Plasma Go: A Scalable Sidechain Protocol for Flexible Payment Mechanisms in Blockchain-based Marketplaces

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Abstract—The rapid proliferation of decentralized marketplace applications demands scaling solutions beyond pairwise channels in order to facilitate high volumes of consumer-provider payment transactions. While sidechains seem to present a possible solution, there are several challenges in realizing them; while simpler state channels have seen wide adoption (e.g. Lightning network), sidechains are not in wide use yet. In this work, we propose Plasma Go, a sidechain mechanism for payment transactions where the computational and monetary costs of the required on-chain activity do not depend on the number of sidechain transactions. Indeed, Plasma Go combines pairwise payment channels and the Plasma construct of off-chain activity with root-chain notarization, to yield a mechanism where consumers and providers are guaranteed safety of their sidechain funds without the typical requirement of having them be online. We exploit efficient Boneh–Lynn–Shacham signature and key aggregation schemes to design a notarization and fund withdrawal process that mitigates well-known attacks and drawbacks in previous sidechain designs. We show that the computational load of Plasma Go is orders of magnitudes lower than the state of the art scaling solution. We also analyze the tradeoffs between the signature-based Plasma Go approach and the state-of-the-art sidechain technique ZK-Rollups and highlight a design decision for marketplace operators to make in choosing the Layer 2 solution to use.

I. INTRODUCTION

Blockchain systems provide secure decentralization of payment and other transactions at the cost of low transaction throughput (block confirmations that can take minutes to hours) and high transaction fees that may exceed the payment amount [1]. Facilitating fast and cheap payments, particularly for small “micropayments,” is important for several decentralized applications, such as rapidly emerging blockchain-based marketplaces. For instance, several blockchain networks aim to facilitate sharing of last-mile network resources like bandwidth and compute, e.g., to create a decentralized wireless service provider for IoT devices [2], [3], [4]. In such networks, consumers may connect with different providers based on factors like location, making incremental payments for every unit of resource consumed. There is also significant interest in replicating well-established centralized marketplaces like Amazon and Uber on blockchain-based distributed ledger technologies (DLT) [5], [6]. Placing such platforms on DLT minimizes users’ required trust in the marketplace operator (e.g., Amazon or Uber), as their transactions are then executed by decentralized miners and secured by rules enforced via smart contracts. For instance, the contract may enforce negotiated limits on the operator’s commission per order. However, realizing such high-volume decentralized marketplaces requires the ability to make fast, cheap payments of arbitrary amounts.

While prior works have proposed off-chain payment channels to overcome blockchain-imposed per-transaction costs, this model is optimized for frequent pair-wise interactions between two entities and does not scale well to marketplaces with consumers placing orders to multiple providers. In fact, it is desirable to allow marketplaces to match consumers with providers asynchronously. For example, Amazon may decide which of multiple providers should fulfill an order well after the consumer has placed and paid for it. Consumers may even make up-front payments unconnected to specific transactions that are then fulfilled by multiple providers over time (e.g., monthly flat-rate data plans).

We develop Plasma Go, a mechanism for enabling flexible payment schemes in blockchain marketplaces, supporting large quantities of frequent payments between consumers and service providers for arbitrary amounts. Plasma Go is based on the insight that a marketplace operator can decompose off-chain payments into consumer-operator and operator-provider transactions. Our decomposition allows the operator to leverage a single pool of liquidity sourced from paying consumers for all provider payments, while also ensuring that providers are neither subject to double-spending attacks from the operator nor subject to any counter-party risk from consumers. Plasma Go imposes no requirements on consumers or providers to guarantee safety of funds already accrued while making it highly expensive for the operator to dishonestly
deviate from the protocol. Further, consumers and the operator transact at near-zero marginal cost via traditional pairwise payment channels requiring no on-chain activity after their initial setup. The operator then pays service providers by running a sidechain that provides scalability and low costs but requires periodic on-chain activity to protect providers from possibly malicious operator actions.

Sidechains as an architectural design for increasing blockchain scalability were first proposed at a high level in 2017 [7] and have gained significant attention from the Ethereum Foundation. Called Plasma, the sidechain mechanism has been conceptualized and revised in a series of blogposts and discussions [8], though its design still faces challenges. The sidechain is a centralized service (or a small application-specific blockchain with few miners, offering fast finality and low costs) that runs outside the main blockchain (also called the “root chain”) and is generally used to facilitate payments. Sidechains convert on-chain payment transactions to payment promises on the sidechain without requiring establishment of pairwise channels; these promises can be exchanged quickly at little cost since the sidechain operates outside the blockchain, while a smart contract on the root chain is used to periodically publish summaries of sidechain activity. Rules encoded in the smart-contract allow users who received funds in the sidechain to withdraw them at any time by directly making calls to the contract, allowing users to minimize their monetary losses if the operator turns malicious.

Sidechains are hard to realize in practice due to the resource requirements they impose on the root chain. Storage is expensive in blockchains since the stored state in smart-contracts takes up permanent disk space in mining nodes once it is mined into a block [9]. Prolonged computations on the root chain can become prohibitively expensive as well, especially since blockchains like Ethereum dynamically price computation resources [10]. Hence periodically having a smart-contract on the root chain verify and store extensive histories of sidechain activity, as would intuitively be needed to protect users from operator and counter-user malfeasance, may be prohibitively expensive.

Minimum Viable Plasma (MVP) [11], [12], one of Ethereum’s first Plasma constructions, addresses this problem by requiring only short hashes (called commitments) of sidechain activity to be published to the smart-contract, significantly reducing the storage requirements. However, this enables the data availability attack [13], wherein the operator may not reveal the transaction history from which this commitment was generated to users. Users can then neither verify that their transactions were included, nor prove that their transaction were excluded. Even the smart-contract cannot verify the validity of off-chain transactions from the (irreversible) hash it receives. Hence, Plasma protocols (and payment channel networks) require users to be online to monitor the root chain for periodic notarizations by the operator and to immediately withdraw their funds if they suspect malicious activity like the data availability attack, which also leads to the problem of mass exits. For applications like marketplaces, this requirement that users be continuously online may not be feasible. While a trivial solution may require all users to sign a commitment submitted for notarization, the number of signatures to be submitted and verified scales linearly with the number of users, compounding resource costs, and still requires users to always participate in the signing.

Plasma Go solves these challenges with novel constructions tailored to the marketplace context. First, we realize that marketplace consumers need not participate in the sidechain. Indeed, unidirectional pairwise payment channels [14], which are easy to engage in and impose practically no system requirements or monetary risks on the payers, are sufficient for consumers to make payments to the marketplace operator. Consumers’ deposited funds in these payment channels are then secure even if they are arbitrarily offline. However, receiving payments in individual consumer channels poses a prohibitively high liquidity requirement on the operator when forwarding these consumer payments to providers. We hence design a sidechain mechanism whereby the operator can make payment promises to providers by revealing the off-chain funds accumulated in their unidirectional channels with consumers. We utilize BLS signature aggregation along with Proofs of Possession [15] to allow Plasma Go to securely and efficiently aggregate providers’ signatures of a commitment into one signature, avoiding the resource costs of large-scale message verification. This construction also enables the smart contract to accept commitments even when some providers are unavailable to sign it, while continuing to protect their funds from operator malfeasance. However, the on-chain execution then imposes monetary costs on the operator that scale with the number of missing signers. Hence, Plasma Go is resilient to the data availability attack. Operators are incentivized to reveal the transactions behind each commitment and obtain provider signatures; providers can access their funds even if the operator does not do so.

Figure 1 provides an overview of our proposed framework where $\xi$ denotes the cryptocurrency unit in use (e.g. ETH or BTC). Consumers make instant off-chain payments via unidirectional payment channels with the operator, who periodically computes the amount owed to each provider and generates a one-way irreversible hash from the resulting set of per-provider payment promises, acquires providers’ signatures on this hash, and publishes it to the smart-contract on the root chain for storage. This design of Plasma Go enables decentralized marketplaces to scale. Since to the best of our knowledge no prior work has characterized Plasma-style Layer 2 sidechains, we first provide a framework for constructing marketplace sidechains like Plasma Go and rigorously model desirable system properties that capture important attack vectors. We briefly review and compare three main sidechain protocols proposed by Ethereum, namely, More Viable Plasma, Plasma Debit, and the very recent Zero Knowledge Rollups (ZK Rollups). We show that Plasma Go enables all the desirable properties identified such as safety of sidechain funds (as does ZK Rollup). Further, we consider the computational as well monetary costs incurred by the operator and the smart-
contract in facilitating marketplaces based on Plasma Go and ZK Rollup sidechains in Ethereum. We show that ZK Rollup’s is up to 5 orders of magnitude more expensive computationally, and 2 – 3 in terms of gas costs.

