports DPZK. The compiled version retains the oracle size, proof size, and the number of rounds. However, the prover time and the verification time increase by $O(N \log N)$ group exponentiations due to oracle construction and validation costs. The distributed version needs secure evaluation of circuits with at least depth one and $O(N)$ multiplication gates in each round.

### 6.3 Non-IOP Protocols

**D-Bulletproofs:**
In Bulletproofs [13], the proof of an R1CS instance is reduced to an inner product argument which is proved recursively for the succinctness of the proof size. The prover constructs two vector polynomials $l(X), r(X)$ of degree 1 using the witness, statement and challenges from the verifier. It commits to the quadratic polynomial $t(X) = \langle l(X), r(X) \rangle$ where $t(X) = \sum_{i=0}^{d} \sum_{j=0}^{d} (l_i, r_j) X^{i+j}$ such that $l_i$ and $r_j$ are $l(X)$'s $i$th and $r(X)$'s $j$th vector coefficients respectively. The verifier sends a random point $x$ and prover obtains $l = l(x)$, $r = r(x)$ and $t = t(x)$. Using the inner product argument the prover proves that $\langle l, r \rangle = t$.

In D-Bulletproofs, provers start with additive sharings of $l(X), r(X)$ and perform secure multiplications to obtain additive sharing of $t(X)$. This requires $O(N)$ multiplications. Upon receiving $x$, each prover locally obtains a sharing of $l, r, t$ and sends these values to the aggregator. The aggregator performs the inner product argument with the verifier to complete the proof.

**D-Spartan:**
In Spartan [42], an R1CS circuit is represented by 3 matrices $A, B, C$. A witness $w$ for the true instance satisfies $A z = B z = C z$, where $z = (x, 1, w)$ for public input $x$. In Spartan, prover obtains low-degree polynomial extensions of $A, B, C, z$. Upon receiving the challenges from the verifier, the prover constructs a polynomial $f$. Then, a sum-check is performed to ensure that $f$ satisfies a consistency condition.

For the distributed proof generation, provers initiate the protocol with an additive sharing of the witness $w$ and achieve an additive sharing of $f$ by performing $O(N^2)$ secure multiplications. In Spartan, zero-knowledge is achieved by producing proofs of dot products. In the distributed setting, this either requires each prover to open its witness of the dot product to the aggregator or all the provers produce a distributed proof for the dot products. The latter case makes it a circular problem, whereas the former one has a privacy issue. Even if a similar protocol could overcome the privacy issue, it would likely still suffer from the high communication complexity of $O(N^2)$ secure multiplication. The above discussion further emphasizes the non-triviality of obtaining DPZK from any ZK protocol.

**Fig. 4.** Comparison amongst the DPZKs. Here $N$ is the size of the circuit and, $c$ is a positive integer of our choice. * indicates non-private variant of Spartan.

<table>
<thead>
<tr>
<th>Protocols</th>
<th>$\tau_p$</th>
<th>$\tau_v$</th>
</tr>
</thead>
<tbody>
<tr>
<td>D-Ligero</td>
<td>$O(\sqrt{N})$</td>
<td>$O(\sqrt{N})$</td>
</tr>
<tr>
<td>D-Aurora</td>
<td>$O(N \log N)$</td>
<td>$O(N \log N)$</td>
</tr>
<tr>
<td>D-Bulletproofs</td>
<td>$O(N)$</td>
<td>$O(N^2)$</td>
</tr>
<tr>
<td>D-Graphene</td>
<td>$O(N^{1+c/2})$</td>
<td>$O(N^{1+c/2})$</td>
</tr>
</tbody>
</table>

**7 Conclusion**
In this work, we presented a formal definition of distributed-prover zero-knowledge (DPZK) and a generic compiler that provides a DPZK protocol from any IOP-based zero-knowledge protocol. We discuss instantiations of this compiler with some recent IOP ZK protocols, and discuss DPZK versions of some state-of-the-art non-IOP ZK protocols.

Furthermore, we provided an efficient single-prover protocol Graphene that achieves DPZK with a minimal overhead of communication among the provers while retaining the proof size and verification time.

In all these protocols, we prove witness confidentiality against semi-honest provers. Extending this to malicious provers is left as an open problem. Another interesting future direction is to construct a universal composable (UC) DPZK.

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References


systems are assumed to be defined over finite field denoted by \( \mathbb{F} \). For a vector \( x \in \mathbb{F}^m \), \( x_i \) and \( x[i] \) represent the \( i \)th component of \( x \) for \( i \in [m] \). For an \( m \times n \) matrix over \( \mathbb{F} \), we use (a) \( A[i,j] \) to denote \( (i,j) \)th entry, (b) \( A[i,:] \) to denote the \( i \)th row of \( A \). Similarly, for an \( p \times m \times n \) matrix \( X \), we use (a) \( X[i,j,k] \) to denote the \( (i,j,k) \)th entry, (b) \( X[i,:,] \) to denote the \( m \times n \) matrix \( Y \) given by \( Y[j,k] := X[i,j,k] \), (c) and analogously \( X[:,j,:] \) and \( X[:,:,k] \) to denote \( n \times p \) and \( p \times m \) matrices respectively. We will refer to sub-matrices \( X[i,:,\cdot] \) as slices of \( X \), sub-matrices \( X[:,j,:] \) as slabs of \( X \) and sub-matrices \( X[:, :, k] \) as the planes of \( X \). \( X^T \) denotes transpose of a two dimensional matrix \( X \). Inner-product of two vectors \( X, Y \) is denoted as \( \langle X, Y \rangle \). Inner-product of two three or two dimensional matrices \( X \) and \( Y \), denoted as \( \langle X, Y \rangle \), implies the inner-product of the corresponding one-dimensional vectors obtained from unrolling the matrices.

Throughout the paper we use several distance metrics on vectors and matrices, which we now introduce. For two vectors \( x, y \) of length \( n \), we define \( \Delta(x,y) = \{i \in [n] : x_i \neq y_i \} \). For two \( m \times n \) matrices \( A, B \) we define \( \Delta_1(A,B) = \{j \in [n] : A[:,j] \neq B[:,j] \} \) and \( \Delta_2(A,B) = \{i \in [m] : A[i,:] \neq B[i,:] \} \). For \( p \times m \times n \) matrices \( X \) and \( Y \), we define \( \Delta_1(X,Y) = \{k \in [n] : X[:, :, k] \neq Y[:, :, k] \} \) (no of planes that are different between the two matrices). Similarly we define \( \Delta_2(X,Y) = \{j \in [m] : X[:,j,:] \neq Y[:,j,:] \} \) (no of slabs that are different between the two matrices). Let \( u \) be a vector and \( S \) be a set of vectors. We use \( d(u, S) := \min \{\Delta(u, v) : v \in S\} \) to denote distance between \( u \) and \( S \). Similarly for a matrix (two or three dimensional) \( U \) and a set of matrices \( M \), we define \( d_i(U, M) := \min \{\Delta_i(U, M) : M \in M \} \) for \( i = 1, 2 \).

We use \( \leftarrow \) to denote drawing from a distribution uniformly at random.

### A.2 Coding Theory primitives

**Definition 2** (Linear Codes). Let \( n, k, d \) be positive integers with \( n \geq k \) and \( \mathbb{F} \) be a finite field. We call \( L \subseteq \mathbb{F}^n \) to be an \([n, k, d]\) linear code if \( L \) is a \( k \)-dimensional subspace of \( \mathbb{F}^n \) and \( d \) is the minimum value of \( \Delta(x,y) \) for distinct \( x, y \in L \). Elements of \( L \) are conventionally called codewords.

For an \([n, k, d]\) code \( L \), an \( n \times k \) matrix \( G \) is called a generator matrix for \( L \) if (i) \( Gx \in L \) for all \( x \in \mathbb{F}^k \) and (ii) \( Gx \neq Gy \) for \( x 
eq y \). Clearly, such a matrix \( G \) has rank \( k \). Similarly an \( n \times (n-k) \) matrix \( H \) such that...
$y^T \mathcal{H} = 0$ for all $y \in L$ is called a parity check matrix for $L$. It is known that the above two matrices exist for any $[n, k, d]$ linear code $L$. We will assume that description of the linear code $L$ includes a generator matrix $G$ and a parity check matrix $\mathcal{H}$.

**Definition 3 (Interleaved Code).** For an $[n, k, d]$ linear code $L$ and a positive integer $m$, we define a row interleaved code $\text{RIC}(L, m)$ to be the set of $m \times n$ matrices $A$ such that each row of $A$ is a codeword in $L$. Similarly, we define a column interleaved code $\text{CIC}(L, m)$ to be the set of $n \times m$ matrices $B$ such that each column of $B$ is a codeword in $L$.

For an $[n, k, d]$ linear code $L$ over $\mathbb{F}$, one can define $\text{RIC}(L, m)$ as an $[nm, mk, d]$ linear code over $\mathbb{F}$ or alternatively, as an $[n, k, d]$ code over $\mathbb{H}$, where $\mathcal{H} \cong \mathbb{F}^m$.

Analogous to the row interleaved code, a column interleaved code $\text{CIC}(L, m)$ can be viewed as an $[n, k, d]$ code over $\mathbb{F}^m$ by viewing each row of the codeword $B \in \text{CIC}(L, m)$ as an element in $\mathbb{F}^m$. Here the distance metric for $\text{RIC}(L, m)$ is given by the matrix distance $\Delta_1$, while the distance metric for $\text{CIC}(L, m)$ is given by the matrix distance $\Delta_2$ as defined in Section A.1.

**Definition 4 (Product Code).** Let $L_i$ be an $[n_i, k_i, d_i]$ linear code for $i = 1, 2$. We define the product code $L_1 \otimes L_2$ to be the code consisting of $n_2 \times n_1$ matrices $A$ such that each row of $A$ is a codeword in $L_1$ and each column of $A$ is a codeword in $L_2$.

Note that by definition, the product code $L_1 \otimes L_2$ is a row interleaved code of $L_1$ and a column interleaved code of $L_2$, i.e $L_1 \otimes L_2 = \text{RIC}(L_1, n_2) \cap \text{CIC}(L_2, n_1)$. For $A, A' \in L_1 \otimes L_2$, we define $\Delta_1(A, A') = \{|i \in [n_1] : A[i, i] \neq A'[i, i]\}$ and $\Delta_2(A, A') = \{|i \in [n_2] : A[i, :] \neq A'[i, :]\}$. The distance $\Delta_1$ corresponds to distance function of the code $\text{RIC}(L, n_2)$, where we view $A, A'$ as codewords in $\text{RIC}(L, n_2)$. Similarly, the distance $\Delta_2$ corresponds to the distance function of the code $\text{CIC}(L, n_1)$.

**Definition 5 (Reed-Solomon Code).** An $[n, k]$ Reed-Solomon Code $L \subseteq \mathbb{F}^n$ consists of vectors $(p(\eta_1), \ldots, p(\eta_n))$ for polynomials $p \in \mathbb{F}[x]$ of degree less than $k$ where $\eta_1, \ldots, \eta_n$ are distinct points in $\mathbb{F}$. We will use $\text{RS}_\eta[n, k]$ to denote the Reed Solomon code with $\eta = (\eta_1, \ldots, \eta_n)$ and deg($p$) $< k$.

**Lemma A.1 ([36]).** Suppose a matrix $U^* \in \mathbb{F}^{h \times n}$ satisfies $d_1(U^*, \text{RIC}(\text{RS}_\eta[n, \ell], h)) < e_1 \leq n - \ell$ and $d_2(U^*, \text{CIC}(\text{RS}_\alpha[h, m], n)) < e_2 \leq h - m$. Then, there exists $U \in \text{RS}_\eta[n, \ell] \otimes \text{RS}_\alpha[h, m]$ and sets $S_1 \subseteq [n], S_2 \subseteq [h]$ with $|S_1| > n - e_1$ and $|S_2| > h - e_2$ such that $U^*[i, j] = U[i, j]$ for $(i, j) \in S_1 \times S_2$.

**A.3 Coding Theory Results for Our Constructions**

The following coding theoretic result is the key to testing proximity of a three-dimensional matrix to a well-formed encoding.

**Proposition A.2 (3D Compression).** Let $L$ be an $[n, k, d]$ code over $\mathbb{F}$, and $C := \text{RIC}(L, m)$ be a row interleaved code of $L$. Let $C^p$ denote the set of $p \times m \times n$ matrices $U$ over $\mathbb{F}$ such that $U[i, \cdot, \cdot] \in C$ for all $i \in [p]$. Let $U^*$ be a $p \times m \times n$ matrix such that $d_1(U^*, C^p) > e$. Then for any $m \times n$ matrix $v_0$ over $\mathbb{F}$, we have

$$
\Pr \left[ d_1 \left( u_0 + \sum_{i=1}^{p} r_i U^*[i, \cdot, \cdot], C \right) \leq e \right] \leq \frac{d}{|\mathbb{F}|}
$$

for a uniformly sampled $(r_1, \ldots, r_p) \leftarrow \mathbb{F}^p$.

We need several observations to prove the proposition, which we present next. Throughout this section, let $L$ be a linear $[n, k, d]$ code over a field $\mathbb{H}$ and let $\mathbb{F} \subseteq \mathbb{H}$ be a subfield. Let $m \geq 1$ be an integer, and let $C$ denote the row interleaved code $\text{RIC}(L, m)$. For a matrix $U \in \mathbb{H}^{m \times n}$ and a vector $u_0 \in \mathbb{H}^n$, let $\text{Aff}(u_0, U)$ denote the affine space as:

$$
\text{Aff}(u_0, U) := \{u_0 + r^T U : r \in \mathbb{F}^m\}
$$

Note that in the above, the scalars in the linear combination come from $\mathbb{F}$.

The following result was proved in [1] for the setting $\mathbb{H} = \mathbb{F}$. For completeness, we present an adaptation of the proof to the setting where $\mathbb{F}$ is a subfield of $\mathbb{H}$.

**Lemma A.3.** Let $L$ and $C$ be codes as defined, and let $e$ be a positive integer such that $e + 2 \leq |\mathbb{F}|$. Then for any $u_0 \in \mathbb{H}^n$ and any $U^* \in \mathbb{H}^{m \times n}$ such that $d(U^*, C) > e$, there exists $v \in \text{Aff}(u_0, U^*)$ such that $d(v, L) > e$.

**Proof.** For sake of contradiction, assume that $d(u, L) \leq e$ for all $u \in \text{Aff}(u_0, U^*)$. Let $x$ be the point in $\text{Aff}(u_0, U^*)$ such that $d(x, L)$ is maximum. By assumption $d(x, L) \leq e$. Let $v \in L$ be such that $\Delta(x, v) = d(x, L)$. Let $E \subseteq [n]$ be the set of positions where $x$ and $v$ differ. Since $d(U^*, C) > e$, there exists row $R$ of $U^*$ and there is some position $j \in [n]\setminus E$ such that $R_j \neq 0$. Let $\alpha_1, \ldots, \alpha_{e+1}$ be distinct non zero elements in $\mathbb{F}$. Let
Let $E_k$ for $k = 1, \ldots, e + 1$ denote the set of positions where $x + \alpha_k R$ and $v$ differ. Fix a position $i \in E$. Then there exists at most one $k \in [e + 1]$ such that $i \notin E_k$. By pigeonhole principle, there exists $k \in [e + 1]$ such that $E \subseteq E_k$. We also observe that since $\alpha_k \neq 0$, $j \in E_k$. Thus $d(x + \alpha_k v) > d(x,v)$, contradicting the choice of $x$. This proves the lemma.

Next we prove a result about lines with respect to linear codes. The result was proved in [1] for the case $\mathbb{H} = F$ and $e < d/4$. The authors in [1] conjectured the result for $e < d/3$. Here we prove the result for $e < d/3$ when $F$ can be an arbitrary subfield of $\mathbb{H}$.

**Lemma A.4 (Affine Line).** Let $L$ be the linear code as defined. Define an affine line $\ell_{u,v}$ in $\mathbb{H}^n$ as $\ell_{u,v} := \{u + \alpha v : \alpha \in F\}$ for $u, v \in \mathbb{H}^n$. Then for $e < d/3$ and any affine line $\ell_{u,v}$:

(i) $d(x,L) \leq e$ for all $x \in \ell_{u,v}$, or

(ii) $d(x,L) > e$ for at most $d$ points in $\ell_{u,v}$.

