

Interplanetary Consensus (IPC)

Consensus Lab

Abstract

TODO

1 Introduction

A blockchain system is a platform for hosting replicated applications (a.k.a. smart contracts in Ethereum [??] or actors in Filecoin [??]). A single system can, at the same time, host many such applications, each of which containing logic for processing inputs (a.k.a. transactions, requests, or messages) and updating its internal state accordingly. The blockchain system stores multiple copies of those applications' state and executes the associated logic. In practice, applications are largely (or even completely) independent. This means that the execution of one application's transactions rarely (or even never) requires accessing the state of another application.

Nevertheless, most of today's blockchain systems process all transactions for all hosted applications (at least logically) sequentially. The whole system maintains a single totally ordered transaction log containing an interleaving of the transactions associated with all hosted applications. The total transaction throughput the blockchain system can handle thus must be shared by all applications, even completely independent ones. This may greatly impair the performance of such a system at scale (in terms of the number of applications). Moreover, if processing a transaction incurs a cost (transaction fee) for the user submitting it, using the system tends to become more expensive when the system is saturated.

The typical application hosted by blockchain systems is asset transfer between users (wallets). It is true that many other applications are often involved in transferring assets and asset transfer may create system-wide dependencies between different parts of the system state. In general, if users interacted in an arbitrary manner (or even uniformly at random), this would indeed be the case. However, in practical systems, users typically tend to cluster in a way that users inside a cluster interact more frequently than users from different clusters. While this "locality" makes it unnecessary to totally order transactions confined to different clusters (in practice, the vast majority of them), many current blockchain systems spend valuable resources on doing so anyway.

An additional issue of such systems is the lack of flexibility in catering for the different hosted applications. Different applications may prefer vastly different trade-offs (in terms of latency, throughput, security, durability, etc...). For example, a high-level money settlement application may require the highest levels of security and durability, but may more easily compromise on performance in terms of transaction latency and throughput. On the other hand, one can imagine a distributed online chess platform (especially one supporting fast chess variants), where most of its state is ephemeral (until the end of the game), but requires high throughput (for many concurrent games) and low latency (few people like waiting 10 minutes for the opponent's move). While the former is an ideal use case for the Bitcoin network, the latter would probably benefit more from being deployed in a single data center.

In the above example, one can also easily imagine those two applications being mostly, but not completely independent. E.g., a chess player may be able to win some money in a chess tournament and later use it to buy some goods outside of the scope of the chess platform. In such a case, few transactions involve both applications (e.g., paying the tournament registration fee and withdrawing the prize money). The rest (e.g., the individual chess moves) are confined to the chess application and can thus be performed much faster and much cheaper (imagine playing chess by posting each move on Bitcoin for comparison).

Interplanetary Consensus (IPC) is a system that enables the deployment of heterogeneous applications on heterogeneous underlying SMR/blockchain platforms, while still allowing them to interact in a secure way. The basic idea behind IPC is dynamically deploying separate, loosely coupled SMR/blockchain systems (that we call *subnets*) to host different (sets of) applications. Each subnet runs its own consensus protocol and maintains its own ordered transaction log.

IPC is organized in a hierarchical fashion, where each subnet, except for one that we call the *rootnet*, is associated with exactly one other subnet (called its *parent*). Conversely, one parent can have arbitrarily many subnets (called *children*) associated with it.

This tree of subnets expresses a hierarchy of trust. All components of a subnet and all users using it are assumed to fully trust their parent and regard it as the ultimate source of truth. Note that, in general, trust in all components of the parent subnet is not required, but the parent system as a whole is always assumed to be correct (for some subnet-specific definition of correctness) by its child.

To facilitate the interaction between different subnets, IPC provides mechanisms for communication between them. In particular:

1. Assuming a common global notion of money (assets / tokens / ...) and accounts that can hold them, IPC also defines how money is moved

between accounts in different subnets. [gg: Globality is unnecessary. We rely on a parent-child common currency. One may create a new token inside a child and use this new token in the grandchild while making all child-grandchild monetary interactions based on that token.]