The rest of this paper is organized as follows. We review relevant background material and related work in Section II. In Section III we introduce a framework for modeling and assessing the security of sidechains for marketplace payments. Subsequently in Sections IV and V we extend the generic model to capture the Plasma Go system, and describe our protocol respectively. We present the Ethereum-based case-study in Section VI and conclude in Section VII.

II. RELATED WORK

We now provide an overview of off-chain payment mechanisms, namely, state channels and side chains.

State channels are a widely used mechanism in which repeated transactions (i.e. exchanges of payment promises) between two users impose no marginal cost once some initial overhead is incurred in setting up and depositing funds (that are then incrementally spent) into a pairwise channel between them. Such channels were first proposed for Bitcoin [16] and are used, e.g., by Raiden Network [17]. Pairwise channels are not sufficient for marketplaces where consumers may connect with unknown providers for potentially one-time payments. Recent works [18] facilitate transactions between users without a direct payment channel by routing the payment through shared intermediary channels. However, in large decentralized marketplaces with sporadically online users, such routes may not exist between arbitrary consumer-provider pairs. Further, the intermediaries must commit funds to the route’s outgoing channel, which then cannot be used to pay other users. Indeed, while the marketplace operator can act as an intermediary by establishing payment channels with each consumer and provider, he must then expend liquidity in each individual provider channel, which could be a prohibitive capital expense for large marketplaces.

Sidechains enable uses well beyond pairwise off-chain payments. Plasma was the first and largely only sidechain model until the recent ZK Rollup. To use Plasma, the application (i.e. operator) defines a Plasma smart-contract on the Ethereum root chain that enforces rules and penalties, and then operates a Plasma sidechain outside the blockchain. Specific constructions from Ethereum’s forums include MVP [11], More Viable Plasma (MoreVP) [12], Plasma Cash [19] and Plasma Debit [20]. MVP allows users to deposit arbitrary amounts to the Plasma contract and send payment promises backed by this deposit to any party off-chain. However, it requires payers to watch the contract for the next operator commitment, ensure their transaction was included, and attest so with a second confirmation signature. It is further prone to data-availability attacks. MoreVP improves MVP by eliminating the second confirmation but has the same overhead; we thus compare Plasma Go to MoreVP instead of MVP by defining new formalisms that capture sidechain primitives not found in pairwise channel models [18]. In Plasma Cash, users receive non-fungible tokens on the Plasma chain; transactions consist of transferring token ownership to another user. Plasma Debit allows users and the operator to transfer fractional token values (subject to current deposits) to each other.

ZK Rollup [21] significantly differs from Plasma variants. Instead of the operator publishing one-way irreversible hashes of off-chain transactions to the contract, it computes a succinct non-interactive argument of knowledge (zk-SNARK) proving that each off-chain payment transaction was legitimate (signed correctly with valid balances) without revealing the entire set of transactions or requiring their validation by the smart-contract. The core novelty is zkSNARK itself [22], [23], which allows for short proofs that are verifiable in constant time.
independent of the input size, i.e. the number of transactions. ZK Rollups have garnered much recent interest; in-fact, Ethereum’s eighth major network update recently implemented changes that specifically optimize zkSNARK functionality. Plasma Go is designed to facilitate efficient marketplace payments. We use a Debit-style construction of unidirectional consumer-to-operator payment channels (guaranteeing security of their funds and preventing double-spending), combined with a Plasma-inspired operator-to-provider payment forwarding that solves the data availability problem even under intermittent provider availability, without any exit games (like MoreVP) to ensure safety of providers’ funds. In comparison with ZK Rollup, we show that Plasma Go is several orders of magnitude cheaper.

III. Framework

We now provide a framework for modeling operator-mediated off-chain marketplace payments that captures the broader sidechain concept of periodic transaction notarizations on the root chain. We discuss important attacks on sidechain designs and rigorously define system properties to evaluate marketplace sidechains. In Sections[V] and [V] we develop the Plasma Go protocol based on this model; in keeping with this, we defer detailed explanations of the various modules to subsequent sections where Plasma Go is developed.

A. Assumptions

As commonly done with Layer 2 scaling solutions, we assume that the underlying blockchain (i.e. Layer 1) has sufficient miners and is secure. Any transaction on the root chain, e.g. executing smart-contract functions, may require several block confirmations (as in Ethereum and Bitcoin) before the computed outcome can be considered “final” (i.e. a high likelihood of finality for the completed transaction). Thus, when we refer to the outcomes of contract functions, we implicitly mean their finalized outcome after sufficient confirmations; and when we refer to wait-times imposed by or time to complete smart contract functions, we exclude this confirmation time. We assume that the frequency at which commitments of sidechain activity are published to the root chain has accounted for the root chain’s typical finality times. For instance, if the blockchain confirms transactions in the order of minutes, we should consolidate sidechain activity every few hours. We assume that the operator provides sufficient funds (e.g. gas in Ethereum) to process transactions that publish new commitments to the contract in their order of submission. We use $\xi$ to denote the cryptocurrency unit, e.g. ETH. We assume an event broadcasting mechanism and that broadcasted events are available for asynchronous reads (e.g. Ethereum Events), and the scripting functionality at the root chain (Layer 1) required to write Plasma contracts such as the ability to store state, and return lists as outputs of function calls (e.g. Ethereum’s Solidity).

B. Marketplace Sidechain Model

Let time be discretized and the resulting points in time be indexed by $t = 1, 2, \ldots$. An operator $\omega$ with public key $pk_\omega$ runs the sidechain by instantiating a smart contract on the root chain and registering $pk_\omega$ as the operator. A consumer $c$ with public key $pk_c$ deposits $d_\xi$ in the smart contract, to be spent incrementally on the sidechain for the orders they place in the marketplace. The consumer may deposit more $\xi$ at any time, so we use $D_{c,t}$ to denote the total funds deposited by the consumer $c$ before $t$ (Figure [2]). An off-chain payment from $c$ for an order consists of a transaction $T = (\mu, pk_c, pk_r)$, where $\mu$ is the quantity in $\xi$ to be paid, $pk_r$ is the public key of the recipient, and the digital signature of the transaction is $\sigma = S(T, sk_c)$, which the consumer generates using their private key $sk_c$. We let $s(T)$ and $\mu(T)$ denote the sending consumer’s public key $pk_c$ and amount $\mu$ specified in transaction $T$ respectively. The recipient $r$ is the service provider if the consumer sends the off-chain payment directly to the provider, e.g. as possible with Plasma MoreVP. In case of an operator-mediated marketplace (e.g. Plasma Go), $r$ is simply the operator $\omega$ (note that the sidechain is always run by the operator; however, the operator may not mediate payments in the sidechain, e.g. as with prior Plasma constructions). In both cases, the recipient $r$ verifies $T^\prime$ by evaluating a payment-verification module $Y(T, \sigma) \in \{0, 1\}$, where $1$ indicates a legitimate off-chain payment and $0$ otherwise (as noted earlier, description of $Y$ and other modules of the sidechain mechanism is deferred to Section[V] where Plasma Go is developed in detail). In case of an operator-mediated marketplace, where the operator $\omega$ receives these off-chain payment transactions from consumers, the operator further generates new transactions that make corresponding payment promises to appropriate the provider(s) $p$ who fulfills the consumer’s order, less any fees charged. We define such a transaction $T^\prime = (\mu^\prime, pk_p, pk_c)$ as a payment promise from the operator to a provider $p$ with public key $pk_p$ for amount $\mu^\prime \xi$, sourced from the off-chain payment transaction made by consumer $c$ with public key $pk_c$ to the operator. We abuse earlier notation and use $\mu(T^\prime)$ and $s(T^\prime)$ to denote the payment amount $\mu$ and the referenced consumer $pk_c$ in $T^\prime$. We further let $\mu^\prime = t$ denote the amount spent by the consumer as of $t$, and use $T_p$ to denote the total set of valid off-chain payment transactions received by provider $p$. In the operator-mediated marketplace scenario, these operator-generated transactions $T^\prime$ constitute $T_p$.