**Proof.** In this proof, let $\delta(x,y)$ denote the set of positions where the vectors $x$ and $y$ differ, and let $\text{wt}(x)$ denote $|\delta(x,0)|$. The above is equivalent to proving that if there exist $d + 1$ distinct points $X = \{x_1, \ldots, x_{d+1}\} \subseteq \ell_{u,v}$ such that $d(x_i, L) \leq e$ for all $i \in [d+1]$, then $d(x_i, L) \leq e$ for all $x \in \ell_{u,v}$. Assume that there exists such a set of $X$ of $d + 1$ points. Let $\ell_i$ denote the point in $L$ closest to $x_i$ for $i \in [d+1]$. Set $\eta_i = x_i - \ell_i$ for all $i$ and let $\eta = \{\eta_1, \ldots, \eta_{d+1}\}$. By assumption we have $\text{wt}(\eta_i) \leq e$ for all $i \in [d+1]$. Since $\ell_{u,v}$ is contained in affine span of any two distinct points on it, we have tuples $\{\alpha_{i,j}\}_{i,j \in [d+1]}$ such that $\alpha_i + \beta_i = 1$ and $x_i = \alpha_i x_1 + \beta_i x_2$ for $i \in [d+1]$. Note that $\{\alpha_i, \beta_i\} = (1,0)$ and $\{\alpha_2, \beta_2\} = (0,1)$. Observe that $\alpha_i$ and $\beta_i$ must be distinct for all $i \in [d+1]$. We call $X$ as degenerate if there exist $i \neq j$ satisfying $\alpha_i = \gamma \alpha_j$ and $\beta_i = \gamma \beta_j$ for some $\gamma \in F \setminus \{0\}$. We consider two cases:

**X is degenerate:** Degeneracy implies there exist $i \neq j$ such that $x_i = \gamma x_j$ for some $\gamma \in F \setminus \{0\}$. In this case we have $0 = \frac{1}{\gamma} x_i - \frac{1}{\gamma} x_j \in \ell_{u,v}$. This implies $\ell_{u,v} = \{\alpha x : \alpha \in F\}$ and hence $d(x,L) = d(x_i, L) \leq e$ for all $x \in \ell_{u,v}$. Thus the statement of the Lemma holds in this case.

**X is not degenerate:** We first prove that $\ell_i = \alpha_i \ell_1 + \beta_i \ell_2$ and $\eta_i = \alpha_i \eta_1 + \beta_i \eta_2$ for all $i \in [d+1]$. We have

$$\ell_i + \eta_i = x_i = \alpha_i x_1 + \beta_i x_2 = \alpha_i (\ell_1 + \eta_1) + \beta_i (\ell_2 + \eta_2)$$

$$= (\alpha_i \ell_1 + \beta_i \ell_2) + (\alpha_i \eta_1 + \beta_i \eta_2)$$

Rearranging we have, $\ell_i - (\alpha_i \ell_1 + \beta_i \ell_2) = \alpha_i \eta_1 + \beta_i \eta_2 - \eta_i$. In the above equation we see that LHS is a vector in $L$. Further $\text{wt}(\alpha_i \eta_1 + \beta_i \eta_2 - \eta_i) \leq \text{wt}(\eta_1) + \text{wt}(\eta_2) + \text{wt}(\eta_1) \leq 3e < d$. Thus the LHS must be equal to 0 and hence $\ell_i = \alpha_i \ell_1 + \beta_i \ell_2$ and $\eta_i = \alpha_i \eta_1 + \beta_i \eta_2$. Observe that any $x^* \in \ell_{u,v}$ can be written as $x^* = \alpha^* x_1 + \beta^* x_2$. Thus $d(x^*, L) = d(\alpha^* x_1 + \beta^* x_2, L) \leq \text{wt}(\alpha^* \eta_1 + \beta^* \eta_2) \leq |E|$ where $E$ denotes the set $\delta(\eta_1,0) \cup \delta(\eta_2,0)$. Our final effort will be to show that $|E| \leq e$.

**Claim:** $|E| \leq e$ where $E = \delta(\eta_1,0) \cup \delta(\eta_2,0)$. We consider the partition of $E$ into sets $E_0 = \delta(\eta_1, 0) \cap \delta(\eta_2, 0)$, $E_1 = \delta(\eta_1,0) \setminus \delta(\eta_2,0)$ and $E_0 = \delta(\eta_1,0) \cap \delta(\eta_2,0)$. Let $t = |E|$. Consider a $t \times (d+1)$ matrix $M = (m_{ij})$ where $m_{ij} = 0$ if $j$th coordinate of $\eta_i$ is zero, and $m_{ij} = 1$ otherwise. We will show that each row of $M$ has at most one 0. Assume that there exists $i$ such that $m_{ip} = 0$ and $m_{iq} = 0$ for $p \neq q$. We consider three cases:

- If $i \in E_0$, the above condition implies $\alpha p \eta_1^i = \alpha q \eta_1^i = 0$, or $\alpha_p = \alpha_q = 0$ as $\eta_1^i \neq 0$ for $i \in E_0$. This contradicts the fact that $X$ is not degenerate.

- The case $i \in E_1$ is similar to above.

- If $i \in E_0$ we have $\alpha_p \eta_1^i + \beta_p \eta_2^i = \alpha_q \eta_1^i + \beta_q \eta_2^i = 0$ which implies $\alpha_p / \beta_p = \alpha_q / \beta_q = -\eta_2^i / \eta_1^i$, or $\alpha_p / \alpha_q = \beta_p / \beta_q$ which contradicts the fact that $X$ is not degenerate. Note that all denominators can be argued to be non-zero for $i \in E_0$.

From the above, we conclude that each row has at least $d$ entries as 1. Counting by columns, we have that each column has at most $e$ entries as 1 (since $\text{wt}(\eta_i) \leq e$ for all $i \in [d]$). Comparing the lower and upper bounds on the number of 1 entries in the matrix we have $td \leq e(d+1)$ which implies $t \leq e + e/d < 1 + e$. Thus $t \leq e$, as we wanted to show. This completes the proof.

The following result underlies proximity protocols in our work and in [1]. Intuitively the result states that if a matrix is far away from the code $C$, a random linear combination of its rows is far away from a codeword in $L$, and thus the proximity of the matrix to $C$ may be tested by testing the proximity of a random linear combination of its rows to $L$.

**Lemma A.5 (Affine Subspace).** Let the codes $L$ and $C$ be as defined and $e < d/3$ be an integer. Let $U \in \mathbb{H}^{m \times n}$ be a matrix such that $d(U, C) > e$. Then for any $u_0 \in \mathbb{H}^n$, $\text{Pr}[d(u_0 + r^TU, L) \leq e] \leq d/|\mathbb{F}|$ for uniformly sampled $r \leftarrow \mathbb{F}^m$.

**Proof.** From Lemma A.3, there exists $u \in \text{Aff}(u_0, U)$ such that $d(u, L) > e$. Now we can write $\text{Aff}(u_0, U)$ as union of affine lines passing through $u$. Applying Lemma A.4 to each line, we see that at most $d$ points $x$ on each
affine line satisfy \( d(x, L) \leq \epsilon \). Thus, a randomly sampled point \( x \) in \( \text{Aff}(u_0, U) \), equivalently obtained as \( u_0 + r^T U \) for a randomly sampled vector \( r \in F^m \) satisfies \( d(x, L) \) with probability at most \( d/|F| \).

We are now in a position to prove Proposition A.2.

**Proof of Proposition A.2.** Let \( \mathbb{H} \) denote the field \( F^m \). Then \( u_0 \) can be viewed as a point in \( \mathbb{H}^n \). Similarly \( U \) can be viewed as \( p \times n \) matrix over \( \mathbb{H} \). We consider \( C \) as \([n, k, d]\) code over \( \mathbb{H} \) and \( C_p \) as the interleaved code of \( C \) over the field \( \mathbb{H} \). Then by applying Lemma A.5 with \( \mathbb{H} = F^m \) and codes \( C \) and \( C_p \) in place of codes \( L \) and \( C \), we have the desired bound.

### A.4 Vector Commitment Schemes and Inner-product Arguments

**Functional Commitment for linear functions**

Let \( D \) be a domain and consider linear functions \((\cdot, \cdot) \colon D^n \times D^n \rightarrow D \) defined by \((x, m) = \sum_{i=1}^{n} x_i m_i \) for \( x, m \in \mathbb{D}^n \) with \( x = (x_1, \ldots, x_n) \), \( m = (m_1, \ldots, m_n) \). A functional commitment scheme FC is a tuple of four probabilistic polynomial-time algorithms - (SetUp, Com, Open, Verify).

- **SetUp\((1^\lambda, 1^n)\)**: takes in a security parameter \( \lambda \in \mathbb{N} \), size of the message \( n \in \text{poly}(\lambda) \) and outputs a commitment key \( CK \).
- **Com\((CK, m)\)**: takes as input the commitment key \( CK \) and a \( n \) length message \( m \) as input. It outputs a commitment \( C \) for \( m \) and auxiliary information denotes aux.
- **Open\((CK, C, aux, x)\)**: takes as input the commitment key \( CK \), a commitment \( C \) (to \( m \)), auxiliary information (possibly containing \( m \)) and a vector \( x \in \mathbb{D}^n \); computes a witness \( W_y \) for \( y = \langle x, m \rangle \) i.e., \( W_y \) is a witness for the fact that the linear function defined by \( x \) when evaluated on \( m \) gives \( y \).
- **Verify\((CK, C, W_y, x, y)\)**: takes as input the commitment key \( CK \), a commitment \( C \), a witness \( W_y \), a vector \( x \in \mathbb{D}^n \) and \( y \in D \); outputs \( W_y \) is a witness for \( C \) being a commitment for some \( m \in \mathbb{D}^n \) such that \( \langle x, m \rangle = y \) and outputs 0 otherwise.

**Correctness:** For every \( CK \leftarrow \text{SetUp}(1^\lambda, 1^n) \), for all \( x, m \in \mathbb{D}^n \), if \( (C, aux) \leftarrow \text{Com}(CK, m) \) and \( W_y \leftarrow \text{Open}(CK, C, aux, x) \), then \( \text{Verify}(CK, C, W_y, x, y) = 1 \) with probability 1.

**Hiding:** For a key \( CK \) generated by an honest setup, for all \( m_1, m_2 \in \mathbb{D}^n \) with \( m_1 \neq m_2 \), the two distributions \( \{CK, \text{Com}(CK, m_1)\} \) and \( \{CK, \text{Com}(CK, m_2)\} \) are indistinguishable.

**Function binding:** A functional commitment scheme \( \text{FC} = (\text{SetUp}, \text{Com}, \text{Open}, \text{Verify}) \) for \((D, n, (\cdot, \cdot))\) is said to be computationally binding if any PPT adversary \( A \) has negligible advantage in winning the following game.

1. The challenger generates \( CK \) by running \( \text{SetUp}(1^\lambda, 1^n) \) and gives \( CK \) to \( A \).
2. The adversary \( A \) outputs a commitment \( C \), a vector \( x \in \mathbb{D}^n \), two values \( y, y' \in D \) and two witnesses \( W_y, W_{y'} \). We say that \( A \) wins the game if the following conditions hold.
   - \( y' = y \),
   - \( \text{Verify}(CK, C, W_y, x, y) \)
   - \( = \text{Verify}(CK, C, W_{y'}, x, y') = 1 \).

Functional commitment is a generalization of vector commitments. In our constructions, vector commitment suffices. We initiate FC with Pedersen commitment scheme or Pedersen vector commitment scheme accordingly.

We define an interactive protocol that allows proving inner-product relation over committed vectors. For this we are using Pedersen vector commitment scheme Com.

We now define the language for inner-product w.r.t. the above as \( L \subseteq F^m \times C \times \mathbb{F} \) given by:

\[
L = \{(x, c, z) : \exists y, r \text{ s.t. } c = \text{Com}(y, r) \text{ and } \langle x, y \rangle = z \}
\]

Our language for inner-product is a simpler version of the one defined in [13], where the first argument is also hidden in a commitment. The inner product argument is used to reduce the communication.

We use inner-product argument from Bulletproofs [13]. Notably, we use a variant of inner-product where one of the vector is public and the other one is private. \( \text{InnerProduct}(pp, x, cm, v, z) \) is the notation we will be using throughout the paper, where the public parameter \( pp \) consists of group description and generator, \( x \) is a public vector and \( cm \) is the commitment of the private vector \( z \) such that \( \langle x, z \rangle = v \).

In our work, we are using Pedersen vector commitment scheme, Com with message space \( F^m \), commitment space \( G \) and randomness space \( \mathbb{F} \). For a set of generators \( g = (g_1, \ldots, g_m, h) \), the commitment of vector \( x \in F^m \) with commitment randomness \( r \in \mathbb{F} \) is given by \( \text{Com}(x, r) = h^r \prod_{i=1}^{m}(g_i)^{x_i} \). This commitment is homomorphic with \( C = G \) as the commitment space. This is a non-interactive perfectly hiding and computationally binding commitment scheme.
Definition 6 (Inner-product Argument [10, 13]). We call an interactive protocol \( \langle P_{\text{ip}}, V_{\text{ip}} \rangle \) consisting of PPT interactive algorithms \( P_{\text{ip}} \) and \( V_{\text{ip}} \) an inner-product argument for commitment scheme \( \langle \text{Gen}, \text{Com} \rangle \) if it recognizes the language \( L \) as defined previously. Namely, \( \langle P_{\text{ip}}, V_{\text{ip}} \rangle \) satisfies the following:

(i) Completeness: For all \( A \), the following should be 1

\[
\Pr\left[ (x, w) \in \mathbb{R}^\wedge \langle P_{\text{ip}}(pp, x, w), V_{\text{ip}}(pp, x) \rangle = 1 \mid pp \leftarrow \text{Gen}(1^n) \; ; \; (x, w) \leftarrow A(1^n, pp) \right] = 1
\]

(ii) Soundness: For all deterministic polynomial time \( \mathcal{P}^* \) and PPT \( A \), the following should be at most \( \operatorname{negl}(\lambda) \).

\[
\Pr\left[ x \notin \mathcal{L}^\wedge \langle P^*(pp, x, s), V_{\text{ip}}(pp, w) \rangle = 1 \mid x, s \leftarrow \text{Gen}(1^n), pp \right] = 1
\]

B Graphene Protocol and Security Proofs

B.1 Primitives for Graphene

This section provides the main primitives that we use extensively to construct Graphene and its components, such as LinearCheck and QuadraticCheck. The primitives are i) Witness Encoding, ii) Codes and matrices, iii) Commitment of product codewords, iv) Oracle construction, and v) Witness decoding.

Our protocol proves membership in the NP-complete language specified by rank one constraint system (R1CS). An R1CS over a field \( F \) is specified by \( M \times N \) matrices \( A, B \) and \( C \), where the associated language \( \mathcal{L}(A, B, C) \) consists of \( w \in \mathbb{F}^N \) such that \( Aw \circ Bw = Cw \), where \( \circ \) defines element-wise product.

Several recent zero knowledge constructions [6, 16, 29], and circuit compilers such as [24] naively support the R1CS formulation. The arithmetic circuit representation can be expressed as an R1CS by introducing a constraint for each multiplication gate. We follow the broad outline of the interactive PCP construction in [1] which includes: (i) extending the witness, denoted as extended witness, to the concatenation of values over all the wires in topological order of an arithmetic circuit representing the statement, (ii) encoding the extended witness via suitable error-correcting code, (iii) checking linear relations on the extended witness, and (iv) checking quadratic relations on the extended witness (for the values concerning the wires going into and coming out from the multiplication gates). Both the linear and quadratic checks require sub-linear (oracle) access to the witness encoding. However, one runs into challenges in converting the IPCP to a non-interactive argument when the witness is distributed across several provers. The naive approach of provers sharing their encoded witnesses with an aggregator, which constructs the oracle breaches privacy among the provers, as these encodings only support bounded independence, i.e., they maintain privacy only when a bounded part of the witness is revealed. We overcome this, and several other technical challenges in our construction. The core techniques behind our construction are summarized below:

- We use homomorphic commitment over witness encoding and provide oracle access to the commitment. This facilitates oracle realization through aggregation.
- We design protocols for checking linear and quadratic constraints with oracle access to the commitment.
- We come up with new witness encoding scheme, to facilitate smaller argument size, and reduce communication amongst the provers during distributed proof generation and verification time.

While our use of homomorphic commitments introduces expensive cryptographic operations, we keep their usage strictly sub-linear. In particular, for an argument size of \( O(N^{1/\epsilon}) \), the verifier incurs \( O(N^{1-2/\epsilon}) \) exponentiations. The prover incurs \( O(N / \log N) \) exponentiations essentially while setting up the oracle. We report the concrete performance of our new zero-knowledge argument Graphene in Section:G.

B.1.1 Witness Encoding

We start by describing a randomized encoding of the prover's extended witness \( w \in \mathbb{F}^N \) (henceforth referred as witness), where \( N \) denotes the number of wires in the arithmetic circuit representing the NP relation. Let \( p, m \) and \( s \) be integers such that \( N = pms \). We canonically view the witness \( w \) as \( p \times m \times s \) matrix with entries \( w[i, j, k] \) for \( i \in [p], j \in [m] \) and \( k \in [s] \). The encoding is specified by an independence parameter \( \beta \), integers \( \ell := s + b, h > 2m, n > 2\ell \), and sequences \( \zeta, \eta, \alpha \) of distinct points in \( F \) with cardinality \( \ell, n, h \) respectively. We write \( \zeta = (\zeta_1, \ldots, \zeta_\ell), \eta = (\eta_1, \ldots, \eta_n) \) and \( \alpha = (\alpha_1, \ldots, \alpha_h) \). Next we define the interpolation do-
main $G$ as $G = \{ (\alpha_j, \zeta_k) : j \in [m], k \in [\ell] \}$ and evaluation domain $H$ as $H = \{ (\alpha_j, \eta_k) : j \in [n], k \in [n] \}$.