2. We define the notion of a *checkpoint* as a snapshot of the state of a subnet after having processed a certain sequence of transactions. IPC enables child subnets to place references to their checkpoints inside the state of their parents.

The operating model described above is simple but powerful. In particular, it enables

- Scaling, by using multiple blockchain/SMR platforms to host a large number of applications.
- Optimization of blockchain platforms for applications running on top of them.
- Governance of a child subnet by its parent, by way of the parent serving as the source of truth for the child (and, for example, maintaining the child's configuration). [mp: Go in more detail already here and mention PoS, collateral, slashing, firewall property, etc...?]
- “Inheriting” by the subnet of some of its parent's security and trustworthiness, by periodically anchoring its state (through checkpoints) in the state of the parent.
- [mp: Explain each item better. Any more items?]

In the rest of this document, we describe IPC in detail. In section 2 we define the system model and introduce the necessary terminology. Section 3 describes the main components of IPC and their interfaces. [mp: TODO: Finish this when sections are written.]

2 Model

The vocabulary used throughout this document is summarized in the IPC Glossary [1]. The reader is encouraged to read the IPC Glossary before continuing.

[mp: When the Glossary becomes stable, we can maybe add it as an appendix to this document.]

2.1 Computation and failure model

We model IPC as a distributed (“message-passing”) system consisting of *processes* that communicate by exchanging *messages*¹ over a network. In practice, a process is a program running on a computer, having some state, and reacting to external events and messages received over a communication network. We describe processes as exemplified in Algorithm 1.

Algorithm 1: Process definition.

```

1 variable = initial value
2 variable = initial value
3 ...
4 ► process:
5   upon event(params...) do
6     | // Logic to execute atomically
7   upon message(params...) do
8     | // Logic to execute atomically
9   ...

```

A process that performs all the steps exactly as prescribed by the protocols it is participating in is *correct*. A process that stops performing any steps (i.e., *crashes*) or that deviates from the prescribed protocols in any way is *faulty*. If a process is correct or may only fail by crashing, it is *benign*. A non-benign process is *malicious*. [mp: We can remove terms we end up not using...]

In general, faulty processes can be malicious (Byzantine), i.e., we do not put any restrictions on their behavior, except being computationally bounded and thus not being able to subvert standard cryptographic primitives, such as forging signatures or inverting secure hash functions. If the implementation of some component in our design requires additional assumptions on the behavior of faulty processes, they will be stated explicitly.

We use the term *participant* to describe an entity participating in the system that controls one or more processes. All processes controlled by one participant are assumed to be in the same trust domain – they trust each other, i.e., assume each other’s correctness. For example, a participant in the child subnet will probably run multiple processes: one for participating in the child subnet’s protocol (child replica), one for participating in the parent subnet (parent replica), and one process that processes the information from the above two and submits transactions accordingly (IPC agent). We precisely define the replicas and the IPC agent (all of them being processes) in Sections 2.2 and 3. The IPC agent of a participant always assumes that the information it receives from “its own” child replica is correct. However, messages received from another participant’s replica or IPC agent are seen as potentially malicious.

¹Network messages are not to be confused with Filecoin actor messages, that this document refers to as transactions.

The synchrony assumptions may vary between different components of IPC. We thus state those assumptions whenever necessary, when describing concrete implementations of IPC components.

2.2 State machine replication (SMR) and smart contracts

SMR and replicated state. A *state machine replication (SMR) system*² is a system consisting of processes called *replicas*, each of which locally stores a copy of (or at least has access to) *replicated state* that it updates over time by applying a sequence of *transactions* to it. Without specifying the details of it, we assume that any process can *submit* a transaction to an SMR system (we call such a process an *SMR client*) and that this transaction will eventually be ordered and applied to the replicated state. We call an SMR system that is part of IPC a *subnet*.

An SMR system guarantees to each correct replica that, after applying n transactions to its local copy of the replicated state, the latter will be identical to any other correct replica’s copy of the replicated state after applying n transactions. The replicas achieve this by executing an *ordering protocol* to agree on a common sequence of transactions to apply to the replicated state.