The sidechain operator eventually generates a Plasma block $\kappa = (T, M)$. In the block $\kappa$, $T$ contains the transactions in sets $T_p$ for each provider $p$ arranged by some fixed ordering and $M$ is the Merkle tree generated from the transactions in $T$. We let $T_p(\kappa)$ denote the transactions for provider $p$ that are included in $\kappa$ and $T(\kappa)$ to denote the total ordered set of transactions included in $\kappa$. $M(\kappa)$ and $R(M(\kappa))$ denote the Merkle tree included in $\kappa$ and the Merkle tree’s root respectively. We introduce a commitment generation module $N(\kappa)$ which yields a tuple $O_\kappa$ as output which includes a short commitment to the Plasma block $\kappa$. $O_\kappa$ contains information that the Layer 1 Plasma contract uses to notarize the sidechain transaction activity corresponding to $\kappa$. In case of MoreVP, for e.g., $O_\kappa$ is simply the root of the Merkle tree $M(\kappa)$. Hence,
Once \( \kappa \) is generated, the operator executes \( \mathcal{N}(\kappa) \) which may take up to \( \gamma \) time-steps for completion.

The operator then submits \( O_\kappa \) to the smart contract on the root chain, triggering the execution of the commitment verification module \( \mathcal{R}(O_\kappa) \) at the contract. When \( \mathcal{R} \) completes, the smart contract either accepts the commitment provided in \( O_\kappa \), thereby storing it in its internal state, or declines it. The final funds that a provider \( p \) acquires may be different from \( T_p(\kappa) \), depending on the commitment information in \( O_\kappa \) that is generated by the execution of \( \mathcal{N} \). Hence, the final funds that \( p \) can access in \( \kappa \) is based on the set of transactions \( T_p(O_\kappa) \) that correspond to the outcome \( O_\kappa \). For instance, \( T_p(O_\kappa) \) may not equal \( T_p(\kappa) \) in MoreVP if the operator, who executes \( \mathcal{N} \), maliciously modifies it to generate an entirely different Merkle root as a commitment for notarization on the root-chain rather than \( R(M(\kappa)) \).

Finally, we denote by \( \mathcal{K}_t \) the set of Plasma blocks \( \kappa \) corresponding to confirmed \( O_\kappa \) as of time \( t \), ordered by the times they were accepted, with \( \mathcal{K}_t(-1), \mathcal{K}_t(-2), \ldots \) denoting the latest block, the previous block, and so on. When a provider \( p \) (or the operator \( \omega \) as well, in case of an operator-mediated marketplace) initiates a withdrawal of funds at time \( t \) (i.e. payment promises) from the sidechain, they call the contract’s withdrawal function module \( \mathcal{W}(\ldots) \) and provide a reference to off-chain payment promises assigned to them that have been included in notarized Plasma block as of \( t \). The exact information to be provided varies based on the Plasma implementation; at the least, a Merkle proof of inclusion of the \( p \)’s transactions in some notarized Plasma block is required. We later explain Plasma Go’s implementation of \( \mathcal{W} \) in detail.

The outcome is either to transfer up to the requested amount to address \( a_p \) or to cancel the exit. We define \( u_{c,t}^* \) as the total funds withdrawn (by the operator and providers) against the operator’s channel with \( c \) as of time \( t \). We use \( W_{p,t}^\prime \) to refer to the total funds withdrawn by a provider \( p \) or operator (\( p = \omega \)) as of time \( t \).

Finally, we define each party’s confirmed funds. A consumer \( c \)'s confirmed funds at time \( t \) is simply their total deposits less off-chain payments made, i.e. \( f_{c,t} = D_{c,t} - u_{c,t}^* \); note that the contract can track \( D_{c,t} \) since it mediates consumer deposits. Figure 2 shows the resulting state of a consumer’s channel with the operator. A provider \( p \) or operator \( p = \omega \)'s confirmed funds at time \( t \) is their accessible funds in the set of notarized Plasma blocks (i.e. \( \kappa \) whose commitment \( O_\kappa \) has been accepted by the smart-contract through the commitment verification process \( \mathcal{R} \)) less any withdrawals already executed against this: \( f_{p,t} = \sum_{j \in T_p(\kappa)} \sum_{T' \in T_p(\kappa)} (O_{ \kappa(t-j)} - W_{p,t}^\prime) - W_{p,t}^\prime \).

In Table I, we summarize operator and smart-contract functions/modules, whose implementation in Plasma Go is deferred for explanation in subsequent sections. Before specifying the details of the Plasma Go protocol in Section V, we describe the attack model relevant for assessing Plasma Go and the properties we aim to guarantee in our design.

C. Attack Model

Most sidechain protocols are designed to prevent attacks from a consumer, provider or operator who deviates from the protocol to steal funds that they are not entitled to or save compute/storage resources. We detail such attacks and ones specific to Plasma Go.

The withdrawal function is a potential source of attacks in Plasma Go. Malicious providers may attempt to withdraw funds belonging to other providers, based on the generation and processing of Plasma block commitments (\( \mathcal{N} \) and \( \mathcal{R} \)) and how they are used in the withdrawal function \( \mathcal{W} \). The operator may also have promised himself excessive funds in a notarized Plasma block and hence be able to maliciously withdraw funds previously confirmed to other providers or owned by consumers.

The operator may also attempt to double-spend funds when generating payment promises in a Plasma block \( \kappa \). That is, the set of payments to providers \( T(\kappa) \) may reference more funds than the operator owns in a channel with a consumer, or may refer to funds in channels with non-existent consumers. Further, depending on the construction of \( \mathcal{N} \), the operator may execute the well-known data availability attack by withholding \( \kappa \) from providers, who therefore do not know the set of transactions that correspond to the one-way commitment in \( O_\kappa \). Providers then cannot withdraw funds that may have been included in \( \kappa \) since they are unable to compute \( T_p(\kappa) \) required by the contract’s withdrawal function \( \mathcal{W} \). This attack also enables the operator to simply withhold payments owed to providers, or worse yet, play back older commitments that assigned lower income to providers than the most recent one, thereby becoming eligible to withdraw the difference in funds.

Or, the operator may collude to send excessive payments to a few providers and deprive others of the payments they are owed. Providers may be exposed to additional risk from one another if the commitment generation process \( \mathcal{N} \) requires them to communicate with the operator. For instance, malicious providers may collude to prevent \( \mathcal{N} \) from proceeding if it requires their signatures.

Indeed, Plasma Go relies on BLS signatures and uses signature aggregation and verification techniques in a novel construction to mitigate these attacks. Hence, unlike other Plasma protocols, Plasma Go is also exposed to attacks related to BLS signature aggregation, which we use to defend against data availability attacks. BLS signature aggregation is generally prone to the rogue public-key attack [25], where a malicious entity in a group can forge the group’s aggregated signature on any message. Consider, for instance, a set of
TABLE I: Description of operator and smart-contract modules in our model of Plasma-style marketplace sidechains

| Name | Input | Output | Description |
|------|-------|--------|-------------|
| Y    | T, σ  | ∈ {0, 1} | Verifies the validity of an off-chain transaction |
| N    | κ     | tuple Oκ | Generate commitment for root-chain notarization |
| R    | Oκ    | ∈ {0, 1} | Verifies the validity of the submitted commitment |
| W    | . . .  | ∈ {0, 1} | If the withdrawal is valid, transfers the specified funds to the specified account |

\( n \) keys \( K = \{(s_k^i, p_k^i) : 1 \leq i \leq n\} \) whose public keys and signatures are to be aggregated via BLS. An attacker who knows the public keys in \( K \) can choose some \( \beta \in \mathbb{Z}_q \) where \( q \) is of prime order and compute a false public key \( p_{ka} = g_1^\beta (\prod_{u=1}^n p_{ku})^{-1} \) where \( g_1 \) is a generator for group \( \mathbb{G}_1 \) of prime order \( q \). The aggregate public key computed by a verifier is \( p_k = p_{ka} \prod_{u=1}^n p_{ku} \). The attacker can then declare the signature \( \sigma_{a,m} = H_0(m)^\beta \) (where \( H_0 \) is a random oracle mapping into \( \mathbb{G}_0 \) which is also of prime order \( q \)) and convince the verifier that this has been signed by all \( n \) \( s_k^i \)'s as well as \( p_k \)’s \( s_k \). To see this, note that verification of \( \sigma_{a,m} \) requires checking if \( e(g_1, \sigma_{a,m}) = e(p_{ka}\prod_{u=1}^n p_{ku}, H_0(m)) \) where \( e \) is a pre-specified non-degenerate bilinear function (\( e : \mathbb{G}_0 \times \mathbb{G}_1 \rightarrow \mathbb{G}_T \)). But \( e(g_1, \sigma_{a,m}) = e(g_1, H_0(m)^\beta) \) as declared by the attacker to the verifier, and \( e(g_1, H_0(m)^\beta) = e(g_1^\beta, H_0(m)) \), and \( g_1^\beta = p_{ka} \prod_{u=1}^n p_{ku} \) by definition of \( p_{ka} \). As shown by Ristenpart and Yilek [25], requiring users to provide a message signed with their secret key (i.e., Proofs of Possession or PoP) thwarts this attack if different hash functions are used for signing PoP vs. other messages.

\[ D. \text{System Properties} \]

Since, to the best of our knowledge, no prior academic work has codified sidechain designs (as opposed to the simpler state channels), we now rigorously formulate properties that a sidechain for marketplace payments like Plasma Go would ideally satisfy, including resiliency to the attacks identified above.