Finally, we encode $w$ as follows and denote the below randomized computation as $U \leftarrow \text{Enc}(w)$, where $\text{Enc}(w)$ is the random variable denoting the encodings of $w$:

(i) First we embed $w$ into a $p \times m \times \ell$ matrix $\hat{w}$ where $\hat{w}[i,j,k] = w[i,j,k]$ for $k \leq s$, while the entries $\hat{w}[i,j,k]$ for $k > s$ are sampled from $\mathbb{F}$ uniformly at random.

(ii) We construct bivariate polynomials $Q^i(x, y)$ with $\text{deg}_x(Q^i) < m$ and $\text{deg}_y(Q^i) < \ell$ such that $Q^i$ interpolates the slice $\hat{w}[i,\cdot,\cdot]$ on $G$, i.e., $Q^i(\alpha_j, \zeta_k) = \hat{w}[i,j,k]$.

(iii) Let $U$ denote the $p \times h \times n$ matrix, where the slice $U[i,\cdot,\cdot]$ consists of evaluations of $Q^i$ on $H$, i.e., $U[i,j,k] = Q^i(\alpha_j, \eta_k)$ for $i \in [p], j \in [h]$ and $k \in [n]$. Then $U$ is a randomized encoding of $w$.

It is easily seen that $U[i,\cdot,\cdot] \in \text{RS}_m[n, \ell] \otimes \text{RS}_n[h, m]$. We remark that the above encoding can be computed using $O(N \log N)$ field operations by applying FFT along the rows and columns of the slices.

The encoding $\text{Enc}$ satisfies the following bounded independence property.

**Lemma B.1 (Bounded Independence).** Let $B \subseteq [n]$ be a set of size $b$. Let $U(p, h, b)$ denote the set of $p \times h \times b$ matrices $X$ such that $X[i,\cdot,\cdot]$ is a codeword in $\text{RS}_n[h, m]$ for all $i \in [p], k \in [b]$. Then for any $p \times m \times s$ matrix $w$, the random variable $U_B = \{ U[i,\cdot,\cdot] : U \leftarrow \text{Enc}(w) \}$ is distributed uniformly on $U(p, h, b)$.

**Proof.** It is sufficient to prove that an arbitrary element from $U(p, h, b)$ is in $U_B$ suffices the lemma.

Let $U \in U(p, h, b)$. Set $U$ such that $U[i,\cdot,\cdot] = U[i,\cdot,\cdot]$ for all $k \in B$.

For $i = 1$ to $p$,

- Construct a bivariate polynomial $Q^i(x, y)$ such that $Q^i(\alpha_j, \zeta_k) = w[i,j,k]$, $\forall j \in [m], k \in [s]$, and $Q^i(\alpha_j, \eta_k) = U[i,j,k]$, $\forall j \in [m], k \in B$.

- $Q^i(x, y)$ is a polynomial such that $\text{deg}_x(Q^i) < m$ and $\text{deg}_y(Q^i) < \ell$, where $\ell = s + b$.

- Since, $U[i,\cdot,\cdot] \in \text{RS}_n[h, m]$, therefore $Q^i(\alpha_j, \eta_k) = U[i,j,k]$, forall $j \in [h], k \in B$.

- Set $U[i,j,k] = Q^i(\alpha_j, \eta_k)$, forall $j \in [m], k \in [n] \setminus B$.

Note that, $\text{Dec}(U) = w$, therefore $U[i,\cdot,\cdot] \in U_B$. This completes the proof. 

### B.1.2 Codes and Matrices

For code $\text{RS}_n[n, \ell]$, let $\Lambda_{n, \ell}$ denote the $n \times \ell$ matrix for the linear transformation that maps a vector $x \in \mathbb{F}^\ell$ to the unique codeword $y$ in $\text{RS}_n[n, \ell]$ such that $y_i = x_i$ for $i \in [\ell]$. For codes $\text{RS}_n[n, s + \ell - 1], \text{RS}_n[n, 2\ell - 1]$, and $\text{RS}_n[h, 2m - 1]$, let $\Lambda_{h,m}, \Lambda_{n,s+n+\ell-1}, \Lambda_{n,2\ell-1}$ and $\Lambda_{n,2m-1}$ be similar matrices. We denote the corresponding parity-check matrices as $\mathcal{H}_{n,t}, \mathcal{H}_{h,n}, \mathcal{H}_{n,s+n+\ell-1}, \mathcal{H}_{n,2\ell-1}$.

We note the set of three dimensional $p \times h \times n$ matrices as $\mathcal{M}_{p,h,n}$ and the set of two dimensional $h \times n$ matrices as $\mathcal{M}_{h,n}$. We assume standard distance metrics on the sets $\mathcal{M}_{p,h,n}$ and $\mathcal{M}_{h,n}$. Let $W_1$ denote the set of matrices $U$ in $\mathcal{M}_{p,h,n}$ such that the $n$-length vector $U[i,j,\cdot]$ is a codeword in $\text{RS}_n[n, \ell]$ for all $i,j$. Similarly let $W_2$ denote the set of matrices $U$ such that the $h$-length vector $U[i,\cdot,\cdot]$ is a codeword in $\text{RS}_n[h, m]$ for all $i, k$. Let $W = W_1 \cap W_2$. $W$ denotes the set of well-formed encodings and consists of $U$ such that each slice $U[i,\cdot,\cdot] \in \text{RS}_n[n, \ell] \otimes \text{RS}_n[h, m]$.

### B.1.3 Commitment of Product Codewords

We now discuss the commitment scheme for matrices in $\text{RS}_n[n, \ell] \otimes \text{RS}_n[h, m]$. Similar scheme works for other product codes also. A matrix $U$ in the above product code is completely determined by the sub-matrix $\overline{U} = \{ U[j, k] : j \in [m], k \in [\ell] \}$ and can be expressed as $U = \Lambda_{h,m} \overline{U} \Lambda_{n,\ell}^T$. A commitment to $U$ is defined as a vector of commitments $c = (c_1, \ldots, c_{\ell})$ where $c_k = \text{Com}(U[i,k])$ is the vector commitment for $k$th column of $\overline{U}$ for $k \in [\ell]$. We use the notation $c = (c_1, \ldots, c_{\ell}) \leftarrow \text{pcCom}(U)$. Given $c$, commitment to $k$th column of $U$ for $k > \ell$ can be computed as $c_k = \prod_{a \in [\ell]} (c_a)^{\Lambda_{n,\ell}^{-1}[a,k]}$, thanks to the homomorphism.

### B.1.4 Oracle Construction

Unlike prior IOP constructions such as [1, 6], we additionally obtain a homomorphic commitment on the encoded witness $\text{Enc}(w)$ and provide oracle access to the commitment. For all $(i,k) \in [p] \times [n]$, we compute the commitment $c_{ik} = \text{Com}(V_{ik})$ for the vector $V_{ik} = (U[i, 1, k], \ldots, U[i, m, k]) \in \mathbb{F}^m$. Note that we commit to the $m$-length vector (and not the $h$-length one) to save on the number of exponentiations. Finally we define $p \times n$ matrix $O$ as $O[i,k] = c_{ik}$. We write this as $O \leftarrow o\text{Com}(U)$. We provide oracle access to $O$ where for
a query $Q \subseteq [n]$, the oracle responds with columns $O[\cdot, k]$ for $k \in Q$. Note that $i^{th}$ row of the matrix $O$ commits to the $i^{th}$ slice of $U$. This is different from commitment of a product codeword where only $\ell$ columns are committed.

### B.1.5 Witness Decoding

We describe a decoding procedure $\text{Dec}$ for obtaining a witness $w$ from an encoding $U$. Let $U \in \mathcal{W}$ be a well-formed encoding. Such an encoding can be decoded slice by slice, i.e., for each $i \in [p]$, we interpolate bivariate polynomial $Q_i \in \mathbb{F}[x, y]$ with $deg_x(Q_i) < m$ and $deg_y(Q_i) < \ell$ such that $Q_i$ interpolates $U[i, \cdot, \cdot]$ on evaluation domain $H = \{(\alpha_j, \eta_k) : j \in [h], k \in [n]\}$. This can be accomplished using standard algorithms. The decoded witness $w$ is then given by $w[i, j, k] = Q_i(\alpha_j, \eta_k)$. We extend the above decoding procedure to recover from slightly malformed encodings. Let $U^* \in \mathcal{M}_{p,h,n}$ be such that $d_1(U^*, W_1) < e_1 < (n - \ell)/2$ and $d_2(U^*, W_2) < e_2 < (h - m)/2$. In this case, from the distance property of the codes $\mathcal{RS}_{\eta}[n, \ell]$ and $\mathcal{RS}_{\alpha}[h, m]$ it follows that there is at most one $U \in \mathcal{W}$ such that $\Delta_1(U^*, U) < e_1$ and $\Delta_2(U^*, U) < e_2$. Such a $U$ may be efficiently “recovered” from $U^*$ using algorithms for Reed-Solomon decoding (c.f. [36]). We then define $\text{Dec}(U^*)$ as $\text{Dec}(U)$.

### B.2 Graphene

#### B.2.1 Linear Check

In this section, we will give an overview of the working of the linear check protocol that is used to construct the Graphene. In the linear check protocol a prover proves knowledge of a witness $w$ satisfying a linear constraint of the form $Aw = b$ for some public $A \in \mathbb{F}^{m \times N}$ and $b \in \mathbb{F}^m$. The verifier needs to check that $Aw = b$ holds, this check can be probabilistically reduced to check $r^T A w = r^T b$, for a randomly chosen $r$. To do that, the verifier $V$ picks a random $r \leftarrow \mathbb{F}^m$ and sends to the prover $P$ as a challenge. Now $P$ needs to show that $(r^T A, w) = r^T b$. Let’s call $R = r^T A$. Further, this check is reduced to check inner product arguments. To facilitate such checks, $P$ encodes and commits to its witness $w$, using the encoding and commitment described in Section B.1.1, and Section B.1.3 respectively. $P$ constructs an oracle as described in Section B.1.4. As $P$ receives $r$ from $V$, both $P$ and $V$ computes $R$, and view it as a cube of dimension $p \times m \times s$. Then interpolate and obtain bivariate polynomials $R_i(x, y)$ for $i \in [p]$ with $deg_x(R_i) < m$ and $deg_y(R_i) < s$ satisfying $R_i^\alpha(\alpha_j, \zeta_k) = R[i, j, k]$. Let $Q^i, i \in [p]$ denote the polynomials used in interpolating (and encoding) witness $w$. Then $w[i, j, k] = Q_i^\alpha(\alpha_j, \zeta_k)$. Therefore the check $(R, w) = r^T b$ reduces to \[\sum_{i,j,k} R_i^\alpha(\alpha_j, \zeta_k) Q_i(\alpha_j, \zeta_k) = r^T b\] where $i, j$ and $k$ run over indices in $[p], [m]$ and $[s]$ respectively. $P$ computes 

\[p_j(y) = \sum_{i \in [p]} R_i^\alpha(\alpha_j, \cdot) Q_i^\alpha(\alpha_j, y),\] for $j \in [h]$. Here all these polynomials are of degree less than $s + \ell - 1$. To reduce the communication instead of sending all $p_j(y)$ polynomials, $P$ constructs an intermediate matrix $P$ of dimension $h \times n$ such that $P[j, k] = p_j(y_k)$ for $j \in [h], k \in [n]$. Note that $P$ is a product codeword from $\mathcal{RS}_{\eta}[n, s + \ell - 1] \otimes \mathcal{RS}_{\alpha}[h, 2m - h]$ and fully determined by sub-matrix $\mathcal{P}$ consisting of the first $2m - 1$ rows and the first $s + \ell - 1$ columns of $P$.

**Reduction to inner product argument:** Now $P$ commits to the matrix $P$ using commitment for product codeword, described in Section B.1.3 that is, $(c_1, \ldots, c_{s+\ell-1}) \leftarrow \text{pcCom}(P)$, and sends $(c_1, \ldots, c_{s+\ell-1})$ to $V$, which they use later in the inner product argument. The check $(R, w) = r^T b$ can be viewed as a following inner product $(*, \mathcal{P} \varphi) = r^T b$, where $*$ and $\varphi$ are public vectors and so the commitment for $\mathcal{P} \varphi$ can be computed given the commitment of $\mathcal{P}$. Let $\Phi$ be a $s \times (s + \ell - 1)$ matrix such that $[p_j(\zeta_1), \ldots, p_j(\zeta_s) ]^T = \Phi [p_j(n_1), \ldots, p_j(n_{s+\ell-1}) ]^T$ for $j \in [h]$. We have:

\[ [\sum_{j \in [m]} p_j(\zeta_1), \ldots, \sum_{j \in [m]} p_j(\zeta_s) ]^T = \Phi \Phi^T [1^m | 0^{m-1}]^T \]

So the check reduces to $\sum_{k \in [s], j \in [m]} p_j(\zeta_k) = r^T b$ reduces to

\[ [1^m | 0^{m-1}] \times \mathcal{P} \times \Phi^T \times [1^s]^T = r^T b \]

Here, $* = [1^m | 0^{m-1}]^T$ and $\varphi = \Phi^T \times [1^s]^T$ are public vectors. Given commitment of $P$, $c_1, \ldots, c_{s+\ell-1}$, the commitment to $\mathcal{P} \varphi$ can be computed as $\text{cm} = \prod_{k=1}^{s+\ell-1} (c_k)^{\text{cm}}$. In the protocol, the prover initially commits to a random $P_0 \in \mathbb{F}^{2m-1}$ subject to $[1^m | 0^{m-1}, P_0] = 0$, and uses $\beta P_0 + \mathcal{P} \varphi$ as witness in the inner product protocol. Here $\beta \leftarrow \mathbb{F} \setminus \{0\}$ is randomly chosen by the verifier. This randomization precludes the need for the inner-product argument to be zero-knowledge, and as we will later see, helps reduce interaction among provers in its distributed variant.

**Consistency of oracle $\pi$ and $P$ via $U$:** The verifier additionally needs to determine if the committed $P$ and the oracle $\pi$ are consistent or not. The verifier proceeds
to check the consistency at randomly sampled $t$ positions given by $\{(j_u, k_u) : u \in [t]\}$ from $[h] \times [n]$ for a $t = O(\lambda)$. It queries the oracle for the columns $\pi[i]$, $k_u$ and the prover for vectors $X_u = U[i, j_u, k_u]$ for $u \in [t]$. For $u \in [t]$, let $1_{j_u}$ denote the unit vector in $\mathbb{F}^h$ with 1 in the position $j_u$. The prover and the verifier run inner-product arguments to establish the following:

1. $\langle 1_{j_u}, P[i, k_u] \rangle = \sum_{i \in [p]} r_i P[i, k_u] X_u[i] \forall u \in [t]$. with $c_{k_u}$ (which can be computed from $c_1, \ldots, c_{2t-1}$, as in Section B.1.3) as the commitment of $P[i, k_u]$.

2. $\langle 1_{j_u}, U[i, k_u] \rangle = X_u[i]$ with $\pi[i, k_u]$ as the commitment for $U[i, k_u]$. A minor technicality arises since the commitment is for $V_{k_u} = \{U[i, 1, k_u], \ldots, U[i, m, k_u]\}$ and not for $U[i, k_u]$. Since $U[i, k_u] = A_{h,m} V_{k_u}$, the above inner-product reduces to $\langle 1_{j_u} A_{h,m} V_{k_u} \rangle = X_u[i]$.

The checks for each $u \in [t]$ can be aggregated, leading to one inner-product check for each $u \in [t]$.

**Proximity Check for Oracle:** This check forces a prover to commit to an encoding which is “close” to well-formed encoding $W$. To check proximity, the verifier initially sends a vector $\rho \leftarrow \mathbb{F}^p$ and asks the prover to send commitments $\tilde{e} = (\tilde{e}_1, \ldots, \tilde{e}_{2t-1})$ to $\tilde{U} = \sum_{i \in [p]} \rho_i U[i, \cdot]$, computed as $\tilde{e}_k = \prod_{i \in [p]} (\pi[i, k_u])^{\rho_i}$ $\forall k \in [t]$. It then checks:

$$\prod_{u=1}^{\ell} (\tilde{e}_u)^{X_u[i, k_u]} = \prod_{i=1}^{\ell} (\pi[i, k_u])^{\rho_i} \forall u \in [t]. \quad (2)$$

It can be seen that for an honest computation, both the commitments open to the vector $\sum_{i \in [p]} \rho_i V_{k_u}$ where $V_{k_u} = \{U[i, 1, k_u], \ldots, U[i, m, k_u]\}$.