Note that replicas do not necessarily all hold the same replicated state at any instant of real time, since each replica might be processing transactions at a different time. In this context, there is no such thing as “the current replicated state of the SMR system”. There is only the current replicated state of a single replica. The replicated state of the system is only an abstract, logical construct useful for reasoning about transitions from one replicated state to another, happening at individual replicas by applying transactions (at different real times). When referring to a “current” replicated state, we mean the state resulting from the application of a certain number of transactions to the initial state.

Smart contracts. The replicated state of an SMR system can be logically subdivided into multiple *smart contracts* (a.k.a. actors in Filecoin). A smart contract is a portion of the replicated state with well-defined semantics. It defines the logic (e.g., expressed in a programming language, like Solidity in Ethereum) that a replica needs to execute when applying transactions and the new state that results from it.

We model a smart contract as a logical object in the replicated state that contains arbitrary variables representing its state. Its associated logic reacts to *events* triggered by (1) the application of transactions or (2) execution of other (or even own) smart contract logic. We describe smart contracts as exemplified in Algorithm 2.

²In this document, we use the terms “SMR system” and “blockchain” interchangeably.

Algorithm 2: smart contract definition

```

1 variable = initial value
2 variable = initial value
3 ...
4 ► smart contract name:
5   upon event(params...) do
6     // Logic to execute
7     trigger event(params...)
8   upon tx(params...) do
9     // Logic to execute
10    trigger event(params...)
11  ...

```

Note that, despite using similar syntax to describe processes and smart contracts, those are fundamentally different. The former usually represent OS-level processes running on some physical machine, the latter are an abstraction over the replicated state of an SMR system and their logic is being executed by all its replicas. While a process can submit a transaction to an SMR system, a smart contract cannot.

Interaction between subnets. In IPC, whole subnets need to interact, i.e., the replicated state of one subnet must react to (changes in) the replicated state of another subnet. As the replicated state of every subnet is distributed among its replicas and evolves independently of other subnets, we must establish a mechanism for interactions between the states of subnets. In particular, we must explicitly link the two replicated states of two subnets. More precisely, for any interaction between two subnets (A and B), define block heights h_A and h_B , such that A 's replicated state at height h_A considers B 's replicated state to have evolved exactly until h_B .

Proofs of finality. To this end, we define a *proof of finality* (PoF) to be data that proves that an SMR system definitively reached a certain replicated state. Regardless of the SMR system's ordering protocol's approach to finality (e.g., immediate finality for classic BFT protocols, or probabilistic finality in PoW-based systems), a PoF convinces the the proof's verifier that the replicated state the PoF refers to will not be rolled back. For example, for a BFT-based SMR system, a quorum of signatures produced by its replicas can constitute a PoF . We denote by $PoF(tx)$ the proof that an SMR system reached a state in which transaction tx already has been applied.

2.3 Money

For each pair of subnets in a parent-child relationship, we assume that there exists a notion of *money* (measured in *coins*) common to both subnets.³ Each end user of the SMR system is assumed to have a personal wallet and a corresponding account in some subnet.

We also assume that the submission, ordering, and applications of transactions is associated with a monetary cost. Each SMR client submitting a transaction to a subnet is assumed to have an account in that subnet, from which this cost is deducted. If the funds are insufficient, the SMR system ignores the transaction.

3 Components and their Interfaces

We now focus on the interaction between two subnets in a parent-child relation. To enable the interaction between them, which comprises running the subnets, observing each other's replicated state, constructing proofs of finality, submitting the necessary transactions, and modifying the replicated state accordingly, the following components need to work together.

- Processes:

1. **Parent replica:** The process that runs the parent subnet. It has a copy of the parent's replicated state, participates in receiving and ordering transactions and updates the replicated state (including the *SA* smart contract) accordingly.
2. **Child replica:** The process that runs the child subnet. It has a copy of the child's replicated state, participates in receiving and ordering transactions and updates the replicated state (including the *GWA* smart contract) accordingly.
3. **IPC agent:** The process that mediates the interactions between the two subnets. It has access to the replicated states of both the parent and the child (e.g., by sharing a trust domain with a child and a parent replica, or by securely downloading the replicated state from other replicas...) and acts as an SMR client (i.e. submits transactions) to both subnets. Depending on the implementation, it might also be responsible for constructing proofs of finality (which might involve communication with other processes).