To do so, we define a user as active at time \( t \) if the user is listening to broadcasts or incoming messages from the operator and the smart-contract at \( t \) and responds by following the Plasma Go protocol. We say the operator revealed a piece of information to a provider if the operator sent (or broadcasted) it through a communication channel with the provider and the provider was online to receive it. Our first property ensures predictable execution time:

\[ \text{Definition 1 (Liveness). A withdrawal initiated by a provider or the operator at } t \text{ must impose no wait-times and execute to completion immediately, subject to transaction processing latency of the underlying root chain.} \]

Irrespective of the outcome of a withdrawal initiated at \( t \) (i.e., whether it is canceled or successful), the outcome must be computed immediately, modulo any transaction processing times in the underlying blockchain. This is especially important because Plasma protocols like Plasma MVP rely on exit games where users often wait for a significant period of time after initiating exits, during which others may “contest” their withdrawals. Such games can lead to the problem of mass exits in MVP [11], [12]. Note that we do not consider consumers withdrawing funds, since consumers in our system need only deposit an amount that they intend to spend in the marketplace. However, it is important to ensure that funds that the consumer has deposited to spend in the marketplace are not maliciously withdrawn by an operator or provider. We now define such desirable properties that provide resiliency against attacks on withdrawal functions or operator attempts to double-spend funds.

\[ \text{Definition 2 (Consumer Safety). For a consumer } c, f_{c,t} = f_{c,t'} \text{ for any time } t' > t \text{ as long as they have not made any off-chain payments between } t \text{ and } t', \text{ regardless of when they are active.} \]

\[ \text{Definition 3 (Operator Safety). The operator can initiate a withdrawal } W(\cdot) \text{ of their confirmed funds at any time } t \text{ and the withdrawal terminates successfully, i.e., } f_{w,t} \text{ is transferred to their address } a_w, \text{ if the required parameters are correctly provided to } W(\cdot). \]

The consumer balance should not decrease unless he makes payments, even if he is sometimes inactive, and an operator should be able to withdraw their confirmed funds successfully at any time.

\[ \text{Definition 4 (Provider Safety). The provider } p \text{ can initiate a withdrawal } W(\cdot) \text{ of their confirmed funds at any time } t \text{ and the withdrawal terminates successfully, i.e., } f_{p,t} \text{ is transferred to their address } a_p, \text{ even if they have been inactive for an arbitrary amount of period, as long as required parameters are correctly provided to } W(\cdot). \]

The provider is also able to withdraw their confirmed funds irrespective of how long they have been inactive. Satisfying these properties ensures that the sidechain is reliable: neither consumers nor providers are at risk anytime of having their confirmed funds stolen or of stealing funds confirmed to others on the sidechain. Further, as defined below, as long as the operator is non-malicious, an active provider should continue receiving payments for new orders (from consumers) irrespective of other providers’ actions.

\[ \text{Definition 5 (Income Certainty). A legitimate off-chain payment } T \text{ and associated } \sigma \text{ sent from a consumer at } t \text{ directly to a provider } p \text{ (or to the operator in lieu of services rendered by } p) \text{ is available as confirmed funds } f_{p,t} \text{ (less any fee charged by the operator) as of some predictable } t' > t, \text{ as long as the provider has been active } A(p, t'') = 1, \forall t'' \in [t, t') \text{ and the} \]


operator follows the Plasma Go protocol, irrespective of the actions of any other providers during that time.

This ensures that users of the chain are not subject to counter-party risk in receiving additional income, as long as the operator is non-malicious. For instance, Plasma Go requires providers’ signatures to publish new commitments; however, malicious providers withholding signatures would ideally not affect legitimate providers. Since providers rely on one-way irreversible commitments of off-chain activity to receive confirmed funds on-chain, we now define a property that protects against the data availability attack.

**Definition 6 (Data Availability).** Consumers, providers, and operators know their confirmed funds $f_{c,t}$ and $f'_{p/ω,t}$ at any time $t$ and are revealed all information necessary to prove ownership of it.

We later show that under data availability, each provider $p ∈ P_κ$ who received confirmed additional income in an accepted block $κ$ (i.e. $f'_{p,t} > f'_{p,t-1}$) is guaranteed to have been revealed $T(κ)$ and $M(κ)$, and the corresponding $T_p(κ)$ and $O(κ)$. Else if $f'_{p,t} = f'_{p,t-1}$, he is guaranteed to have been revealed $T_p(O_κ)$, which is sufficient for $p$ to prove ownership of confirmed funds $f'_{c,t}$ to the contract and successfully withdraw them with $W(κ)$. Since the operator generates $κ$ and $O(κ)$, it always knows and can use this information to access and ensure their own funds $T_ω$, which are also a part of committed Plasma blocks. Finally, we define **Liquidity Pooling**.

**Definition 7 (Liquidity Pooling).** The sidechain mechanism is said to provide Liquidity Pooling if the liquidity created by consumers’ off-chain payments can be directly pooled for paying providers.

As in typical payment channels, an operator is not required to provide his own liquidity to forward consumers’ payments to providers.

**Comparison of sidechain protocols.** We now briefly survey proposed sidechain designs. Table [III] summarizes the system properties satisfied by each, including Plasma Go; detailed explanations of Plasma Go and proofs of its properties are provided in Section [V]. Rigorous definitions for some properties like Income Certainty and Liveness may change slightly for specific sidechain protocols; for instance, confirmed funds for a provider do not necessarily involve Plasma blocks in the Plasma Debit construction, since providers and the operator would interact via pairwise payment channels. In Table [III] we consider appropriately modified definitions.

With MoreVP, consumers and providers interact directly via the sidechain run by the operator (i.e. the operator is solely in charge of consolidating transactions, verifying them and publishing commitments for transactions to the root-chain). This construction can facilitate consumer-operator-provider interactions (e.g. if consumers do not know the provider(s) to pay when placing orders). However, it has multiple drawbacks. First, since balances are tracked based on the Unspent Transaction Output model (UTXO [26]), operators may insert “out of nowhere” fake transactions in the Plasma block where they assign non-existent UTXOs to themselves. MoreVP thus violates consumer and provider safety; users can only protect their funds if they are online to detect such transactions and withdraw their funds. Further, the operator may entirely fail to convey the Plasma block (and its transactions) associated with a commitment that it publishes to the contract, violating data availability.

In Plasma Debit, the operator establishes payment channels with each consumer and provider and acts as the forwarding intermediary between them. Plasma Debit violates liveness; a withdrawal initiated by the operator must wait to allow the provider sharing the pairwise channel to check if the operator is attempting to withdraw funds already promised to him. Thus, Plasma Debit also violates Provider Safety: a malicious withdrawal may be successful if the provider is not at least intermittently active to contest it. Further, Debit requires the operator to provide its own liquidity for making payments to providers since the operator’s channels with the provider and consumer are independent. Since sidechains are used to avoid expensive on-chain transactions, the operator presumably deposits sufficient funds in each provider channel to forward payments from consumers for a long period of time. If many providers are present, such upfront liquidity requirements may be prohibitive.

Finally, the marketplace on a ZK Rollup sidechain satisfies Consumer and Provider Safety, as well as Data Availability, since the operator provides zero-knowledge proofs to the smart contract that establish the validity of each included transaction while also revealing the state transitions in users’ account balances. While this enables ZK Rollup to appear equivalent to Plasma Go in Table [III], the computational resources it requires from the blockchain for processing commitments scales much worse than those of Plasma Go as the number of transactions increases (Section [VI]).

**IV. Plasma Go Model**

We extend the generic framework for marketplace sidechains introduced previously with notations that capture Plasma Go-specific interactions, which allows us to explain the protocol subsequently in Section [V].

**A. Assumptions**

We assume the root chain supports BLS signature [27] verification and other relevant operations like multiplication in group $G_2$, where BLS public keys live. BLS is currently being standardized [28]. BLS curves are already in use [29], and Ethereum is expected to support BLS curves and avail BLS functionality such as key aggregation with its Casper release [30]. We use the multiplicative notation for groups in this paper and references to signatures in Plasma Go implicitly mean BLS signatures.