### B.2.2 Quadratic Check

Here we will describe the quadratic check protocol, which aids in validating the honest evaluation of the circuit’s multiplication gates. $P$ proves the knowledge of $w_x$, $w_y$ and $w_z$ in $\mathbb{F}^N$ satisfying $w_x \circ w_y = w_z$. This protocol is similar to the linear check protocol, described in Section B.2.1. Here also it has 3 stages, i) Reduction to inner product argument, ii) Consistency of the oracle and the intermediate matrix $P$, and iii) Proximity check.

Here $V$ checks if the polynomials $Q_i' = Q_i^2 - Q_i^1$ interpolate to $0^{m \times s}$ on the set $\{(\alpha_j, \zeta_k) : j \in [m], k \in [s]\}$ for all $i \in [p]$. In three simple steps, we derive a simple probabilistic check below compressing in all the three dimensions. First, the above check reduces to checking that the polynomial $F := \sum_{i \in [p]} r_i Q_i'$ interpolates $0^{m \times s}$ on the same set for a randomly sampled $r \in \mathbb{F}^p$. Second, this further reduces to checking $p(\cdot) := \sum_{j \in [m]} \gamma_j F(\alpha_j, \cdot)$ interpolates $0^s$ on $\mathbb{F}$ for randomly sampled $\gamma = (\gamma_1, \ldots, \gamma_m) \in \mathbb{F}^m$. Third, this further reduces to checking $\langle \gamma, p(\mathbb{F}) \rangle = 0$ for a random $\gamma \in \mathbb{F}^s$. Similar to the linear check protocol, $P$ constructs the intermediate matrix $P$, which is in the product code $RS_n[h, 2t-1 \ominus RS_n[h, 2m-1]]$, and commits to it similarly. Let $(c_1, \ldots, c_{2t-1}) \leftarrow pcCom(P)$. Similar to the linear check, quadratic check reduces to $\langle [\gamma] \cdot [0^{m-1}]^T, z \rangle = 0$, where $z = \beta P_0 + TF_\varphi$ and $P_0$ is a random vector such that $P_0[j] = 0$ for $j \in [m]$, and $\varphi = \Phi \times \tau$. The differences are: (a) $p(\cdot) = \sum_{j \in [m]} \gamma_j F(\alpha_j, \cdot)$ is a polynomial of degree $< 2t - 1$, (b) $\Phi$ is a $s \times 2t - 1$ matrix that takes $p(\mathbb{F})$ to $p(\mathbb{F})$, where $p(\mathbb{F}) = [p(\eta_1), \ldots, p(\eta_{2t-1})]$ and $\mathbb{F} = [p(\zeta_1), \ldots, p(\zeta_s)]$. Commitment $c_0$ of $P_0$ is sent to the verifier a-priori. Therefore, commitment to $z$ is $c_0 \prod_{k=1}^{2t-1} (c_k)^{\rho_k}$.

**Consistency of the oracles and P:** Similar to linear check, the verifier checks the consistency at randomly sampled positions $Q = \{(j_u, k_u) : u \in [t]\} \subset [h] \times [n]$. It queries the oracles for the columns $\pi_{\cdot} [\cdot, k_u]$ for $u \in [x, y, z]$ and $u \in [t]$. Then it queries the prover for vectors $X_u = U_x[i, j_u, k_u]$, $Y_u = U_y[i, j_u, k_u]$, and $Z_u = U_z[i, j_u, k_u]$ for $u \in [t]$. Let $1_{j_u}$ denote the unit vector in $\mathbb{F}^h$ with 1 in the $j_u^h$ position. The prover and verifier run inner-product arguments to establish:

1. $\langle 1_{j_u}, P[i, k_u] \rangle = \sum_{i \in [p]} r_i P[i, k_u] X_u[i] \cdot Y_u[i] - Z_u[i] \forall u \in [t]$ with $c_{k_u}$ which can be computed from $c_1, \ldots, c_{2t-1}$, as in Section B.1.3) as the commitment of $P[i, k_u]$.

2. $\langle 1_{j_u}, U_x[i, \cdot, k_u] \rangle = X_u[i]$, $\langle 1_{j_u}, U_y[i, \cdot, k_u] \rangle = Y_u[i]$ and $\langle 1_{j_u}, U_z[i, \cdot, k_u] \rangle = Z_u[i]$. These inner-products check the consistency of the vectors sent by the prover with the respective oracles. These can be verified in a similar manner to that in the linear check protocol.

**Proximity Check for Oracle:** We combine the proximity check for the three encodings $U_x, U_y$ and $U_z$. The verifier sends a vector $\rho \leftarrow \mathbb{F}^p$ and asks the prover to commit to the matrix $U = \sum_{i=1}^{p} [P_0 U_x[i, \cdot, \cdot] + \rho P_{2t-1} U_y[i, \cdot, \cdot] + \rho P_{2p+1} U_z[i, \cdot, \cdot]]$ by sending commitments $\tilde{e} = (\tilde{e}_1, \ldots, \tilde{e}_{2t-1})$, which are computed as $\tilde{e}_k = \prod_{i=1}^{p} (\pi_x[i, k])^{\rho_i} \cdot (\pi_y[i, k])^{\rho_{p+1}} \cdot (\pi_z[i, k])^{\rho_{2p+1}} \forall k \in [t]$. 

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Thereafter, for \( u \in [t] \), the verifier checks:

\[
\prod_{a \in [t]} e_T^{\frac{\lambda(u)}{N_a,k_u}} \prod_{i=1}^P (p_{u,i}^{[i,k_u]}(\pi_y^{[i,k_u]} p_{v,i}^{[i,k_u]} + \pi_z^{[i,k_u]} p_{w,i}^{[i,k_u]} + \pi_r^{[i,k_u]} p_{x,i}^{[i,k_u]}))
\]

\[
Pr \left[ \begin{array}{l}
\sigma \xleftarrow{} Gen(1^\lambda) \\
U \xleftarrow{} Enc(\sigma) \\
w \xleftarrow{} Dec(U)
\end{array} \right] \geq \epsilon(P^*) - \kappa_{ic}(\lambda)
\]

B.2.3 Graphene

We use the linear and quadratic check protocols from Section B.2.1 and Section B.2.2 respectively to describe an efficient protocol for rank one constraint system (R1CS). Let \( A, B \) and \( C \) be \( M \times N \) matrices. We prove existence of \( w \in \mathbb{F}^N \) satisfying \( Aw + Bw = Cw \) by showing existence of \( w_x, w_y, w_z \) and \( w \in \mathbb{F}^N \) satisfying the linear relations \( A w = w_x, B w = w_y \) and \( C w = w_z \) and a quadratic relation \( w_x \circ w_y = w_z \). We probabilistically reduce the three linear relations to the linear relation:

\[
\begin{bmatrix}
\gamma_x I & \gamma_y I & \gamma_z I \\
\gamma_x A & \gamma_y B & \gamma_z C
\end{bmatrix}
\]

\[
= 0
\]

for \( \gamma_x, \gamma_y, \gamma_z \leftarrow \mathbb{F}^3 \). As before, we view \( w_x, w_y, w_z \) and \( w \) as \( p \times m \times s \) matrices. Let \( \mathcal{W} \) denote the \( 4p \times m \times s \) matrix formed by stacking \( w_x, w_y, w_z \) and \( w \) along “slices”. The encoding \( U \xleftarrow{} Enc(\mathcal{W}) \) and commitment to the encoding \( O \xleftarrow{} Com(U) \) are computed as in Sections B.1.1 and B.1.4. Note that \( O \) is a \( 4p \times n \) matrix. Let \( D \) be the \( M \times 4N \) sized matrix given in Equation 4. For the R1CS instance \((A, B, C)\), \( \mathcal{P} \) and \( \mathcal{V} \) run linear check protocol B.2.1 for \( D \mathcal{W} = 0 \) and run quadratic check protocol for \( w_x \circ w_y = w_z \).

B.2.4 Linear Check Protocol

**Linear Check Soundness**

**Lemma B.2** (Soundness). For all polynomially bounded provers \( P^* \) and all \( \pi \in \mathbb{G}^{p \times n}, A \in \mathbb{F}^{p \times N}, b \in \mathbb{F}^N \), there exists a polynomial time extractor \( E \) with rewinding access to transcript \( tr = (P^*(\cdot), V^*(\cdot)) \) such that \( E \) either breaks the commitment binding or outputs a witness with overwhelming probability whenever \( P^* \) succeeds, i.e.

\[
Pr \left[ \begin{array}{l}
U \xleftarrow{} Enc(\pi) \\
A w = b \\
\sigma \xleftarrow{} Gen(1^\lambda) \\
U \xleftarrow{} Enc(\sigma) \\
w \xleftarrow{} Dec(U)
\end{array} \right] \geq \epsilon(P^*) - \kappa_{ic}(\lambda)
\]

where

\[
\epsilon(P^*) := \Pr \left[ (P^*(x,\sigma), V^*(x,\sigma)) = 1 \mid \sigma \xleftarrow{} Gen(1^\lambda) \right]
\]

denotes the success probability of \( P^* \), \( \kappa_{ic} \) denotes a negligible function, and \( x \) denotes the tuple \((A,b,M,N)\).

**Proof.** Suppose the oracle \( \pi \) commits to \( U \). \( U \) can be “extracted” by the appropriate extractor. Note that \( U \in (\mathcal{W}_1)^P \) as a commitment implicitly corresponds to such a matrix. Let \( e < (n - \ell)/3 \) be a parameter. First we show that an adversarial prover succeeds in negligible probability if \( d(U, (\mathcal{W}_1)^P) > e \). Second, we show that for \( d(U, (\mathcal{W}_1)^P) \leq e \), the prover succeeds with negligible probability when \( Aw \neq b \) where \( w = Dec(U) \).

Consider the case when \( d(U, (\mathcal{W}_1)^P) > e \). Then for \( \bar{U} = \sum_{i \in [p]} p_{i\cdot} U_{[i\cdot]} \), by Proposition A.2, we have \( d(U, \bar{C}_1) > e \) with probability \( 1 - o(1) \). Let \( \hat{e} = (\hat{e}_1, \ldots, \hat{e}_\ell) \) be the commitments to \( \bar{U} \) sent by the prover (Step 3 in Figure 5). Define the vector \( \hat{C} = (\hat{C}_1, \ldots, \hat{C}_n) \) where \( \hat{C}_k = \prod_{i=1}^{\ell} (\hat{e}_a)^{\Lambda_{\hat{e}_a}^{[a,k]} \pi_i} \) for \( k \in [n] \). Let \( C^* = (\hat{C}_1, \ldots, \hat{C}_n) \)}
where $\hat{C}_k = \prod_{i=1}^{p} (\pi[i, k])^\alpha_i$. Now if $\Delta(\hat{C}, \hat{C}) > \epsilon$, we see that the prover succeeds in the proximity check equation (2) with probability at most $(1 - \epsilon/n)^\ell$. If $\Delta(\hat{C}, \hat{C}) \leq \epsilon$, while $d(U, C_1) > \epsilon$, then it is easy to break the binding property of the commitment scheme. Thus an adversarial prover succeeds with probability at most $(1 - \epsilon/n)^\ell$ when $d(U, (W_1)^p) > \epsilon$.

We now consider the case when $d(U, (W_1)^p) \leq \epsilon$. From Lemma A.1, there exists (unique) $U^* \in (W)^p$ such that $\Delta_1(U, U^*) \leq \epsilon$. Let $w = \text{Dec}(U) = \text{Dec}(U^*)$. We consider the prover’s success probability when $Aw \neq b$, and thus with overwhelming probability $r^T Aw \neq rt^b$. Let $P^*$ denote the correctly computed intermediate matrix from $U^*$ and let $\hat{P}$ denote the correctly computed intermediate matrix from $U$. We note that $\Delta_1(\hat{P}, P^*) \leq \epsilon$. Let $c_1, \ldots, c_{s+\ell-1}$ be the commiters to a matrix in $U^*$ and let $\bar{P}$ denote the correctly computed intermediate matrix from $U$. We note that $\Delta_1(\bar{P}, P^*) \leq \epsilon$. For any $k \leq n$, the following holds when the distinct code-words $P^*[i, k]$ and $P[i, k]$ in $RS_{n/h, 2m - 1}$ agree on the position $j_u$, which happens with probability at most $2m/h$. Thus probability $Pr[\mathcal{E}]$ that a corrupt prover with $U$ such that $d(U, (W_1)^p) \leq \epsilon$ succeeds is bounded by:

\[
Pr[\mathcal{E}] \leq \left(\frac{s+\ell-\epsilon}{n}\right)^t + \left(\frac{n-s-\ell-\epsilon}{n}\right)^{\ell(\frac{k}{t})}
\]

The above probability is smaller than a constant $\epsilon < 1$ for suitable choices of parameters. Hence, the overall probability of prover’s success is $\text{neg}(\lambda)$ for $t = O(\lambda)$.

**Extraction:**
Let $\mathcal{E}_{ip}$ be the extractor of the inner product argument which takes, in expectation, $\mathcal{P}_p(n)$ amount of time, where $\mathcal{P}_p(\cdot)$ is polynomial, to output the private vector of length or breaking the binding of the commitment scheme. We will design an extractor $\mathcal{E}$ for LinearCheck, which uses $\mathcal{E}_{ip}$.

If $\mathcal{P}^*$ fails in the proximity check (step 12) then $\mathcal{V}$ outputs reject, and so the extractor $\mathcal{E}$ terminates with abort. If $\mathcal{P}^*$ succeeds in the proximity check (step 12) then $U \in W_1$ and $\mathcal{E}$ proceeds in the following way:

$\mathcal{E}$ plays the role of the verifier and rewrites the provers polynomially many times if required.

$\mathcal{E}$ runs the protocol till step 8, sends $Q$ and receives $U[i, j_u, k_u]$.

$\mathcal{E}$ picks random $\delta \in \mathcal{F}$ and $\beta \in \mathcal{F}$ and proceeds to run the inner product arguments. $\mathcal{E}$ uses $\mathcal{E}_{ip}$ and gets:

- $\mathcal{P}^*[i, k_u]$ in expected time $\mathcal{P}_p(m)$, $\forall u \in [t]$.
- $z = \mathcal{P}_0 + \mathcal{P}_\phi$ in expected time $\mathcal{P}_p(m)$.
- $V_u = \sum_{i \in [p]} \delta_i U[i, \cdot, k_u]$ in expected time $\mathcal{P}_p(m)$, $\forall u \in [t]$.

Then $\mathcal{E}$ rewinds $\delta, \beta O(p \log(p))$ times and gets $P_0$ from $z$ and from $V_u$, $\mathcal{E}$ gets $U[i, \cdot, k_u]$. $\mathcal{E}$ checks $U[i, j_u, k_u]$ received in step 8, matches with the extracted $U[i, \cdot, k_u]$'s $j_u$ position or not. If does not, then $\mathcal{E}$ gets two opening of $\pi[i, k_u]$ and outputs abort, otherwise $\mathcal{E}$ proceeds in the following way: $\mathcal{E}$ rewinds $\mathcal{P}^*$ and sends uniformly random $Q$ and keeps repeating until all the $Q$'s together cover all the columns. It takes $n \log(n)$ rewinding s in expectation. Then $\mathcal{E}$ extracts the whole $U$ and checks if all the vectors are consistent or not. If not, that gives the break for the binding of the commitment scheme and if consistent, then it decodes $U$ and outputs correct witness $w$. Therefore, expected Run time of $\mathcal{E}$ is $O(n \log(n)(O(p \log(p))(\mathcal{P}_p(m)) + \mathcal{P}_p(m) + \mathcal{P}_p(m)))$, which is polynomial in the size of the circuit.

**B.2.5 Quadratic Check Protocol**

**Quadratic Check Soundness**

**Lemma B.3** (Soundness). For all polynomially bounded provers $P^*$ and all $\pi \in \mathbb{G}^3p \times n$, there exists an expected polynomial time extractor $\mathcal{E}$ with rewinding access to the transcript oracle $\text{tr} = (P^*(\cdot), V^*(\cdot))$ such that either $\mathcal{E}$ breaks the commitment binding, or it outputs a witness with overwhelming probability whenever $P^*$ succeeds, i.e,
QuadraticCheck\( (pp, [\pi_x, [\pi_y], [\pi_z]; U_x, U_y, U_z]) \):

Relation: \( U_x = \text{Open}(\pi_x) \) for \( a \in \{x, y, z\} \), \( w_a \circ w_y = w_z \) where \( w_a = \text{Dec}(U_a) \) for \( a \in \{x, y, z\} \).