- Smart contracts:

³One can easily generalize the design to decouple the use of money between a parent and its child, but we stick with using the same kind of money in both subnets for simplicity.

1. **Subnet actor (*SA*):** The smart contract in the parent subnet’s replicated state that stores all information about the child subnet that the parent subnet needs. The IPC agent’s transactions submitted to the parent subnet mostly invoke the *SA*. The state of the *SA* includes:

- *Accounting data.* This data describes the money that has been deposited to the child. It is considered locked inside the *SA* until it is withdrawn from the child. This data might consist of just a single value representing the sum of all such coins (“custodial” approach), but might also contain finer-grained information about balances for each account in the child subnet (“non-custodial” approach).
- *Governance account.* This account facilitates the economic design of a subnet. It can be used for collecting fees or making payments to accounts of participants that perform operations on behalf of the child subnet. For example, when an IPC agent submits (and thus pays for) transaction linking a child’s checkpoint to the parent’s replicated state, the IPC actor logic might reimburse the associated account.
- *Ordering protocol data.* This is the data (or a pointer to it) that is needed to run the ordering protocol of the child subnet. It is protocol-specific, but is generally expected to contain information such as
 - * The ordering protocol used by the subnet.
 - * Subnet configuration such as the validator set, voting rights, collateral deposits, etc.
 - * Subnet governance mechanisms, e.g., transaction fees, block rewards, conditions for participation, ...
- *Child state finality verification.* Logic to verify (based on only the parent’s replicated state) that a given child’s replicated state/*tx* is final⁴ or that a particular *tx* has been definitively included in the child’s state. We expect that this logic will verify a PoF submitted (through transactions) by one or more IPC agents to the *SA*.

The above suffices for an Interplanetary Consensus system with a minimal inter-subnet functionality of users’ asset transfer, and a general SMR per subnet. We continue with further state required for additional functionality.

⁴Finality is an elusive concept that we do not take upon ourselves to define here. For simplicity, we assume finality in a Boolean manner, either *tx* is final or it is not. This could easily be generalized to parameterized finality of the sort “the probability of *tx* persisting is at least *x*.”

- *Slashing.*
 - * List of slashable misbehaviors and a proving methodology. That is, for each slashable misbehavior there is a definition of what constitutes a valid proof of misbehavior (*PoM*).
 - * Penalties for misbehavior and rewards for reporting, as well as the logic performing the necessary actions within the parent subnet.
 - *Checkpointing.*
 - * Child subnet’s checkpoint data or a pointer to it.
 - * Checkpoint validity rules (and logic enforcing them). E.g., ”Checkpoints must be at least every Δ subnet blocks apart”, or ”A checkpoint must contain a reference to (hash of) a previous checkpoint.”, etc.
2. **IPC coordinator/gateway actor (*GWA*):** a smart contract that exists in every subnet in the IPC hierarchy and contains all information and logic the subnet itself needs to hold in order to be part of IPC. The state of the *GWA* includes:
- *Parent state finality verification.* Analogously to the *SA*’s child state finality verification logic, this is the logic to verify that a state/*tx* is final in the parent subnet, using a PoF submitted as transaction(s) to the child subnet by the IPC agent(s).
 - *Inter-subnet transactions service* (denoted POST-OFFICE). The *GWA* contains a registry of subnets and a functionality that can be used to transfer data from one subnet to another. The POST-OFFICE specifies the methods and the state locations that are used for these services. This functionality is required for the communication of two smart contracts across subnets⁵, i.e., a smart contract emitting an event that contains data to be processed by the replicated state machine logic of a different subnet.