**B. Plasma Go Model**

We now describe extensions introduced by Plasma Go model in the marketplace sidechain framework. 
**Liveness**

- Consumer
- Provider
- Income
- Data
- Liquidity

| Protocol   | Liveness | Consumer Safety | Provider Safety | Income Certainty | Data Availability | Liquidity Pooling |
|------------|----------|----------------|-----------------|------------------|------------------|------------------|
| MoreVP     | □        | □              | □               | □                | -                | □                |
| Debit      | □        | □              | □               | □                | □                | □                |
| ZK Rollup  | □        | □              | □               | □                | □                | □                |
| Plasma Go  | □        | □              | □               | □                | □                | □                |

**TABLE II:** We summarize the properties guaranteed by different sidechain mechanisms applied to the marketplace context. Note that operator safety always holds.

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**Consumer Transactions.** As Figure [1] shows, Plasma Go is based on the premise that consumers place orders (to avail services offered in the marketplace) and pay the operator instantly at the time of order placement. Hence, in Plasma Go, a consumer’s deposit includes a set of transactions $T$ also submit their commitments in the root chain. The operator is not be signed since the operator is the only one authorized to access transactions $T$ made by the consumer. Further, since the consumer-operator payment channel is unidirectional, the amount $\mu$ specified in $T$ indicates the total amount promised by the consumer to the operator as of the time that the $T$ is generated, incorporating the incremental amount the consumer intends to pay for their latest order in the marketplace. Hence $\mu$ is the total amount of the consumer’s funds in the contract that is owned by the operator as of this transaction. Note that $T$ need not correspond directly to a consumer-provider exchange; for instance, it could be an upfront fee paid before the operator coordinates with providers to fulfill specific consumer needs (e.g. monthly fees paid for mobile data in a marketplace between data users and access points). Hence, $\mu^*_c,t$ denotes the operator-owned amount of the consumer’s deposited funds as of $t$. Further, we denote $C_t$ as the set containing the last operator-verified transaction from each consumer as of time $t$.

**Provider Transactions.** In Plasma Go, a provider $p$ enrolls in the sidechain by first calling the smart-contract function $E(\sigma_{\omega,p})$ to register; as done earlier, we defer the generation of $\sigma_{\omega,p}$ and specification of $E$ to Section [V]. As Figure [1] shows, in Plasma Go, the operator periodically consolidates payments owed to each provider every $t_o$ time slots based on verified off-chain consumer transactions, potentially deducts an operator fee, and forwards the remainder to appropriate (registered) providers (e.g., determined by which providers fulfilled these consumers’ orders in the past $t_o$ time slots). A transaction $T^o$ in $T_p$ is then a payment promise from the operator to a provider $p$ that is sourced from the operator-owned balance in his unidirectional channel with the consumer of public key $pk_o$. Note that $\mu^*$ is the total amount owed by the operator to $pk_o$ in this channel as of current time and thus may include promises made previously (e.g. if the provider has not withdrawn any funds since the start of sidechain yet). Unlike consumers’ off-chain payments, these transactions need not be signed since the operator is the only one authorized to submit their commitments in the root chain. The operator also includes a set of transactions $T_\omega$ assigned to himself $pk_\omega$, reflecting fees charged for providing the sidechain service.

Since $\mathcal{P}_\omega$ is identical to any other $\mathcal{P}_p$, we do not differentiate between the operator and the provider when referring to the payees of a Plasma block, unless required.

At every $t_o$, when the operator generates the Plasma block $\kappa$ from the total set $\mathcal{T}$ of these consolidated payment promises made to providers, each leaf $L_p(M)$ in the resulting Merkle tree $M(\kappa)$ corresponds to the hash of the set of all payment transactions $T_p(\kappa)$ for some provider $p$. Hence, $\mathcal{T}$ contains the sets $\mathcal{T}_p$ for each provider $p$, appearing in the order that the corresponding hashes appear in the leaves of the $M(\kappa)$. We denote the Merkle proof $\mathcal{P}_\kappa$ of inclusion $P_p(M(\kappa))$ can be provided for each leaf $L_p(M(\kappa))$. Figure [3] depicts an example.

**On-chain Notarizations and Withdrawals.** Since each Plasma block reflects the total funds owed by the operator to providers, $\mathcal{K}_\omega(\kappa)$ incorporates all relevant payment history from previous blocks. When a provider $p$ or the operator $\omega$ initiates a withdrawal of funds at $t$, they provide the set of accessible transactions $T_p(O_{\mathcal{K}_\omega(\kappa)})$ in the last Plasma block that assigns them funds as input to the withdrawal function $W$. As depicted in Figure [3], the funds promised to a payee in a Plasma block refers to funds the operator has collected in
corresponding channels with consumers. Hence the outcome is either to transfer up to \( \sum_{T' \in \mathcal{T}} (c_{\mathcal{O}_{\mathcal{G}}(t)}) - \mu(T') \) to address \( a_{p, o} \) or to cancel the exit. Hence \( \omega_{c,t}^2 \) is the total funds withdrawn (by the operator and providers) against the operator’s channel with \( c \) as of time \( t \). Further, \( W_{c,t}^2 \) then refers to funds withdrawn by a provider \( p \) or operator \( p = o \) in the latest block published as of time \( t \), i.e., \( \mathbb{E}_c(-1) \), and confirmed funds \( f_{p,t}^2 \) at time \( t \) refers to net accessible funds in the latest notarized Plasma block, i.e., \( \sum_{T' \in \mathcal{T}^2} (c_{\mathcal{O}_{\mathcal{G}}(t)}) - \mu(T') - W_{p,t}^2 \).

Table III provides a summary of the notation used for Plasma Go’s system model, including those introduced in this section.

**Numerical Example.**

To illustrate the consumer and provider transaction models, consider \( t = t_1 \ldots t_8 \). Consumers \( c_1 \) and \( c_2 \) deposit 30\( \sigma \) and 20\( \sigma \) respectively into the Plasma contract at time \( t_1 \). Suppose \( c_1 \) additionally deposits another 40\( \sigma \) at \( t_3 \). Then, \( D_{c_1,t} = 30 \) \( \forall t \in \{t_1,t_3\} \) and \( 70 \) \( \forall t \in \{t_3,t_4\} \), and \( D_{c_2,t} = 20 \) \( \forall t \in \{t_1,t_4\} \). To send 10\( \sigma \) to the operator at \( t_4 \), \( c_1 \) generates a transaction \( T_a = \langle 10, pk_{c_1} \rangle \) and signature \( \sigma_{T_a} = S(T_a, sk_{c_1}) \) such that \( \gamma(T_a, \sigma_{T_a}) = 1 \); then \( \mu_{c_1,t_4} = 10 \). Suppose \( c_2 \) similarly sends 10\( \sigma \) to the operator at \( t_4 \) via legitimate transaction \( T_b \). To send another 10\( \sigma \) at \( t_5 \), \( c_1 \) generates a transaction \( T_c = \langle 20, pk_{c_1} \rangle \) and the corresponding \( \sigma_{T_c} \) such that \( \gamma(T_c, \sigma_{T_c}) = 1 \); then \( \mu_{c_1,t_5} = 20 \). At \( t_5 \), the latest transactions \( C_{t_5} = \{ T_B, T_c \} \) and the confirmed funds \( f_{c_1,t_5} = 50 \) and \( f_{c_2,t_5} = 10 \). Suppose two registered providers \( p_1 \) and \( p_2 \) participate in the system, with no operator fees, and the orders for \( T_a \) and \( T_b \) are fulfilled by \( p_1 \) while \( T_c \) is fulfilled by \( p_2 \). At \( t_8 \), the operator generates the block \( \kappa = \langle T, \mathcal{M} \rangle \), where \( T = \{ \langle 10, pk_{p_1}, pk_{c_1} \rangle, \langle 10, pk_{p_2}, pk_{c_1} \rangle, \langle 0, pk_{c_2} \rangle \} \). We then have \( \mathcal{T}_{p_1}(\kappa) = \{ \langle 10, pk_{p_1}, pk_{c_1} \rangle, \langle 10, pk_{p_2}, pk_{c_1} \rangle, \langle 0, pk_{c_2} \rangle \} \), \( \mathcal{T}_{p_2}(\kappa) = \{ \langle 10, pk_{p_2}, pk_{c_1} \rangle \} \), and \( \mathcal{T}(\kappa) = \{ \langle 0, pk_{c_2} \rangle \} \). Further, the Merkle tree \( \mathcal{M}(\kappa) = H(H(H(\mathcal{T}_{p_1}(\kappa)), H(\mathcal{T}_{p_2}(\kappa)), H(\mathcal{T}(\kappa))) \rangle \), where \( H \) is the one-way irreversible hash function used for generating the Merkle tree and the leaves of \( \mathcal{M} \) are \( L_p(\mathcal{M}) = H(\mathcal{T}(\kappa)) \).