1. \( V \rightarrow P; \rho \leftarrow \in \mathbb{F}^m \).
2. \( P \) computes: (a) \( U = \sum_{j} \rho_1 U_x[j, \cdot] + \rho_{21} U_y[j, \cdot] + \rho_{22} U_z[j, \cdot] \) \( + \rho_{23} U_y[i, \cdot] \), (b) commitments \( c_1, \ldots, c_\ell \) as \( c_k = \prod_{j=1}^{n} (\pi_x[j, i])^{\rho_1}; (\pi_y[j, i])^{\rho_2}; (\pi_z[j, i])^{\rho_3} \) \( \forall k \in [\ell] \).
3. \( P \rightarrow V; \tilde{\varsigma} \leftarrow (c_1, \ldots, c_\ell) \).
4. \( V \rightarrow P; r \leftarrow \in \mathbb{F}^m \).
5. \( P \) computes: (a) \( p_i(\cdot) = \sum_{j} (Q_1 \circ (\pi_y, j) \circ Q_2 \circ (\pi_z, j) - Q_2 \circ (\pi_x, j)) \forall j \in [n] \), (b) matrix \( P \) such that \( P[j, k] = p_i(\eta_k) \) as described in Section B.2.2, (c) computes commitments \( c_1, \ldots, c_\ell \) from \( P \). \( P \) also samples \( P_0 \leftarrow \in \mathbb{F}^{2m-1} \) with \( P_0[j] = 0 \) \( \forall j \in [n] \) and computes commitment \( c_0 \) to \( P_0 \).
6. \( P \rightarrow V; c_0, c_1, \ldots, c_\ell \leftarrow \in \mathbb{F}^{m-1} \).
7. \( V \rightarrow P; Q = \{j \cup k; u \in [\ell] \} \) for \( \in \mathbb{F}[x] \times [n] \), \( u \in [\ell] \) and \( \tau \leftarrow \in \mathbb{F}^m \).
8. \( V \rightarrow P; \pi; \{j \cup k; u \in [\ell] \} \).
9. \( P \rightarrow V; X_u = U_x[j, u, k], Y_u = U_y[j, u, k] \) and \( Z_u = U_z[j, u, k] \) for \( u \in [\ell] \).
10. \( P \rightarrow V; \pi; \{j \cup k; u \in [\ell] \} \).
11. \( V \rightarrow P; \delta \leftarrow \in \mathbb{F}^m, \beta_\ell \leftarrow \in \mathbb{F}^m, \beta_\ell \leftarrow \in \mathbb{F}^m, \beta_\ell \leftarrow \in \mathbb{F}^m \).
12. \( P \) and \( V \) run inner-product arguments to check:
   (a) \( \text{InnerProduct}(pp, T^j_{m \times n}, \lambda_{2m-1}, \text{cm}, \pi; F[i, k]) \)
   for \( u \in [\ell] \) where \( \text{cm}_{\pi} = \prod_{j=1}^{2m-1} (c_\ell)^{\lambda_{2m-1}[u, k]} \)
   \( \forall u \in [\ell] \). \( \text{cm}_{\pi} = \prod_{j=1}^{2m-1} (c_\ell)^{\lambda_{2m-1}[u, k]} \).
   \( U_u = \sum_{j} r_i[X_u[i, \cdot] \circ Y_u[i, \cdot] - Z_u[i, \cdot]] \) (check consistency of \( P \) with \( \pi \)).
   (b) \( \text{InnerProduct}(pp, T^j_{m \times n}, \lambda_{2m-1}, \text{cm}, 0, z) \) where \( z = \beta_\ell \beta_\ell \leftarrow \in \mathbb{F}^m \) (consistent with \( \pi \)).
   (c) \( \text{InnerProduct}(pp, T^j_{m \times n}, \lambda_{2m-1}, \text{cm}, 0, x) \) where \( x \) stands for first m entries of \( \pi_x \) and \( \pi_y \) \( \beta_\ell \beta_\ell \leftarrow \in \mathbb{F}^m \).
13. \( V \) checks proximity of \( U_x, U_y \) and \( U_z \) according to Eqn (3).
14. \( V \) accepts if all the checks succeed.

for some negligible function \( \kappa_{qd} \). In the above, \( \epsilon(P^*) \) denotes the success probability of the prover \( P^* \) as before.

Proof. Suppose the oracle \( \pi \) commits to \( U_x, U_y, U_z \). \( U_x, U_y, U_z \) can be “extracted” by the appropriate extractor. Note that \( U_x || U_y || U_z \in (W_2)^3 \), where \( U = U_x || U_y || U_z \) is the juxtaposing along \( p \) direction, as a commitment implicitly corresponds to such a matrix.

Let \( e < (n - \ell)/3 = 3 \) be a parameter. First we show that an adversarial prover succeeds with negligible probability if \( d(U, (W_1)^3) \). Second, we show that for \( d(U, (W_1)^3) \) \( \leq e \), the prover succeeds with negligible probability when \( w_x \circ w_y \neq w_z \) where \( w_a = \text{Dec}(U_a) \) for \( a \in \{x, y, z\} \). Consider the case when \( d(U, (W_1)^3) \). Then for \( \bar{U} = \sum_{j} \rho_1 U[j, \cdot] \), by Definition 3 in Figure 6. Define the vector \( \tilde{C} = (\tilde{C}_1, \ldots, \tilde{C}_m) \) where \( \tilde{C}_k = \prod_{j=1}^{2m-1} (c_\ell)^{\lambda_{2m-1}[u, k]} \). Now that \( \Delta(\tilde{C}, \tilde{C}) \) \( \geq e \), while \( d(U, (W_1)^3) \) \( \leq e \), then it is easy to break the binding property commitment scheme.

Thus an adversarial prover succeeds with probability at most \((1 - e/n)^3 \). In this case \( d(U, (W_1)^3) \) \( \leq e \).

We now consider the case when \( d(U, (W_1)^3) \) \( \leq e \). From Lemma 3.1, there exists (unique) \( U^* \) such that \( \Delta(U, U^*) \) \( \leq e \). Let \( w_a = \text{Dec}(U_a) = \text{Dec}(U_x) \).

We consider the prover’s success probability when \( w_x \circ w_y = w_z \). and thus with overwhelming probability \( \sum_{j} r_i[X_u[i, \cdot] \circ Y_u[i, \cdot] - Z_u[i, \cdot]] = 0 \).

Thus \( \epsilon(P^*) \) denotes the correctly computed intermediate matrix from \( U^* \) and let \( \hat{P} \) denote the correctly computed intermediate matrix from \( U \). We note that \( \Delta(\hat{P}, P^*) \) \( \leq e \). Let \( c_1, \ldots, c_{2\ell-1} \) be the commitments to the intermediate matrix sent by the prover. If these commitments correspond to a matrix \( P \neq P^* \), the inner product check \( \text{InnerProduct}(pp, [\gamma](m, 0, z), \text{cm}) \) fails when using the commitment \( \text{cm} = \prod_{k=1}^{2m-1} c_k^{\lambda_{2m-1}[u, k]} \) for \( \gamma = \Phi \times \tau \). This is because \( \gamma = \prod_{k=1}^{2m-1} c_k^{\lambda_{2m-1}[u, k]} \).

Thus there exists a set \( E \) of at least \( n - 2\ell - e \) columns, such that for \( k \in E \), \( \hat{P}[i, k] = P^*[i, k] \neq P[i, k] \). The checks \( \langle 1_j, U_a \rangle = \sum_{i} r_i[X_i[j, \cdot] \circ Y_i[j, \cdot] - Z_i[j, \cdot]] \) for some negligible function \( \kappa_{qd} \). In the above, \( \epsilon(P^*) \) denotes the success probability of the prover \( P^* \) as before.

Fig. 6. Quadratic Check Protocol
\[ i \in [p] \text{ and } u \in [t] \text{ force the prover to provide vectors} \]
\[ X_u = U_x[i] \cdot j_u(k_u), Y_u = U_y[i] \cdot j_u(k_u), Z_u = U_z[i] \cdot j_u(k_u) \]
\[ \text{with overwhelming probability. Then the consistency check succeeds for the uniformly sampled query point} \]
\[ (j_u, k_u) \text{ when:} \]
\[ \Pr[j_u, k_u] = \sum_{i \in [p]} r_i(X_u[i] \cdot Y_u[i] - Z_u[i]) = \tilde{P}[j_u, k_u] \]

For \( k_u \in E \), the above holds when the distinct codewords \( P^*[i, k_u] \) and \( P[i, k_u] \) in \( RS_n[h, 2m - 1] \) agree on the position \( j_u \), which happens with probability at most \( 2m/h \). Thus probability \( \Pr[E] \) that a corrupt prover with \( U \) such that \( d(U, (V_1)^{3p}) \leq e \) succeeds is bounded by:

\[
\Pr[E] \leq \frac{(2\ell + e)(n)}{\ell} + \frac{n - 2\ell - e - (2m)}{h} = \frac{(2\ell + e)}{n} + \frac{(n - 2\ell - e)}{h} \]

The above probability is smaller than a constant \( \epsilon < 1 \) for suitable choices of parameters. Hence, the overall probability of prover’s success is \( \text{negl}(\lambda) \) for \( t = O(\lambda) \). We will set \( 2n > 5\ell \).

**Extraction:**

Let \( E_{ip} \) be the extractor of the inner product argument which takes, in expectation, \( p_{ip}(n) \) amount of time, where \( p_{ip}(\cdot) \) is polynomial, to output the private vector of length or breaking the binding of the commitment scheme. We will design an extractor \( E \) for QuadraticCheck, which uses \( E_{ip} \).

If \( P^* \) fails in the proximity check (step 15) then \( V \) outputs reject, and so the extractor \( E \) terminates with abort. If \( P^* \) succeeds in the proximity check (step 15) then \( U \in W_1 \) and \( E \) proceeds in the following way:

\( E \) plays the role of the verifier and rewinds the provers polynomially many times if required.

\( E \) runs the protocol till step 7, sends \( Q, \gamma, \tau \) and receives \( U_x[i] \cdot j_u(k_u), U_y[i] \cdot j_u(k_u), U_z[i] \cdot j_u(k_u) \). \( E \) picks random \( \delta \in \mathbb{F}^p, \beta_x, \beta_y, \beta_z \in \mathbb{F} \) and \( \beta \in \mathbb{F}^2 \) and runs the inner product arguments. \( E \) uses \( E_{ip} \) and gets:

\[ P[i, k_u] \text{ in expected time } p_{ip}(m), \forall u \in [t]. \]
\[ z = \beta P_0 + P \phi \text{ in expected time } p_{ip}(m). \]
\[ V_u = \sum_{i \in [p]} \delta_i(\beta_x U_x[i] \cdot k_u + \beta_y U_y[i] \cdot k_u + \beta_z U_z[i] \cdot k_u) \text{ in expected time } p_{ip}(m), \forall u \in [t]. \]

Then \( E \) rewinds \( \delta, \beta_x, \beta_y, \beta_z, \beta \) \( O(p \log(p)) \) times and gets \( V_u \). \( E \) gets \( U_x[i] \cdot k_u, U_y[i] \cdot k_u, U_z[i] \cdot k_u \) by solving a system of equation with \( 3p \) unknowns. \( E \) checks \( U_u[i, j_u, k_u] \) received in step 7, matches with the extracted \( U_u[i, j_u, k_u]’s \) j_u position or not, for \( a \in \{x, y, z\} \).

If not, then \( E \) gets two opening of \( \pi_a[i, k_u] \), for some \( a \in \{x, y, z\} \) and outputs abort, otherwise \( E \) proceeds in the following way: \( E \) re-winds \( P^* \) and sends uniformly random \( Q \) and keeps repeating until all the Q’s together cover all the columns. It takes \( n \log(n) \) rewinds in expectation. Then \( E \) extracts the whole \( U_x, U_y, U_z \) and checks if all the vectors are consistent or not. If not, that gives the break for the binding of the commitment scheme and if consistent, then it decodes \( U_a \) and outputs correct witness \( w_a \) for \( a \in \{x, y, z\} \).

Therefore, expected Run time of \( E \) is \( \mathbb{O}(n \log(n)(O(p \log(p)))(p_{ip}(m)) + p_{ip}(m) + p_{ip}(m))) \), which is polynomial in the size of the circuit. \( \square \)

**B.2.6 Graphene Protocol**

For a cheating prover either \( d(U, (V_1)^{3p}) \geq e \), or \( d(U, (W_1)^{3p}) \leq e \) for some \( e \). Here we will set \( e < (n - \ell)/3 \). Then for the first case, that is, if \( d(U, (W_1)^{3p}) > e \) then either the hamming distance of the commitment matrix will be more than \( e \), which leads to fail in the proximity check with very high probability. Otherwise, if the hamming distance of the commitment matrix are not \( > e \), then this leads to opening of a commitment to multiple values, which breaks the binding property of the commitment scheme. For the latter case, if \( d(U, (W_1)^{3p}) \leq e \), then there exists unique codeword \( U^* \) such that \( \Delta_1(U, U^*) \leq e \) and let \( w = \text{Dec}(U) = \text{Dec}(U^*) \).

Since the prover is cheating, we assume that \( w \) is not the correct witness, i.e., either it fails to satisfy the linear constraint or the quadratic constraint or both. In such a case, either of the inner product check fails.

**Lemma B.4 (Soundness).** For all polynomially bounded provers \( P^* \) and all \( \pi \in \mathbb{G}^{4p \times n} \), there exists an expected polynomial time extractor \( E \) with rewinding access to the transcript oracle \( tr = \langle P^*, V^* \rangle \) such that either \( E \) breaks the commitment binding, or it outputs a witness with overwhelming probability whenever \( P^* \) succeeds, i.e.,

\[
\Pr\left[ \begin{array}{c}
|U_x||U_y||U_z||U| = \text{Open}(\sigma) \\
\land w_x = w_x \circ w_y \\
w_x = Aw \\
w_y = Bw \land w_z = Cw
\end{array} \right] \geq \epsilon(P^*) - \kappa_{3d}(\lambda) - \kappa_{3e}(\lambda)
\]

\[
\sigma \leftarrow \text{Gen}(\lambda)
\]

\[
[U_x||U_y||U_z||U] \leftarrow E^*(\sigma)
\]

\[
w_a = \text{Dec}(U_a), \quad a \in \{x, y, z\}
\]

\[
w = \text{Dec}(U)
\]
Distributed-prover Zero-Knowledge Protocols

B.3 Zero-knowledge

Lemma B.5 (Zero-knowledge). There exists a simulator \( S \) that outputs a perfectly indistinguishable extended view of the verifier in honest execution of the protocol GrapheneR1CS for \( t \leq b \).

Now we will discuss the zero knowledge property of GrapheneR1CS, which has the similar idea of linear check and quadratic check. The verifier’s extended view for the Graphene protocol consists of:

- **Verifier Randomness:** \( \mathcal{V} \)’s messages consist of: \( \{\gamma_x,\gamma_y,\gamma_z,\gamma_{lc},r_{qd},p,Q = \{(j_u,k_u)\}_{u \in [t]},\delta_{lc},\delta_{qd},\beta_{lc},\beta_y,\beta_z,\beta_{qd},r_{qd},\gamma_{qd}\} \).