**V. Plasma Go Specification**

We now expand on the Plasma Go functions defined in Sections III and IV, namely, 1) \( \gamma \), the process by which an operator verifies a consumer’s off-chain payment; 2) \( \mathcal{E} \), the process by which a provider registers with the Plasma smart-contract; 3) \( \mathcal{N} \), the process of generating the commitment information for a Plasma block; 4) \( \mathcal{R} \), the process by which the Plasma contract decides whether to accept a commitment; and 5) \( \mathcal{W} \), the process by which providers and operators withdraw their confirmed funds from the contract. In detailing Plasma Go, we highlight how we satisfy the properties in Section III.

We first introduce temporal restrictions on when withdrawals and commitment verification can occur. Suppose the sidechain starts at \( t_0 \). We use \( \gamma \) to denote the wait-time imposed by \( \mathcal{N}(\cdot) \) (elaborated below). To protect against timing-related attacks, the smart-contract enforces freeze periods where funds may not be withdrawn (here \( t_0 \) is the frequency at which new commitments are generated by the operator, i.e. \( \mathcal{N} \) is triggered) of \( \{t_0 + t_a, t_0 + t_a + 2\gamma, t_0 + 2t_a + 2\gamma, t_0 + 2t_a + 4\gamma, \ldots \} \). We use \( U(t) \) to denote the set of time-slots corresponding to an active freeze window at time \( t \). If \( U(t) = \emptyset \) if there is no freeze window currently. For instance, \( U(t = t_0 + t_a + 1) = \{t_0 + t_a, t_0 + t_a + 2\gamma\} \).

**Verifying Consumers’ Off-chain Payments**

When the operator receives an off-chain payment transaction \( T \) from the consumer \( c \) at time \( t \), he verifies it by evaluating \( \gamma(T, \sigma) \in \{0, 1\} \). The verification succeeds (\( \gamma(T, \sigma) = 1 \)) if the sender \( pk_c \) has sufficient confirmed funds \( \{\mu_{c,t}^2 \leq \mu(T) \leq D_{c,t}\} \); i.e., the operator knows the deposited funds \( D_{c,t} \) since deposits, top-ups, and provider/operator withdrawals happen through the contract on the root chain which stores and updates \( D_{c,t} \). Updates to these values can be broadcast to all participants.

**Provider Registration**

To participate in Plasma Go, providers first register with the smart-contract. To do so, the provider sends her signed public key \( \sigma_{p, init} = S(\langle pk_p, sk_p \rangle) \) to the operator, where \( S \) is the signature generated using \( p \)’s secret key \( sk_p \) to sign \( pk_p \). If \( \gamma(\langle pk_p, pk_p, \sigma_{p, init} \rangle) = 1 \), i.e., the operator verifies \( p \)’s signature, then the operator signs a message \( m \) (chosen as \( m = pk_p \)) and returns the signature \( \sigma_{p, init} = S(m, sk_p) \) to the provider, else he does not. The provider then calls the smart-contract’s endorsement function \( \mathcal{E}(\sigma_{p, init}) \in \{0, 1\} \). Enrollment succeeds (\( \mathcal{E} = 1 \)) if and only if the smart-contract verifies the operator’s signature, i.e., \( \mathcal{E}(\sigma_{p, init}) = 1 \), the contract updates the aggregated public key \( apk = apk \cdot pk_p \) (if this is the first provider to register) and broadcasts \( apk \) to providers. Further, the contract stores \( pk_p \) in list \( \mathcal{B} \), the list of providers with zero on-chain balance. This procedure prevents rogue public-key attacks:

**Lemma 1.**

Public-key aggregation and signature verification in Plasma Go is not subject to rogue public-key attacks.

**Proof Sketch.**

By design of the underlying blockchain, miners process transactions only if the transaction is signed by the stated sender, in this case, \( pk_p \); hence registering providers have implicitly provided proofs of possession (POP) to the blockchain. Plasma Go can therefore use the aggregate public key \( apk \) that is generated by the process described in \( \mathcal{E} \) for aggregate BLS signature verification while explicitly blocking the usual rogue public-key attack. However, POPs can be attacked with an oracle \( OMSign(pk, msq) \) that returns \( msq \) signed by \( sk_p \). In that case, the attacker with a maliciously computed \( pk_{att} = y_{i,j}^b \cdot \prod_{i \in \mathcal{P}_{pk}} pk_i \) may provide a signed transaction on the root chain by computing \( \sigma_{m, att} = H_0(m)^b / \prod_{i \in \mathcal{P}_{pk}} OMSign(pk_i, m) \) where \( m \) is the transaction to be submitted to the blockchain calling the contract’s \( \mathcal{E} \) function and registering \( pk_{att} \) as a vendor, \( i \) iterates over the registered providers, and some \( \beta \in \mathbb{Z}_q \). In
| Symbol | Meaning |
|--------|---------|
| $\omega$ | Operator |
| $pk_\omega$ | Public key of the operator |
| $c$ | Consumer |
| $pk_c$ | Public key of consumer $c$ |
| $\xi$ | Deposited by consumer $c$ |
| $D_{c,t}$ | Total funds deposited by consumer $c$ by time $t$ |
| $T$ | Off-chain payment transaction from consumer to operator |
| $s(T)$ | Sender of the transaction |
| $\mu(T)$ | Specified in a transaction |
| $\mu_{c,t}$ | Total balance owned by the operator as of time $t$ in their channel with the consumer $c$ |
| $C_t$ | Set containing the last operator-verified transaction from each consumer as of time $t$ |
| $p$ | Provider |
| $\sigma_{\omega,p}$ | Registration information given by provider $p$ to the contract for enrollment in the sidechain |
| $t_a$ | Time-interval between payment consolidation and forwarding operations executed by the operator |
| $T'$ | Payment promise from the operator to a provider |
| $s(T')$ | Public key of the consumer whose payment channel is referred to in $T'$ |
| $T_p$ | Set of payment-promise transactions, issued by the operator to provider $p$, specifying $\xi$ owed to $p$ against each relevant consumer’s payment channel with the operator |
| $T_\omega$ | Issued payment promises where the operator is the recipient |
| $\kappa$ | Plasma block generated from a set of payment-promise transactions |
| $\mathcal{T}(\kappa)$ | Ordered set of transactions included in $\kappa$ |
| $\mathcal{T}_p(\kappa)$ | Transactions for provider $p$ in $\kappa$ |
| $\mathcal{M}(\kappa)$ | Merkle tree generated from $\mathcal{T}(\kappa)$ |
| $L_p(\mathcal{M}(\kappa))$ | Leaf in the tree $\mathcal{M}(\kappa)$ corresponding to the hash of $\mathcal{T}_p(\kappa)$ |
| $R(\mathcal{M}(\kappa))$ | Root of the Merkle tree $\mathcal{M}(\kappa)$ |
| $P_p(\mathcal{M}(\kappa))$ | Merkle proof of inclusion for $L_p(\mathcal{M}(\kappa))$ |
| $O_\kappa$ | Output of the commitment generation process $\mathcal{N}$ which includes a short commitment to $\kappa$ |
| $\mathcal{T}_p(O_\kappa)$ | Final accessible funds that $p$ has in $\kappa$ based on commitment generation output $O_\kappa$ |
| $\mathcal{K}_t$ | Set of Plasma blocks $\kappa$ corresponding to confirmed $O_\kappa$ as of time $t$ ordered by the times they were accepted |
| $\mathcal{K}_t(-1)$ | The latest accepted Plasma block |
| $w_{c,t}$ | Total funds withdrawn by the operator and providers against the operator’s channel with $c$ as of time $t$ |
| $W_{p,t}$ | Total funds withdrawn by a provider $p$ or operator in the latest block published as of time $t$, i.e., $\mathcal{K}_t(-1)$ |
| $f_{c,t}$ | Consumer $c$’s confirmed funds as of time $t$ |
| $f'_{p,t}$ | A provider’s (or interchangeably the operator’s) confirmed funds at time $t$ |

**TABLE III: Summary of Notation**

Plasma Go, however, this requires that all registered providers (even honest ones) to sign this transaction asking for $pk_\omega$’s enrolment, which they have no reason or incentive to do so. Further, guaranteed safety can be achieved even if OMSign is somehow available by users employing separate hash functions for signing their POP messages and other ones [25].

**Generating Commitments** As discussed in Section IV, every $t_a$ time-steps, the operator consolidates new payments received from consumers in the previous $t_a$ time slots, and generates corresponding payments to be made to (registered) providers; the latter payments constitute a new Plasma block $\kappa$. The operator generates a commitment to $\kappa$ at $t$ by executing $\mathcal{N}(\kappa, C_t)$, which we now describe. The operator broadcasts the Merkle tree $\mathcal{M}(\kappa)$, set of transactions $\mathcal{T}(\kappa)$, the set of the latest consumer-operator transactions $C_t$, and a time-stamp $t_a$ of current time $t$, to all providers $p \in \mathcal{P}(\kappa)$ and waits up to $\gamma$ time-steps. During this time, each provider $p$ signs $H(R(\mathcal{M}(\kappa)), t_a)$, a combined hash of the Merkle tree’s root and the time-stamp $t_a$, and sends it to the operator if four conditions are met. Note that the operator’s signature is not required since he implicitly authorizes $\kappa$ by generating it and publishing the commitment.

First, the tree should be valid: $t_a$ should closely reflect
current time \( t \), and the provider \( p \) should have exactly one leaf in the Merkle tree corresponding to payment promises for \( p \), i.e. exactly one \( L_p(\mathcal{M}(\kappa)) = H(T_p(\kappa)) \). Second, the consumer source \( s(T') \) for each transaction \( T' \in T_p(\kappa) \) sending funds to provider \( p \) should have verified its latest transaction, i.e., \( \mathcal{V}(pk_s(T'), T, \sigma) = 1 \), where \( (T, \sigma) \in \mathcal{C}_p \) and \( s(T) = s(T') \). Further, the total payments from each source \( s(T') \) that the operator promises to other providers should not exceed the current operator-owned balance in that channel. That is, for each transaction \( T' \in T_p(\kappa) \) and a corresponding consumer-operator transaction \( (T, \sigma) \in \mathcal{C}_p \), the operator verifies if the sum over all transactions (payment promises) in \( \kappa \) exceeds the current operator-owned balance in that channel.

A consumer \( c \) was published; note that includes the Merkle proof \( \mathcal{P} \). When the operator triggers the commitment after verifying additional transaction information, i.e, \( \mathcal{V}(pk_s(T'), T, \sigma) = 1 \), the contract accepts the commitment. However, if this is not true, or if at least one provider declared as exiting in \( \mathcal{X}_t \) is not present in \( \mathcal{X} \), the commitment is rejected. If these checks pass and \( \mathcal{V}(apk_{\text{active}}, m, \sigma s) = 1 \), then the contract first verifies that a correct \( \sigma_{p,\text{init}} \) has been provided for newly missing providers \( p \in \mathcal{M}_t - \mathcal{B} \), i.e. \( \mathcal{V}(apk_{p}, pk_p, \sigma_{p,\text{init}}) = 1 \). If so, the contract accepts the commitment after verifying additional transaction information. For all missing providers not in \( \mathcal{B} \), \( p \in \mathcal{M}_t - \mathcal{B} \), the contract requires that \( p \)'s transactions in \( \kappa \), \( T_p(\kappa) \geq T_p(O_{\mathcal{X}(\kappa)}(T_p(\kappa) - 1)) \) and the operator's provided Merkle proof of the declared \( T_p(\kappa) \) should be verifiably correct. Additionally, for newly missing providers, i.e \( p \in \mathcal{M}_t - \mathcal{M} - \mathcal{B} \), the contract requires that the Merkle proof showing \( T_p(\mathcal{X}(\kappa) - 1)) \) in the previous Plasma commitment be valid. For each missing provider \( p \) whose signature was also absent from the last round, i.e. \( p \in \mathcal{M}_t \cap (\mathcal{M}_t - \mathcal{B}) \), the contract also requires that the hash of \( T_p(\mathcal{X}(\kappa)) \) corresponds to \( p \)'s hash in \( \mathcal{L} \), i.e. \( H(T_p') = L_p \).

If these conditions are met, the contract accepts the commitment (\( R(\mathcal{M}(\kappa)) = 1 \)) and sets \( apk = apk_{\text{active}} \prod_{p \in \mathcal{M}_t} p \), removing exited providers from the aggregate public key \( apk \). It then updates \( \mathcal{M}, \mathcal{N}, \mathcal{L} \). Each \( p \in \mathcal{M} \cap \{ \mathcal{M}_t - \mathcal{B} \} \) is removed from \( \mathcal{M} \) (since \( p \) is no longer missing) and its corresponding hash from \( \mathcal{L} \). If all providers in the subset \( \mathcal{M}_t(x) \) for some \( x \) are removed, the corresponding \( \mathcal{N}_t(x) \) is also cleared. All existing subsets of \( \mathcal{M} \) and \( \mathcal{N} \) are then shifted back by one; e.g., \( \mathcal{M}_t(2) \) and \( \mathcal{N}_t(1) \) are set to \( \mathcal{M}_t(-2) \) and \( \mathcal{N}_t(-1) \) respectively. Any new provider \( p \in \mathcal{M}_t - \mathcal{M} \) is added to \( \mathcal{M}_t \), his leaf in the current commitment \( L_p(\mathcal{M}(\kappa)) \) added to \( \mathcal{L} \), and the key-sets and total sourced funds to providers in \( \mathcal{M}_t(1) \) for the appropriate consumers added to \( \mathcal{N}_t(1) \). The contract
also clears the list of recently exited providers $X$ and removes any public keys in $B$ that are not present in $M_t$. Prior Plasma commitments are cleared, freeing up storage.

This process ensures that, while not storing individual providers’ public keys (which incurs storage cost), the contract correctly detects and removes only registered providers from $apk$ who have recently exited. Further, a registered provider whose signature is not accounted for in $ars$ is declared in $M_t$; else $\kappa$ is rejected.

**Lemma 2.** If a registered provider $p$’s signature $\sigma_{p,\kappa}$ is not included in $ars_{s,\kappa}$ for a committed submission $O_{\kappa}$, and $p \notin M_t \cup X_t$ (the missing and exiting providers’ keys submitted with $O_{\kappa}$), $\kappa$ is rejected.

Thus, exiting providers do not prevent $apk$ from verifying messages signed by legitimate providers who have funds on the root chain. Since *Plasma Go* requires provider signatures on the committed root, signees are revealed relevant information. Further, by storing the hash of the last transaction set that missing providers signed for, *Plasma Go* ensures that missing providers can always access their confirmed funds (i.e. their funds). We thus show:

**Theorem 1.** *Plasma Go* ensures Data Availability.

Note that only registered providers benefit from data availability assurance since the operator is forced to include them in $M_t$ list if their signature is not included in $ars_{s,\kappa}$. Finally, we also note that the design of $R$ incentivizes providers to be online and follow the *Plasma Go* protocol in order to receive new/additional income assigned to them by the operator in subsequent commitments.

**Withdrawals.** To withdraw funds at time $t$, a provider $p$ or the operator triggers the exit function $\mathcal{W}(\cdot)$ in the smart-contract. If $\mathcal{H}(t) \neq 0$, there is an active freeze on withdrawals and the exit is canceled. Otherwise, $\mathcal{W}$’s input must contain a set of transactions $T_p$ assigning funds to $pk_p$ (or $pk_o$). For each $T' \in T_p$, a transaction $T$ and signature $\sigma$ from consumer $c = s(T')$ assigning funds to $pk_c$ must be provided, with $\mathcal{V}(pk_c, T, \sigma) = 1$ and $\mu(T') \leq \mu(T) \leq D_{c,t}$, showing that $c$ has the funds to execute $T$. The input may also specify whether the withdrawal is a permanent exit.

Let $n_t$ denote the largest number of consecutive signatures missed by a provider currently tracked in $M_t$ at time $t$. Let $N_t(x)^{pk_c}$ denote the amount (in $x$) stored in $N_t(x)$ corresponding to consumer $pk_c$’s channel. Then $W$ checks if $p$ is in any of the missing provider lists, i.e. $\exists x \ni \exists M_t(x) \ni p \in M_t(x)$.

If so, the contract checks if $H(T_p) = L_p$, i.e. whether the provided transactions correspond to $p$’s hash in $L$. If so, the contract checks that each $T' \in T_p$ with $c = s(T')$ is transferred to $a_p$. Otherwise the withdrawal is canceled. Note that $w_{c,t}$ is known to the contract since withdrawals happen through the contract. $\mu_{c,t}$ represents the highest operator-owned balance in the channel with $c$ that the contract knows of (as revealed by any previous withdrawals).