- **Commitments:** \( \mathcal{P} \) sends the following commitments to \( \mathcal{V} \):
  \[
  \{c_u\}_{u \in [t]}, \{c_u\}_{u \in [\ell-1]} , \{d_u\}_{u \in [0,\ldots,2t-1]} , \{\delta_{lc}\}_{l \in [0,1,\ldots,s]}, \{\gamma_{lc}\}_{l \in [0,1,\ldots,s]}, \{\gamma_{qd}\}_{l \in [0,1,\ldots,s]}, \{\tau_{lc}\}_{l \in [0,1,\ldots,s]}, \{\tau_{lc}\}_{l \in [0,1,\ldots,s]}, \{\kappa_{lc}\}_{l \in [0,1,\ldots,s]} \text{ for all } u \in [t] \}
  \]

- **Vectors:** \( \mathcal{P} \) sends the following vectors to \( \mathcal{V} \): \( z_{lc} = (\beta_{lc}U_{lc} + \mathcal{P}_{lc}[\kappa_{lc}]), z_{qd} = (\beta_{qd}U_{qd} + \mathcal{P}_{qd}[\gamma_{qd}]) U[\cdot,[k_u],U_x[\cdot,[k_u],U_y[\cdot,[k_u],U_z[\cdot,[k_u] \text{ for all } u \in [t]]

**Proof.** Simulator \( S \) picks:

- \( \{\gamma_x,\gamma_y,\gamma_z,\gamma_{lc},r_{lc},r_{qd},p,Q = \{(j_u,k_u)\}_{u \in [t]},\delta_{lc},\delta_{qd},\beta_{lc},\beta_y,\beta_z,\beta_{qd},r_{qd},\gamma_{qd}\} \text{ uniformly at random from their respective domains. Then it picks } U[\cdot,[k_u],U_x[\cdot,[k_u],U_y[\cdot,[k_u],U_z[\cdot,[k_u] \text{ for all } u \in [t]]\}

For \( S \)’s commitments, \( z_{lc} \) and \( z_{qd} \text{ from } \mathbb{F}_m^{2m-1} \text{ such that } \sum_{t \in [m]} z_{lc}[t] = r_{lc}^{T}\text{ and } (\gamma_{qd})_{t \in [m]} \text{ uniformly at random from their respective domains. Then it picks } U_{lc} \text{ and } U_{qd} \text{ from } \mathbb{F}_m^{2m-1} \text{ such that } (1^m)^{0^m-1},U_{lc} = 0 \text{ and } U_{qd}[j] = 0 \forall j \in [m]. \text{ } S \) picks \( w_{lc}, w_{qd}, w_{0lc}, w_{0qd} \) and computes the following commitments:

\[
\begin{align*}
  c_0 & \leftarrow \text{Com}(U_{lc},w_{0lc}), \quad d_0 \leftarrow \text{Com}(U_{qd},w_{0qd}) \\
  c_{\text{mlc}} & \leftarrow \text{Com}(z_{lc},w_{lc}), \quad c_{\text{mqd}} \leftarrow \text{Com}(z_{qd},w_{qd})
\end{align*}
\]
\[ S \text{ picks } O, O_x, O_y, O_z \text{ uniformly at random. } S \text{ computes for all } u \in [t]: \]
\[
\begin{align*}
\hat{U}[i, k_u] = \sum_{i \in [p]} \rho_i U[i, \cdot, k_u] + \rho_{p+i} U_x[i, \cdot, k_u] + \\
\rho_{2p+i} U_y[i, \cdot, k_u] + \rho_{3p+i} U_z[i, \cdot, k_u] \\
\hat{O}[k_u] = \sum_{i \in [p]} \rho_i O[i, k_u] + \rho_{p+i} O_x[i, k_u] + \\
\rho_{2p+i} O_y[i, k_u] + \rho_{3p+i} O_z[i, k_u] \\
\end{align*}
\]
\[ S \text{ picks } w_{u_{11}}, w_{u_{22}} \text{ uniformly at random for all } u \in [t] \text{ and computes } c_{k_u} \leftarrow \text{Com}(\bar{U}[i, k_u], w_{u_{11}}) \text{ and } d_{k_u} \leftarrow \text{Com}(\bar{U}_d[q][i, k_u], w_{u_{22}}). \]
\[ S \text{ picks } \tilde{c}_{k_u} \text{ such that } \tilde{c}_{k_u} = \prod_{a \in [p]} (\bar{c}_a)^{\lambda_{a, u_{11}}[a, k_u]} \forall u \in [t], \text{ it can be done efficiently since the number of unknowns is more than the number of constraints, and the coefficient matrix has full row rank.} \]
\[ S \text{ picks } \pi[i, k_u] \text{ such that } \tilde{c}_{k_u} = \prod_{a \in [p]} (\bar{c}_a)^{\lambda_{a, u_{11}}[a, k_u]} \forall u \in [t] \]
\[ S \text{ picks } c_{11}, c_{22}, \ldots, c_{s+\ell -1} \text{ subject to the following constraints:} \]
\[ c_{k_u} = \prod_{a \in [s+\ell -1]} (c_a)^{\lambda_{a, u_{11}}[a, k_u]} \forall u \in [t] \]
\[ \text{cm}_c = c_{\bar{c}_0}^{\beta_c}, \prod_{a \in [s+\ell -1]} (c_a)^{\gamma_{u_{11}}a}, \]
\[ d_{k_u} = \prod_{a \in [2t-1]} (d_a)^{\lambda_{a, u_{22}}[a, k_u]} \forall u \in [t] \]
\[ \text{cm}_d = d_{\bar{c}_0}^{\beta_d}, \prod_{a \in [2t-1]} (c_a)^{\gamma_{u_{22}}a} \]
\[ S \text{ can efficiently pick such } c_{11}, \ldots, c_{s+\ell -1} \text{ and } d_{11}, \ldots, d_{2t-1}. \]

The output of \( S \) is perfectly indistinguishable from the extended view of an honest execution of the protocol.

\[ \langle w \rangle^\xi \text{ denote the prover } P_\xi \text{'s share of the witness } w. \text{ We assume that the sharing is additive, i.e, } \sum_{\xi \in [D]} \langle w \rangle^\xi = w. \]

Recall from Section 4, that there is an algorithm \( A \) which aggregates the messages received from provers \( P_1, \ldots, P_D \) and constructs the message to be sent to \( V \).

We assume one of the provers executes \( A \). We specify the algorithm \( A \) implicitly by describing the construction of message to \( V \) from the provers’ messages for each round.

We first discuss a protocol secure against semi-honest provers and then briefly discuss how to ensure the privacy of the honest provers when the corrupt provers are malicious (barring the one who runs \( A \)).

\section*{C. D-Graphene and Security Proofs}

\subsection*{C.1 D-Graphene: Distributed Prover Variant}

We now describe the distributed protocol to produce a Graphene proof for a statement, when the witness is shared between D provers \( P_1, \ldots, P_D \). For \( \xi \in [D] \), let

\[ \langle w \rangle^\xi \text{ denote the prover } P_\xi \text{'s share of the witness } w. \text{ We assume that the sharing is additive, i.e, } \sum_{\xi \in [D]} \langle w \rangle^\xi = w. \]

In the distributed setting, each prover \( P_\xi \) encodes her share \( \langle w \rangle^\xi \) as \( \langle \langle \langle \langle w \rangle^\xi \rangle^\xi \rangle^\xi \rangle^\xi \) and computes the commitment \( \langle \langle \langle \langle \langle w \rangle^\xi \rangle^\xi \rangle^\xi \rangle^\xi \rangle^\xi \) of \( \langle \langle \langle \langle \langle w \rangle^\xi \rangle^\xi \rangle^\xi \rangle^\xi \rangle^\xi \). The provers then share \( \langle \langle \langle \langle \langle w \rangle^\xi \rangle^\xi \rangle^\xi \rangle^\xi \rangle^\xi \) with the aggregator \( A \) which sets the oracle \( \pi \) as \( \pi := \text{Combine}(\langle \langle \langle \langle \langle \langle w \rangle^\xi \rangle^\xi \rangle^\xi \rangle^\xi \rangle^\xi \rangle^\xi) \)

The homomorphism and the fact that the witnesses are additively shared ensure that \( \pi \) contains commitment to the witness.

\subsection*{C.2 Distributed Oracle Setup}

The messages sent by the prover to the verifier in the linear check protocol include:

- Commitments \( \bar{c} = (\bar{c}_1, \ldots, \bar{c}_\ell) \) to the matrix \( \hat{U} = \sum_{i \in [p]} \rho_i U[i, \cdot, \cdot] \) for verifier’s challenge \( \rho \leftrightarrow \mathbb{F}_p \).
- Commitments \( c_0, \ldots, c_{s+\ell-1} \) where \( c_0 \) is a commitment to random vector \( P_0 \in \mathbb{F}^{2n-1} \) satisfying \( \langle 1^m || 0^{m-1} || P_0 \rangle = 0 \) and \( c_1, \ldots, c_{s+\ell-1} \) are commitments to the matrix \( P \) of order \( h \times n \).
- The vectors \( X_u = U[i, j_u, k_u] \) for \( u \in [t] \), for verifier’s query \( Q = \{(j_u, k_u) : u \in [t]\} \).

Given the verifier’s challenges, we see that each of the messages is a linear function of the encoding (which itself is a linear function of the witness). Hence, the provers compute the respective messages on their shares, which can be trivially combined by \( A \). In addition to above messages, we also want \( A \) to receive witnesses to the inner-products protocols namely, the vectors \( \bar{P}_-[i, k_u], W_u = \sum_{i \in [p]} \delta_i U[i, k_u] \) for \( u \in [t] \), \( z = \beta P_0 + \bar{P}_p \) and the randomness used to commit the vectors. Each of these can again be obtained by combining the respective shares. Note that the share \( \langle z \rangle^\xi \) leaks \( r^T A \langle w \rangle^\xi = \langle 1^m || 0^{m-1} || \langle z \rangle^\xi \rangle \), which is non-trivial knowl-
edge about an individual witness share. Thus provers use a random share $(0^{2m-1})^ξ$ to randomize their share of $z$, and send $(z)^ξ = β(R_0)^ξ + (P)^ξψ + (0^{2m-1})^ξ$. We provide the complete distributed linear protocol in Figure 8.

**C.4 Distributed Quadratic Check**

Here the distributed variant requires an additional interaction among the provers. Recall that in response to $V$‘s challenge $r \in \mathbb{F}^p$, the provers need to compute $P$ as:

$$P[j,k] = \sum_{i \in [p]} r_i(Q_x^i(\alpha_j, \eta_k)Q_y^i(\alpha_j, \eta_k) - Q_z^i(\alpha_j, \eta_k))$$

$$= \sum_{i \in [p]} r_i(U_x[i,j,k].U_y[i,j,k] - U_z[i,j,k])$$

where $U_x$, $U_y$ and $U_z$ are the encodings of the witness vectors $w_x$, $w_y$ and $w_z$ respectively. Since the matrix $P$ above is completely determined by it’s first $2m - 1$ rows and first $2\ell - 1$ columns, the provers need to obtain the shares $(U_x[i,j,k].U_y[i,j,k])^ξ$ for $i \in [p], j \in [2m - 1], k \in [2\ell - 1]$. From the shares of witness $(w_x)^ξ, (w_y)^ξ$ and $(w_z)^ξ$ the provers can locally compute shares $(U_x)^ξ, (U_y)^ξ$ and $(U_z)^ξ$ of $U_x, U_y$ and $U_z$. The provers call $F_{\text{Mult}}$ on inputs $(U_x)^ξ, (U_y)^ξ$ and $U_z$ and obtain $(U_x[i,j,k],U_y[i,j,k])^ξ$, where $F_{\text{Mult}}$ is the functionality that takes linear sharings two vectors as input and outputs a linear sharing of the component-wise multiplication of these vectors. We can instantiate $F_{\text{Mult}}$ with any state-of-the-art dishonest majority protocol for arithmetic circuits. This requires evaluation of $p.(2m - 1).(2\ell - 1) \approx 4N$ multiplication gates, and depth 1, to obtain the shares $(U_x[i,j,k].U_y[i,j,k])^ξ$ for $i \in [p], j \in [2m - 1], k \in [2\ell - 1]$. Thereafter, each prover obtains a share of matrix $P$, and the remaining protocol proceeds similar to the the distributed linear check protocol. The complete protocol for distributed quadratic check appears in Figure 9, additionally, we discuss how to optimize the MPC overhead when the size of the shared circuit (see Appendix E) is small.

**C.5 Security Proofs**

As discussed in the definition of DPZK given in Section 4, depending on the corruption scenario there are 4 possible cases:

- All the provers are corrupt and do not have a valid witness. Together they try to cheat so that the verifier accepts the proof. If a DPZK protocol withstands this corruption model, then we state that it has the **Soundness with Witness Extraction (SoWE)** property.
- The verifier is corrupt and tries to learn about the provers’ secrets. A protocol secure under this corruption scenario has the **Zero-Knowledge (ZK)** property.
- Among all the provers, $t$ are corrupt and try to learn about the honest provers’ secrets. A DPZK protocol is said to have **Witness Confidentiality with Collusion (WCwC)** property if it is secure against this corruption scenario.
- A corrupt verifier colludes with $t$ corrupt provers and tries to learn honest provers’ secrets. A DPZK protocol is said to have **Witness Confidentiality with Cooperation (WCwC)** property if it is secure against this corruption scenario.

**Soundness with Witness Extraction:** A DPZK protocol has SoWE property if there exists an (expected) polynomial-time extractor $E$ that interacts with the prover on behalf of the verifier. If the verifier accepts the proof, $E$ outputs a valid witness corresponding to the statement, with a very high probability.

**Lemma C.1.** For the protocol D-Graphene given in Figure 10, there exists an (expected) polynomial-time extractor $E$. If $V$ accepts the proof given by a set of provers, then $E$ can output a witness with overwhelming probability.

**Proof.** From Lemma B.4, we know that Graphene has proof of knowledge property. Therefore by Lemma 5.2, we know that D-Graphene has the soundness with witness extraction property. This proves the above lemma.

**Zero Knowledge:** If a verifier in a DPZK protocol learns nothing more that the assertion of the statement, then it has the zero-knowledge property. In other words, there exists a simulator $S_{DP}$ that generates a transcript $τ$ without having a witness, such that $τ$ is indistinguishable from a real execution of the protocol. Note that $τ$ consists of the verifier’s challenges and the provers’ messages.

**Lemma C.2.** There exists a simulator $S_{DP}$ that outputs a perfectly indistinguishable extended view of the verifier in an honest execution of the protocol D-Graphene for $t \leq b$.

**Proof.** From the Lemma B.5, we know that Graphene has the zero-knowledge property. Coupled with
Lemma 5.2, this ensures the zero-knowledge property of D-Graphene. Thus there exists a polynomial-time simulator that generates a transcript which is indistinguishable from the real transcript.

Witness Confidentiality and Witness Confidentiality with Collusion: Our work is mainly concerned with building a public coin proof system, specifically NIZK so that anyone can verify the proof, and any prover can play a verifier’s role yet learn nothing. Therefore witness confidentiality and witness confidentiality with collusion are the same in this setting.

For the Distributed Linear Check protocol described in Figure 8 has witness confidentiality property.

The transcript generated by $S$ is perfectly indistinguishable from an honest execution of the protocol. Hence the linear check described in Figure 8 has witness confidentiality property.

The distributed quadratic check protocol described in Figure 9 has witness confidentiality property if the multiplication of the secrets held by the provers is performed.
securely. Suppose \( \Pi_{\text{Mult}} \) be a protocol that securely realizes \( \mathcal{F}_{\text{Mult}} \) functionality, which can withstand \( t \) corrupt parties. Distributed quadratic check has witness confidentiality property against \( t \) corrupt provers. The following lemma ensures the claim.

**Lemma C.4.** Let \( \Pi_{\text{Mult}} \) be a \( D \)-party \( t \)-secure protocol where the inputs of the \( t \)th party are \( (a)^{\xi}, (b)^{\xi} \) and the protocol outputs \( (\sum_{\xi \in [D]} (a)^{\xi} \cdot \sum_{\xi \in [D]} (b)^{\xi})^\xi \) to \( \mathcal{F}_t \), where \( a, b \) are vectors of length \( 2m - 1 \). Then corresponding to a subset of \( t \) provers corrupted semi-honestly by a PPT adversary \( A \), there exists a polynomial-time simulator \( S \) that takes private values of the provers controlled by \( A \) as input and outputs a view which is indistinguishable from the view of \( A \) in the Distributed Quadratic Check protocol (Figure 9).

**Proof.** Since \( \Pi_{\text{Mult}} \) is a secure protocol, there exists a simulator \( S_M \) which can generate a view that is indistinguishable from an honest execution of the protocol. \( S \) takes inputs of the corrupt parties and outputs of the protocol to simulate the view. Similar to the Lemma C.3, we consider \( C \) as the set of corrupt parties and \( H \) as the set of honest parties. We follow the same notations.

The view of \( A \) in the distributed quadratic check consists of:

1. **Verifier’s Randomness:** \( \rho, r, Q, \tau, \gamma, \delta, \beta, \beta_x, \beta_y, \beta_z \)
2. Commitments: \( (O_x^y)^H \forall a \in \{x, y, z\}, (\tilde{c}_1)^H, \ldots, (\tilde{c}_k)^H \)
3. Vectors: \( (y)^H, (\tilde{y})^H \)

\( S \) does the following:

- \( S \) picks \( \rho, r, Q, \tau, \gamma, \delta, \beta, \beta_x, \beta_y, \beta_z \) uniformly at random from their respective domains.
- \( S \) picks \( (u_1, \ldots, u_k) \in \mathbb{R}^n \) for all \( a \in \{x, y, z\} \) and computes \( (O_x^y)^H \mid u \) and \( (\tilde{y})^H \) which is commitment of \( (O_x^y)^H \mid u \) for all \( a \in \{x, y, z\} \).
- \( S \) computes \( (u_1, \ldots, u_k) \) for all \( a \in \{x, y, z\} \), for all \( a \in \{x, y, z\} \).
- \( S \) picks \( (\tilde{c}_1)^H, \ldots, (\tilde{c}_k)^H \) such that \( (\tilde{c}_k)^H = \sum_{\ell \in [t]} (\tilde{c}_k^\ell)^H A^T_{n, \ell} \), \( \forall k \in \{k : u \in [t]\} \).

The view generated by \( S \) is indistinguishable from a transcript of an honest execution.

Since D-Graphene is the combination of linear check and quadratic check, simulator for the complete protocol follows the same strategies as the simulators described in Lemma C.3 and C.4. Hence, the D-Graphene (Figure 10) has the witness confidentiality property.

**Lemma C.5.** Let \( \Pi_{\text{Mult}} \) be a secure protocol described in Lemma C.4 which is used in D-Graphene (step 5), then \( \exists \) polynomial-time simulator \( S \) such that \( S \) can generate a view of the adversary \( A \) which is indistinguishable from the view of \( A \) in a real execution of the protocol.