If $\mu_{c,t} = 0$ or $\mu'_{c,t} < \mu(T')$, then the contract simply updates $\mu_{c,t} = \mu(T')$ where $c = s(T')$. If the provider is not in the missing provider list $M_t$, then $\exists = 0$ and the same expression is evaluated to compute the funds to be transferred to $a_p$. However, in this case, the contract expects a valid Merkle proof $P_p(M(X_t(-1)))$ for $T_p$. After the withdrawal, the contract updates $w_{c,t}$ and, if $p \in M_t$, it updates $N_t(-x)^{pk_c}$ as well to deduct the withdrawn funds from that channel.

If the withdrawal is indicated as a permanent exit, $pk_p$ is added to the list of recently exited providers $X$. Otherwise, the provider is added to $B$, indicating it has zero funds. If $p \in M_t$, then $L_t$, $N$ and $M_t$ are updated accordingly. We allow an operator to force a provider’s exit using $\mathcal{W}$, which allows operators to curtail the computation and cost incurred by missing providers (these are large, as shown in Section VI). Finally, a provider (or the operator) can only withdraw funds once per commitment; if $pk_p \in X \cup B$, the exit is canceled.

**Lemma 4.** *Plasma Go* satisfies Liveness.

By design of $R$, $N$ and $\mathcal{W}$, we ensure that providers, consumers and operators following *Plasma Go* can access their confirmed funds.

**Theorem 2.** *Plasma Go* provides Provider, Consumer and Operator Safety.

Indeed, the provider’s loss from operator malefeasance is capped by the payments he was due to receive in a given window $t_a$. No payments to a provider, once confirmed as per *Plasma Go*, can be revoked. A provider who is arbitrarily unavailable may access his missed event broadcasts by traversing logs (e.g., Ethereum events).

**Lemma 5.** *Plasma Go* provides Income Certainty and allows for Liquidity Pooling.

Plasma blocks may be committed with new confirmed funds even if some providers do not sign the commitment, provided the operator correctly generates the block. Further, $\mathcal{W}$ is such that missing providers may only withdraw the funds they last signed for. Hence, providers are incentivized to participate in $N$. They also risk being forcibly exited by the operator if they do not.

**Optimizing for Storage Resources.** We note as an aside that *Plasma Go* can be easily modified to move the bulk of its state (consumer information) off-chain. Per the design above, the *Plasma Go* smart-contract stores the public key $pk_c$ of each consumer $c$ along with their net deposited funds $D_{c,t}$ on the contract at any time $t$, the highest owner-operated balance in their channel revealed to the contract as of time $t$, $\mu'_{c,i}$; and the total funds $w_{c,t}$ withdrawn by providers and the operator from this channel. Clearly, the required storage is $O(n)$ in the number of registered consumers (and $O(1)$ in the number of registered providers). If storage is significantly more expensive than compute on the underlying DLT, we can optimize for storage at higher computational cost. Similar to the storage
mechanism proposed in ZK Rollup [21], the contract can track just two Merkle roots instead of individual consumer data: one of a Merkle tree \( A \) of registered consumers’ public keys \( pk_c \); and the other of a Merkle tree \( B \) of tuples \((D_{c,t}, \mu_{c,t}, w_{c,t})\), such that \( pk_c \) is stored in the \( n \)-th leaf of \( A \) corresponds to \((D_{c,t}, \mu_{c,t}, w_{c,t})\) in the \( n \)-th leaf of \( B \). Consumer registrations can use the same process as ZK Rollup [21]; however, note that these functions are now more compute-intensive since each requires the contract to verify Merkle proofs. Similarly, provider and operator withdrawals require computation to verify the Merkle proofs for the consumer’s balance in \( B \) against which they attempt withdrawal. However, all changes to \( B \) can be broadcast to others (stored in blockchain’s logs), hence all providers and operators can compute the leaves and Merkle proofs in \( B \) for any consumer, even if they have been offline.

VI. EVALUATION

We now compare the costs involved in running Plasma Go vs ZK Rollup sidechains for facilitating a scalable marketplace when deployed in the Ethereum blockchain, as a case study. We focus on the periodic commitment operations that happen on-chain as withdrawals and registration are likely less frequent.

Though there is no current deployment of a ZK Rollup sidechain and zkSNARKs are still being optimized, we conservatively estimate the cost of a ZK Rollup. Groth16 is a popular zkSNARK technique and one of the cheapest to verify; as of the Istanbul update [24], a zkSNARK verification is estimated to cost 200,000 gas. The SNARK prover’s (operator) computation is \( 4n + m \) group exponentiations, where \( n \) and \( m \) are the numbers of gates and wires. Though the number of constraints that the prover has to solve depends on the implementation, we use recently published test results [32] and estimate 150,000 constraints. Very conservatively, we consider only 150,000 group exponentiations on the operator (instead of \( 4n + m \)). Based on this benchmark [32], since 1600 transactions were packed in a SNARK and 3000+ may be possible with optimizations, we estimate the final number of transactions possible in a SNARK as 3000. Since transactions have to be published on the root-chain at least in CALLDATA to avoid data availability issues [21], CALLDATA is a recurring cost linear in the number of transactions, 16 gas per byte as of Istanbul [24]; each transaction is 15 bytes. We use an overhead of 50,000 gas [21].

We only consider group exponentiation and signature verifications for assessing computation load as they dominate other operations [23]. In Plasma Go, the operator performs as many signature verifications as the number of commitment signers, and the contract performs one verification (2 pairings) if there are no missing providers. If there are \( n \) missing providers, the contract performs \( n+1 \) pairings [27]. To estimate gas costs, we consider multiplication of \( n \) public keys and two Merkle proofs per missing provider (the worst-case gas consumption). Currently, the cost of pairings is \((34000 + num_{pairings}) + 45000 \) gas, cost of a key multiplication 150 and cost per hash 42. While BLS12-381 and operations in \( G_2 \) (though equivalent ones may be performed in \( G_1 \)) are not yet available in Ethereum, these are expected to be supported soon at presumably comparable costs [33], [34]. Finally, Ethereum allows transactions up to 10M gas per block. Since the SNARK allows only 3000 transactions at best, the ZK Rollup transaction will not hit this limit. For Plasma Go, if a commitment contains excessive missing providers that lead to gas costs over 10M, the operator forces the exit of these excess missing providers. We account for the gas spent in doing so.

Figures 4a and 4b depict the combined computational load (on the operator and contract) and gas costs respectively, for the two protocols, varying the number of transactions from 10K to 1M, and the % of missing providers who do not provide signatures for Plasma Go. There are 10K providers. The number of computations of Plasma Go remains constant in the number of transactions, while ZK Rollup does computations several orders of magnitude higher. Similarly, ZK Rollup’s gas cost scales with the number of transactions. Plasma Go’s gas increases significantly if providers are missing, but stays constant as the portion of missing providers continues to increase. Since missing providers are forcefully exited if their count is too high to commit the root, the cost is limited (the exit operation only involves a Merkle proof and does not contribute in log order to gas costs). However, as the number of providers increases, the gas cost imposed by a higher fraction may outweigh ZK Rollup’s cost (Figure 4c).

Hence, while ZK Rollup imposes significant computational costs that Plasma Go does not, the gas cost of ZK Rollup scales with the number of transactions while that of Plasma Go scales with the number of missing providers. Operators choosing between these solutions must assess these two factors; when providers’ devices can reasonably be expected to participate in the signing process (once every day or hour, based on the configuration), Plasma Go is highly beneficial by scaling throughput at no marginal gas cost.

VII. CONCLUSION

Highly scalable and low-cost payment solutions are crucial for decentralized applications. We develop Plasma Go, a sidechain mechanism inspired from Ethereum’s Plasma architecture, where payment transactions between arbitrary participants can happen off-chain while a single short commitment to these transactions is published on-chain routinely. In Plasma Go, we guarantee safety of consumer and provider funds while they may be arbitrarily offline in the sidechain by combining a novel state-channel model with our sidechain design. We provide robustness to data availability attacks that popular Plasma constructions are prone to, and reduce the computational costs of large scale message signing and verification. None of our costs (computational, storage) scale with the number of transactions. When compared to the state of the art ZK Rollup, Plasma Go is at least \( 2 - 3 \) orders of magnitude cheaper in gas costs.
Fig. 4: Mean and standard deviation (log scale) for Plasma Go and ZK Rollup of (a) estimated computational and (b) gas cost with 10K providers and varying number of transactions, and (c) estimated gas costs with 100K transactions and varying number of providers.

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