**Proof.** \( S \) starts with picking the verifier’s randomness and does the same as the simulators for the linear check (Lemma C.3) and the quadratic check (Lemma C.4). Therefore the transcript generated by \( S \) is indistinguishable from the adversary’s view.
D.1 DPZK of Bulletproof for R1CS

In [10], [13], authors present a proof for a Hadamard-product relation. Suppose C is a circuit of size $N$. In their formulation, $a_L$, $a_R$ and $a_C$ denote the vectors corresponding to the left wire, right wire and output wire respectively. Then, $a_L \odot a_R = a_O$ holds and satisfy the following linear constraints:

$$\langle w_{L,q}, a_L \rangle + \langle w_{R,q}, a_R \rangle + \langle w_{O,q}, a_O \rangle = c_q \forall q \in [Q]$$

with $w_{L,q}, w_{R,q}, w_{O,q} \in \mathbb{Z}_p^N$ and $c_q \in \mathbb{Z}_p$. Consider $W_A = [w_{A,1}, \ldots, w_{A,Q}]^T$, for $A \in \{L, R, O\}$ and $c = [c_1, \ldots, c_q]^T$.

In [13], these above checks are reduced to a single inner product argument. $\mathcal{P}$ commits to the inner vectors $a_L, a_R, R$ and sends the commitment values $A_l$ and $A_O$ to $\mathcal{V}$. $\mathcal{P}$ picks $s_L$ and $s_R$ uniformly at random and computes the commitment $S$ and sends to $\mathcal{V}$. $\mathcal{V}$ gives random challenges $y, z \in \mathbb{Z}_p^+$ to the prover. Then $\mathcal{P}$ computes vector polynomials $l(X)$ and $r(X)$ using $a_L, a_R, a_C, s_L, s_R, y, z$ and other public vectors, and computes a polynomial $t(X) = \langle l(X), r(X) \rangle$. The construction of $l(X)$ and $r(X)$ is such that the co-efficient of $X^2$ in $t(X)$ is independent of $a_L, a_R, a_C, s_L, s_R$, which can be computed by $\mathcal{V}$, if $a_L, a_R, a_O$ satisfy the Hadamard-product relation and linear constraints. To prove this, $\mathcal{P}$ commits to all the co-efficients of $t(X)$ other than the co-efficient of $X^2$, and verifier gives a random point $x$ to evaluate $l = l(x)$ and $r = r(x)$. Which reduces to an inner product check whose witness is $l$ and $r$, where $l$ and $r$ are vectors of length $N$.

We give a DPZK version of Bulletproofs, where $\mathcal{P}_\xi$ starts the protocol with $(a_L)_{\xi}, (a_R)_{\xi}, (a_O)_{\xi} \in [D]$ such that $\sum_{\xi \in [D]} (a_A)_{\xi} = a_A \forall A \in \{L, R, O\}$. $A$ is an aggregator. $\mathcal{P}_\xi$ computes the commitment $\langle a_L \rangle_{\xi}, \langle a_R \rangle_{\xi}, \langle a_O \rangle_{\xi}$ and sends these values to $\mathcal{A}$. $\mathcal{A}$ combines and sends $a_L, a_R, a_O$ to $\mathcal{V}$. The verifier broadcasts the random challenge $y, z \in \mathbb{Z}_p^+$. Then each prover computes $\langle l \rangle_{\xi}(X)$ and $\langle r \rangle_{\xi}(X)$. All the provers interact securely to compute shares of $t(x) = \langle l(x), r(x) \rangle$, where $l(X) = \sum_{\xi \in [D]} \langle l \rangle_{\xi}(X)$ and $r(X) = \sum_{\xi \in [D]} \langle r \rangle_{\xi}(X)$, i.e., output for $\mathcal{P}_\xi$ is $\langle t \rangle_{\xi}(X)$ such that $\sum_{\xi \in [D]} \langle t \rangle_{\xi}(X) = t(X)$. $\mathcal{P}_\xi$ commits to all the co-efficients of $\langle t \rangle_{\xi}(X)$ other than the co-efficient of $X^2$. $\mathcal{S}$ sends these committed values to $\mathcal{A}$. $\mathcal{A}$ combines and sends them to $\mathcal{V}$. $\mathcal{V}$ sends a random $x$. $\mathcal{P}_\xi$ evaluates $\langle l \rangle_{\xi}(x) = \langle l \rangle_{\xi}$ and $\langle r \rangle_{\xi}(x) = \langle r \rangle_{\xi}$ and sends these values to $\mathcal{A}$. $\mathcal{A}$ computes $l = \sum_{\xi \in [D]} \langle l \rangle_{\xi}$ and $r = \sum_{\xi \in [D]} \langle r \rangle_{\xi}$. Finally, $A$ and $V$ run the inner product protocol, same as the single prover protocol, where the witness is $l$ and $r$. Since, $l$ and $r$ are vectors of length $N$, MPC is required for $N$ multiplications or in other words, a MPC for a depth 1 circuit of size $N$.

D.2 DPZK of Spartan for R1CS

We will describe the distributed version of the interactive proof given in Spartan [42]. We do not have a proof of privacy of the distributed version of the protocol.

Let $C$ be an R1CS circuit of size $N$. For every R1CS circuit $\exists$ matricies $A$, $B$, $C$ and public input $io$ which defines the circuit. If the instance is true, then $\exists$ a witness $w \in \mathbb{F}^N$ such that $Az \odot Bz = Cz$ where $z = (io, 1, w)$ is the extended witness of $C$.

Now, the prover wants to convince the verifier that the prover knows $z$ such that $Az \odot Bz = Cz$ holds. To that the verifier defines a polynomial

$$\tilde{F}_{io}(x) = \left( \sum_{y \in \{0,1^*\}} \tilde{A}(x,y) \tilde{Z}(y) \right) \left( \sum_{y \in \{0,1^*\}} \tilde{B}(x,y) \tilde{Z}(y) \right) - \left( \sum_{y \in \{0,1^*\}} \tilde{C}(x,y) \tilde{Z}(y) \right)$$

Where $\tilde{A}(x,y) = A(x,y) \forall x, y$. $A(\cdot, \cdot)$ is defined as a function such that $A(x,y)$ is the $(x,y)$th entry of the matrix $A$. Similarly, $B(\cdot, \cdot)$ and $C(\cdot, \cdot)$. And $\tilde{A}$, $\tilde{B}$, $\tilde{C}$ are the low-degree polynomial extensions of $A$, $B$, $C$ respectively, defined in Spartan [42]. And $\tilde{Z}(y) = Z(y) \forall x$. $Z(\cdot)$ is defined as a function such that $Z(y)$ is the $y$th entry of the vector $z$, and $\tilde{Z}(\cdot)$ is the low-degree polynomial extensions of $Z$, defined in Spartan [42]. If $Az \odot Bz = Cz$ holds then $\tilde{F}_{io}(x) = 0 \forall x \in \{0,1\}^*$. That means the verifier needs to check for all $x \in \{0,1\}^*$, $\tilde{F}_{io}(x) = 0$. To get rid of such check a new polynomial $Q_{io}(t) = \sum_{x \in \{0,1\}^*} F_{io}(x) \cdot eq(t, x)$ where $eq(t, x) = \prod_{i \in [n]} [t_i \cdot x_i + (1 - t_i)(1 - x_i)]$. Note that if $\tilde{F}_{io}(x) = 0 \forall x \in \{0,1\}^*$ then $Q_{io}$ is a zero polynomial i.e. $Q_{io}(\tau) = 0$ for any random $\tau$.

Define $G_{io, \tau}(x) = \tilde{F}_{io}(x) \cdot eq(\tau, x)$. Then $\sum_{x \in \{0,1\}^*} G_{io, \tau}(x) = Q_{io}(\tau)$. Therefore, it is enough to check that $\sum_{x \in \{0,1\}^*} G_{io, \tau}(x) = 0$. This check is done using the sum-check protocol described in Spartan [42].

In the DPZK version of Spartan [42] each prover holds a share of the witness $w$, say $\mathcal{P}_\xi$ has $\langle w \rangle_{\xi}$. In other words, $Z$ is distributedly shared among the provers. In the above protocol described in Spartan [42] only $G_{io, \tau}$ generation is required interaction among the provers. Remaining all the messages can be generated by each
prover locally, and an aggregator can combine the messages to obtain the corresponding message. Note that, \( G_{\alpha,\tau}(x) \) computation requires \( O(N^2) \) multiplications which are shared across the provers.

E Shared Circuit Complexity

E.1 Reducing MPC Overhead for Small Shared Circuits

Let \( C \) be a circuit with \( N \) wires (we assume a unique incoming wire for each input gate), let \( w = (w_1, \ldots, w_N) \) denote the vector of wire values in a satisfying assignment according to some ordering on the wires. We consider the case, when each input wire is “assigned” to a unique prover. Let \( M \) be the number of multipication gates in \( C \), and let \( A, B, C \) be \( M \times N \) matrices such that \( w_x = Aw \), \( w_y = Bw \) and \( w_z = Cw \) are vectors of left, right and out values of multiplication gates. For \( i \in [m] \), we say that multiplication gate \( i \) is isolated if \( w_x[i], w_y[i] \) and \( w_z[i] \) depend on inputs of only one prover. We call the remaining multiplication gates as shared. Let \( N_s \) be the number of shared gates. Without loss of generality, we can assume that the gates \( 1, \ldots, N_s \) are shared (rows of \( A, B, C \) can be permuted suitably). Now an additive sharing of the extended witness may be obtained by (i) each prover locally computing the wires for isolated gates from their inputs, while setting the shares of other parties for these wires to be 0 and (ii) running a secret sharing MPC on the subcircuit containing shared gates. Let \( p_s = [N_s/ms] \). Then the multiplication MPC Mult in distributed quadratic check can be restricted to obtaining shares \( \{U_x[i, j, k],U_y[i, j, k]\}^5 \) for \( i \in [p_s] \), as each prover can canonically the shares of other slices of \( U_x \) and \( U_y \). For slices, which depend on the provers inputs, the prover computes randomized encoding of the slice, for other slices (where its share is 0) it computes a deterministic encoding by setting the buffer columns to 0. Note that, a similar approach can be used to restrict the MPC only to the shared columns if the shared circuit is sufficiently small. This gives an MPC of depth 1 on circuit of size \( O(\max(N_s, m)) \). Towards improving the efficiency in the distributed setting, usage of secure multiplication can be reduced. Suppose for a gate \( g \) among all the provers, \( P_1, \ldots, P_G \), only \( P_1 \) and \( P_2 \) have input to \( g \). Thus the shares of the remaining provers corresponding to the gate \( g \) is 0. Hence running an MPC between \( P_1 \) and \( P_2 \) maybe sufficient. Then resharing the outcome among all the provers is required. However, this approach requires end-to-end formal analysis. Moreover, this is circuit specific and maybe hard to implement.

F Parameters

F.1 Performance Parameters for Ligero and Bulletproofs

Ligero: Let \( m, s \) be such that \( N = ms \). Let \( t \) be a parameter, and let \( \ell = s + t, n = O(\ell) \) and \( e \leq (n - \ell)/4 \). Then the performance parameters for Ligero are then given by:

\[
\begin{align*}
\kappa_m &= N + 6t + 4s + 4mt + 5t - 5, \\
\tau_p &= O(N)C_F + 4m(C_{\text{FFT}}(s) + C_{\text{FFT}}(n)), \\
\tau_g &= O(N) + 4mC_{\text{FFT}}(s), \\
\kappa_{pr} &= (1 - e/n)^4 + 5((2t + e)/n)^4.
\end{align*}
\]

Bulletproofs: \( \kappa_r = 2\log(N) + 13 \), \( \tau_p = 9C_{\text{EXP}} + 2C_{\text{MXP}}(2N) + 3C_{\text{MXP}}(N), \tau_x = NC_{\text{EXP}} + C_{\text{MXP}}(2N), \kappa_{bp} = N/|\mathbb{F}| \).

For computing prover communication in distributed setting we use the expressions:

\[
\begin{align*}
\kappa_{pr} &= MPC(D,\max(N_s, 4m\ell), 1) + D \times [(4m + 5\ell + s + 2)B_G + (4t + 4m + h)B_2], \\
\kappa_{bp} &= MPC(D, N_s, 1) + D \times [8B_G + N|\mathbb{F}|] \text{ for Bulletproofs. Here } \text{MPC}(D, N_s, 1) \text{ denotes communication in an } D \text{ party } \\
& \text{MPC with circuit size } N_s \text{ and depth as 1.}
\end{align*}
\]

G Performance Evaluation

In Section B.2.3, we present protocol for an R1CS instance. Here we summarize several performance parameters attained by our protocol for R1CS. Let \( N = pms \), \( \ell = s + t \) and \( h \) be as in the previous sections. Let \( C_F \) denote the time taken for a field operation, \( C_{\text{FFT}}(x) \) denote the time to compute FFT of a \( x \) length vector, \( C_{\text{MXP}}(x) \) denote the time taken for a multi-exponentiation of length \( x \), and \( C_{\text{EXP}} \) denote the time required for an exponentiation. Let \( B_2 \) and \( B_G \) denote the number of bits required to represent an element of \( \mathbb{F} \) and \( G \) respectively. Our protocol Graphene achieves following efficiency parameters:

- **Number of rounds**: \( r_{zk} = O(\log N) \).
- **Argument size**: \( c_{zk} = 4p\ell B_G + (4p\ell + 8t \log m + 4\ell + s + 8t + 4)B_G \).
- **Prover complexity**: \( \tau_p = 4p((m + n)C_{\text{FFT}}(m) + mC_{\text{FFT}}(l) + sC_{\text{FFT}}(h) + 4pC_{\text{MXP}}(m) + (n - \ell)C_{\text{MXP}}(\min(\ell, m))) + (s + 3\ell)C_{\text{MXP}}(2m) + (48tm + 32m)C_{\text{EXP}} \).
Distributed-prover Zero-Knowledge Protocols

DistLinearCheck(pp, A ∈ M_{M,N}, b ∈ F^M, [π]; ϕ(U)ξ, (2^{m-1}m)^ξ):

Relation: U = Open(π) ∧ Aw = b for (w)^ξ = Dec(ϕ(U)) for all ξ ∈ [D] and \( \sum_{ξ \in [D]} (w)^ξ = w \).

1. V \rightarrow \mathcal{P}_ξ; \rho \leftarrow F^M.
2. \mathcal{P}_ξ computes: (U)^ξ = \sum_{i \in [p]} ρ_i (U)^ξ[i, \ldots, –1], commitments (ξ_1)^ξ, \ldots, (ξ_t)^ξ as (ξ_i)^ξ = \prod_{i \in [p]} ((O[i, k])^ξ)^ρ_i \forall k \in [t].
3. \mathcal{P}_ξ \rightarrow A; (ξ)^ξ = (ξ_1)^ξ, \ldots, (ξ_t)^ξ.
4. A \rightarrow V; \tilde{c} = \text{Combine}(\tilde{c})^ξ.
5. V \rightarrow \mathcal{P}_ξ; r \leftarrow F^M.
6. \mathcal{P}_ξ and V compute Polynomials R_i, i \in [p] interpolating R = r^T \text{,} A as in Section B.2.1.
7. \mathcal{P}_ξ computes: Matrix (P)^ξ from R and (U)^ξ as described in Section B.2.1. Samples (P_0)^ξ \leftarrow F^{2m-1}, (w_0)^ξ \leftarrow F and (c_0)^ξ \leftarrow \text{Com}(P_0)^ξ, (w_0)^ξ, and (d_0)^ξ \leftarrow \text{Com}(2^{m-1})^ξ, (o)^ξ) where (o)^ξ \leftarrow F. Computes commitments (c_1)^ξ, \ldots, (c_{a+\ell-1})^ξ from (P)^ξ.
8. \mathcal{P}_ξ \rightarrow A; (c_0)^ξ, (c_1)^ξ, \ldots, (c_{a+\ell-1})^ξ, (d_0)^ξ.
9. A \rightarrow V; \xi = \text{Combine}(\xi)^ξ \forall k \in [s + \ell - 1] and sends c_0, c_1, \ldots, c_{a+\ell-1}.
10. V \rightarrow \mathcal{P}_ξ; Q = \{(j_n, k_n) : u \in [t]\} for Q \leftarrow [h] \times [n] for u \in [t].
11. V \rightarrow \pi; \{k_u : u \in [t]\}.
12. \mathcal{P}_ξ \rightarrow A; (X_u)^ξ = (U)^ξ[j, u, k], (P_u)^ξ = (P)^ξ[j, k, u] for u \in [t].
13. A \rightarrow V; X_u = \sum_{ξ \in [D]} (X_u)^ξ, P_u = \sum_{ξ \in [D]} (P_u)^ξ and sends X_u for u \in [t].
14. \pi \rightarrow V; \pi_k for u \in [t].
15. V \rightarrow \mathcal{P}_ξ; δ \leftarrow F^M, \beta \leftarrow F^\{\{0\}\}.
16. \mathcal{P}_ξ \rightarrow A; (ξ)^ξ = \beta P_0)^ξ + (P)^ξφ + (2^{m-1})^ξ, (V_u)^ξ = \sum_{i \in [p]} δ_i (U)^ξ[i, u, k, u] and sends (ξ)^ξ, (V_u)^ξ.
17. A computes: z = \sum_{ξ \in [D]} (ξ)^ξ, V_u = \sum_{ξ \in [D]} (V_u)^ξ.
18. A and V run inner product arguments to check:
   (a) \text{InnerProduct}(pp, u^T_n Λ_h, 2^{m-1}, cm_u, u; \mathcal{P}[i, k, u]) for u \in [t] where cm_u = \prod_{i=1}^{s+\ell-1} (c_0)^{h, u, k, u} = \sum_{u=1}^{r^T} (a_{u}^l) \sum_{u=1}^{r} X_u[i] (check consistency of P with \pi).
   (b) \text{InnerProduct}(pp, u^T_1 \text{,} c_{m}, r^T b, z) where = \beta P_0 + \mathcal{P} and \text{cm} = (c_0)^x \beta \cdot \prod_{i=1}^{s+\ell-1} (c_0)^{x_u} (check the condition r^T \text{,} AU = r^T b).
   (c) \text{InnerProduct}(pp, u^T_n Λ_h, m, C_u, u; \mathcal{P}[i, k, u]) for u \in [t] where C_u = \prod_{i=1}^{r} (\pi[i, k, u]) and w_u = \sum_{v \in [p]} δ_v X_u[i] (check the consis-
19. V checks: \prod_{\xi \in [D]} (ξ)^ξ A_{\xi[n, k, u]} = \prod_{\xi \in [D]} (ξ)^ξ w_u for u \in [t] (check proximity of U to W_1).

Fig. 8. Distributed Linear Check Protocol

- Verifier complexity: t_V = O(N)C_F + 4pmC_{FFT}(s) + (2t + 2)C_{MXP}(2m) + tC_{MXP}(4p + \ell)
- Soundness error κ_{gr} = (1 - e/n)^s + 2(2m/h + 1 - 2m/h)(2t + e/n)^t.

In Appendix F.1, we give similar expressions for Ligero and Bulletproofs protocols.

For c ≥ 2, setting p = s = O(N^{1/c}), m = O(N^{1-2/c}), t = O(\lambda), n = O(\ell) and h = O(m), we get κ_{gr} =\ negl(\lambda) with argument size O(N^{1/c}), verifier’s complexity as O(N) field operations and O(N^{1-2/c}) exponentiations.

In Figure 2, we compare Graphene with Ligero [1] and Bulletproofs [13] in single prover setting based on the expressions in Appendix F.1. The concrete estimates were obtained by timing the FFT operations, exponentiations and multiexponentiations for different sizes, in a single threaded setting using libff library. Parameters for Graphene were optimized to yield best proving time, while those for Ligero were optimized to yield best proof size. From the table in Figure 2, we see that our protocol offers much more practical argument sizes compared to Ligero, while still retaining low verifier complexity.

Performance Evaluation of D-Graphene.
D-Graphene achieves the following efficiency, where the notations are the same as above and MPC(x, y, z, w) denotes the cost of running a secure evaluation among z parties with w corruption for x many multiplication gates with depth y.

- Number of rounds: r_{zk} = O(\log N).
- Argument size: c_{zk} = 4ptBG + (4pt + 8t \log m + 4t + s + 8t + 4)BG.
- Provers’ complexity: t_P = D(4p((m + n)C_{FFT}(m) + mC_{FFT}(h) + nC_{FFT}(h) + 4ptC_{MXP}(m) + (n -
DistQuadraticCheck(\(pp, [\pi_x], [\pi_y], [\pi_z]; (U_x)^{\xi}, (U_y)^{\xi}, (U_z)^{\xi} (2^m)^{\xi}\)).

Relation: \(|U_x||U_y||U_z| = \text{Open}(\pi) \land \text{w} \cdot \text{w} = \text{w} \text{ for } (\text{w})^{\xi} = \text{Dec}(U_z)^{\xi}\) for all \(\xi \in [D]\) and \(\sum_{\xi \in [D]} (w_a)^{\xi} = w_a \forall a \in \{x, y, z\}\).

1. \(V \rightarrow P_\ell: r \leftrightarrow F_P^r\).
2. \(P_\ell\) computes: \((U)^{\xi} \sum_{i=0}^{m} (\beta + \rho_{p+i}(U)^{\xi}[i, i] + \rho_{p+i}(U_x)^{\xi}[i, i] + \rho_{p+i}(U_y)^{\xi}[i, i])\), commitments \((\tilde{c}_1)^{\xi}, \ldots, (\tilde{c}_6)^{\xi}\) as \((\tilde{c}_1)^{\xi} = \sum_{i=0}^{m} ((O_1)^{\xi}[i, k])^p_{p+i}, ((O_2)^{\xi}[i, k])^p_{p+i} \forall k \in [\ell]\).
3. \(P_\ell\) \(\rightarrow A\): \((\tilde{c})^{\xi} = (\tilde{c}_1)^{\xi}, \ldots, (\tilde{c}_6)^{\xi}\).
4. \(A \rightarrow V\): \(\tilde{c} = \text{Combine}(\tilde{c})^{\xi}\).
5. \(V \rightarrow P_r: r \leftrightarrow F_P^r\).
6. Provers invoke \(F_{\text{Main}}(U_x, U_y)^{\xi} \leftarrow \text{Mult}(U_x)^{\xi}, (U_y)^{\xi}\) to obtain shares of the hadamard product of the encodings.
7. \(P_{\ell}\) computes: Matrix \((P)^{\xi}\) from \(r\) and \((U_x, U_y)^{\xi}, (U_z)^{\xi}\) as described in Section \(B.2.2\). Samples \((P_\theta)^{\xi} \leftrightarrow F_{2^2m-1}\) such that \(P_\theta[j] = 0 \forall i \in [m], \langle \omega_0 \rangle \leftrightarrow F\) and \((c)^{\xi} \leftrightarrow \text{Com}(P_\theta)^{\xi}, \langle \omega_0 \rangle^{\xi}\), and \((d_0)^{\xi} \leftrightarrow \text{Com}(0^{2m-1})^{\xi}, (\phi_\xi)^{\xi}\) where \((d)^{\xi} \leftrightarrow F\).

Computes commitments \((c_1)^{\xi}, \ldots, (c_{2p-1})^{\xi}\) from \((P)^{\xi}\).
8. \(P_\ell\) \(\rightarrow A\): \((c_0)^{\xi}, (c_1)^{\xi}, \ldots, (c_{2p-1})^{\xi}, (d_0)^{\xi}\).
9. \(A \rightarrow V\): \(c_k = \text{Combine}(c_k)^{\xi} \forall k \in [2p - 1]\) and sends \(c_0, c_1, \ldots, c_{2p-1}\).
10. \(V \rightarrow P_\ell: Q = \{\langle j, k, u \rangle: u \in [t]\} \times [n]\) for \(Q \leftrightarrow [h] \times [n]\) for \(u \in [t]\). And \(r \leftrightarrow F^r, \gamma \leftrightarrow F^r, \beta \leftrightarrow F^r\).
11. \(V \rightarrow \pi: \{t_1^r, k^r, u \in [t]\}
12. \(P_\ell\) computes: \((Q_0)^{\xi} = \sum_{j=0}^{m} \beta_0(U_x)^{\xi}[j, j], U_0^{\xi} = (U_y)^{\xi}[j, j], U_0^{\xi} = (U_z)^{\xi}[j, j], (P_\pi)^{\xi} = (P)^{\xi}[j, k], u \in [t]\)
13. \(A \rightarrow V: A = \sum_{\xi \in [D]} A^{\xi}\) where \(A \in \{X, Y, Z, P\}\) and sends \(X_u, Y_u, Z_u\) for \(u \in [t]\).
14. \(\pi \rightarrow V: \tilde{z}^r, k^r, u \in [t]\).
15. \(V \rightarrow P_\ell: \delta \leftrightarrow F_\ell, \beta_0 \leftrightarrow F_\ell, \beta_0 \leftrightarrow F_\ell, \beta_0 \leftrightarrow F_\ell(0)
16. \(P_\ell\) computes: \((V_0)^{\xi} = \sum_{j=0}^{m} \beta_0(U_x)^{\xi}[j, j], U_0^{\xi} = (U_y)^{\xi}[j, j], U_0^{\xi} = (U_z)^{\xi}[j, j]\) and \((z)^{\xi} = \beta \cdot P_\theta + (P)^{\xi} + (d)^{\xi}\).
17. \(P_\ell\) \(\rightarrow A\): sends \((z)^{\xi}, (V_u)^{\xi}\).
18. \(A\) computes: \(z = \sum_{\xi \in [D]} (z)^{\xi}\) and \(V_u = \sum_{\xi \in [D]} (V_u)^{\xi}\).
19. \(A\) and \(V\): Both compute \(W_u = \beta_0 X_u + \beta_0 Y_u + \beta_0 Z_u\) for \(u \in [t]\). \(T_u = (C_u)^{\beta_0} \cdot (D_u)^{\beta_0} \cdot (E_u)^{\beta_0}\) for \(u \in [t]\) where \(C_u = \prod_{i=1}^{m}(\pi_x[i, k], k)^{\beta_0}, D_u = \prod_{i=1}^{m}(\pi_x[i, k], k)^{\beta_0}\) and \(E_u = \prod_{i=1}^{m}(\pi_x[i, k], k)^{\beta_0}\).
20. \(A\) and \(V\) run inner product arguments to check:
   (a) \(\text{InnerProduct}(pp, 1^{T_p}\pi_x, 2^{m-1}, \text{cm}_{k^u}, v_u, P(u)^{\xi})\) for \(\xi \in [D]\) where \(\text{cm}_{k^u} = \phi_Y \prod_{i=0}^{m-1} (\text{cm}_{k^u})^{\xi} = \phi_Y \prod_{i=0}^{m-1} (\text{cm}_{k^u})^{\xi}\).
   (b) \(\text{InnerProduct}(pp, 1^{m-1}, \text{cm}, 0; z)\) where \(z \leftrightarrow \beta \cdot P_\ell + \tilde{r} \land \varphi = \Phi^{\xi} T \land \text{cm} = \prod_{i=0}^{m-1} (\text{cm}_{k^u})^{\xi}\).
   (c) \(\text{InnerProduct}(pp, 1^{T_p}\pi_x, h, m, T_u, w_u, \overline{V_u})\) where \(\overline{V_u}\) stands for first \(m\) entries of \(V_u\) and \(w_u = \langle \delta, W_u \rangle\) (consistency of \(X_u, Y_u, Z_u\) with \(\pi\)).
21. \(V\) checks proximity of \(U_x, U_y\) and \(U_z\) according to the Equation (3).

Ensure the coins \(c_1\) and \(c_2\) are in the Merkle tree of coins. Each coin authentication takes around \(1.8 \times 10^6\) gates (see [5, Section 5.2.2]).

Check that \(s_{n1}\) and \(s_{n2}\) are correctly computed from \(c_1\) and \(c_2\). This take around 54,000 gates.

Check that \(v_1 + v_2 > v\) and \(v_1 + v_2 < 2^{64}\), where \(v_1\) and \(v_2\) are values of the coins. This takes around 66 constraints.

For the above circuit, we consider \(N \approx 4 \times 10^9\). For different values of parameters of our protocol, we set \(N_s = \max(66, 4m^3)\). For Bulletproofs, we take \(N_s = 66\). Optimizing for total prover communication, our protocol achieves a total communication of 83.64 MB, with a proof size of 4.2 MB. Prover and verification time for our protocol is 9100 sec and 30-1 second respectively.
<table>
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<th>$N$</th>
<th>Arg. Size(c zk) MB</th>
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<th>Prover Time($t_P$) sec</th>
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<td>L</td>
<td>B</td>
</tr>
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<td>$2^{23}$</td>
<td>1.31</td>
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</table>

Table 2. Comparison of Graphene(G), Ligero(L) and Bulletproofs(B) in single prover setting for 80 bits of security.

distributed variant of Bulletproofs yields total prover communication of 168 MB, with proof size of 0.001 MB, proving and verification time of 5297 sec and 713 sec respectively. We used state-of-the-art dishonest majority semi-honest protocol (Oblivious Transfer based) MASCOT [32] for the MPC communication among the provers. All the experiments were done on 8-core Ubuntu Linux 18.04 Machine with 2 GHz processor and 32GB memory. We used libff and libqfft libraries for finite field and elliptic curve implementation, and also for the FFT and multi-exp algorithms. The elliptic curve used was 181-bit Edwards curve.
Oracle Setup: Compute $O$ as described above. Set $\pi := O$.

1. $V \rightarrow P_\xi$: $\gamma_x, \gamma_y, \gamma_z \leftarrow \mathbb{F}$, $r_{lc} \leftarrow \mathbb{F}^M$, $r_{qd} \leftarrow \mathbb{F}^P$, $\rho \leftarrow \mathbb{F}^{4p}$.
2. $P_\xi \rightarrow A$: $P_\xi$ computes $(U \xi = \bigoplus_{i \in [4p]} \rho_i(U \xi[i, \cdot])$ and sends commitments $(\tilde{c}_1, \ldots, \tilde{c}_t) \xi$ to $(U \xi)$. $A \rightarrow V$: $A$ computes $\tilde{c}_k = \bigoplus_{\xi \in [4]} \xi^k$ and sends $\tilde{c}_1, \ldots, \tilde{c}_t$.
3. $P_\xi \rightarrow V$: $P_\xi$ computes: $R = r_i^t W$ for $W = [\gamma_x I || \gamma_y I || \gamma_z I || (\gamma_x A + \gamma_y B + \gamma_z C)]$, polynomials $R_i, i \in [4p]$ interpolating the slices of $R$ viewed as a $4p \times m \times n$ matrix.
4. $P_\xi \rightarrow A$: $P_\xi$ computes $\mathcal{F}_{\text{eval}}$ on inputs $(Q^x_\xi)^k, (Q^y_\xi)^k$ and $P_\xi$ gets $Q_{xy}^k$, share of the polynomial $Q_{xy}$.
   - $h \times n$ matrices $(P_{lc}^k), (P_{qd}^k)$ as “$P$” matrices for the linear check and quadratic check respectively.
   - Note that $(p_i)^k \xi$ is given by $(p_i)^k \xi() = \bigoplus_{i=1}^p \sum_{j=1}^{q} (R^x_{ij}(\alpha_j), (\xi(\gamma_j))^k(\alpha_j), + R^{2p+i}(\alpha_j), (\xi(\gamma_j))^k(\alpha_j) + \ldots )$. The $(p_j)^k \xi()$ polynomials for the matrix $(P_{qd}^k)$ are given by $(p_j)^k() = \bigoplus_{i=1}^q r_{qd} \xi[(Q_{xy}^k)^k(\alpha_j), -(Q_{xy}^k)^k(\alpha_j),].$
   - Blinding vectors $(U_{lc}^k), (U_{qd}^k) \in \mathbb{F}^{2m-1}$ for linear and quadratic check protocols respectively, and commitments $(\alpha_0)^k, (d_0)^k, (d_1)^k, \ldots, (d_{2t-1})^k$ for matrix $(P_{qd}^k)$.
5. $P_\xi \rightarrow A$: $P_\xi$ computes $\xi = \bigoplus_{k \in [0, s + \ell - 1]} (d_k \xi) \forall k \in [0, 2t - 1]$ and sends $c_0, c_1, \ldots, c_{s+\ell-1}, d_0, d_1, \ldots, d_{2t-1}$.
6. $V \rightarrow P_\xi$: $V$ accepts if all the subprotocols accept.
7. $A \rightarrow V$: $A$ computes $c_k = \bigoplus_{\xi \in [4]} (c_k) \xi \forall k \in [0, \ldots, s + \ell - 1]$ and sends $c_0, c_1, \ldots, c_{s+\ell-1}, d_0, d_1, \ldots, d_{2t-1}$. $V \rightarrow P_\xi$: $V$ accepts if all the subprotocols accept.
8. $A \rightarrow P_\xi$: $P_\xi$ computes $(U_{lc}) = \bigoplus_{[0,t]} (U_{lc})^k, (P_{lc}) = \bigoplus_{[0,t]} (P_{lc})^k, (P_{qd}) = \bigoplus_{[0,t]} (P_{qd})^k, (V_{lc}) = \bigoplus_{[0,t]} (V_{lc})^k, (V_{qd}) = \bigoplus_{[0,t]} (V_{qd})^k$.
9. $A \rightarrow V$: $V$ accepts if all the subprotocols accept.

Fig. 10. Distributed GrapheneRICS Protocol