We now define minimal interfaces between the different modules that enable the correct operation of an Interplanetary Consensus system. A guiding principle in the interface design is to minimize changes to the SMR codebase; therefore, most extra logic of the IPC will be added into the IPC agent and the smart contracts *SA* and *GWA*. Doing so should facilitate the

⁵When inter-subnet data transfer happens between users (Externally Owned Accounts — *EOA*— in Ethereum’s jargon), they can actively participate in the propagation by submitting transactions to the parent and child subnets. Smart contracts, on the other hand, do not have that power and, therefore, cannot communicate inter-subnets as efficiently as users (*EOA*) and must do so through IPC agents.

deployment of IPC with new SMR protocols by not requiring a developer familiar with IPC to be an expert on SMR: some understanding is still needed to optimize the agent’s implementation, but the SMR code would remain portable.

We require four interfaces: (i) IPC agent — parent SMR, (ii) IPC agent — child SMR, (iii) parent SMR— *SA*, and (iv) any SMR— *GWA*. Both (i) and (ii) can comprise of only:

1. Agent submits a transaction tx to the SMR process.⁶
2. Agent queries the state of the SMR process. The SMR process returns its current state (possibly limited to only a requested part of the state).
3. SMR process notifies the agent on events of interest (e.g., changes to the state of *SA*).

The interface between an SMR and *SA* or *GWA* is based on the execution engine of that SMR and the functionality desired by *SA*. The specifics of the execution engine’s system calls depend on implementation. Whenever such a call is not clear from context we provide a description of what it entails.

Figure 1 illustrates the components and their interfaces.

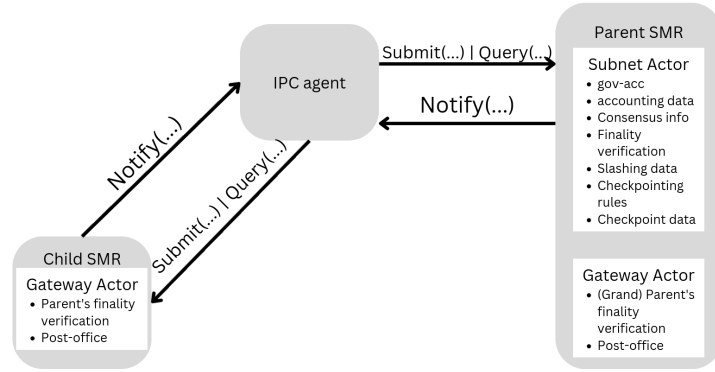


Figure 1: The basic components and their interfaces.

4 IPC functionality

We list in this section the functionality that should be provided by the IPC components. We first list the minimal functionality required for every

⁶As part of the notification defined below, it could be that after submitting tx , until the SMR process returns *complete* (perhaps with a finality parameter) or *declined*, tx is considered *pending*.

subnet (deposits and withdrawals), to then extend it with enhanced functionalities. We model components as processes that produce and consume events. Events consumed by the IPC agent are the result of either a notification from one of the SMRs or the response of a query made by the IPC agent. Events produced by the IPC agent result in the IPC agent submitting a transaction that will change the state of the SMR that consumes the event.

We note that our focus is on the core functionalities, disregarding optimizations for the moment. Batching is a prime example of this. It is expected that batching will be a key optimization whenever *verifyGlobalFinality*(tx, PoF) is used, as calling *verifyGlobalFinality*(tx, PoF) can be costly. Batching allows us to perform multiple operations for one *verifyGlobalFinality*(tx, PoF) call, reducing its overall cost.

4.1 Minimal Functionality

We show in this section the functionalities for deposits and withdrawals.

4.1.1 Deposits

[**arp**: Consider need to pause/remedy subnet after deposit (e.g. collateral not enough with new supply). IPC agent should check in that case]

A deposit is a transfer of funds (of some amount amt) from user u_P 's wallet in the parent subnet to user u_C 's wallet in the child subnet. We assume that u_P is a participant running a parent replica, a child replica, and an IPC agent.⁷ The deposit is performed by the user controlling the IPC agent as follows:

1. The local IPC agent submits to the parent SMR replica the corresponding (properly signed) transaction $tx = Deposit(src, amt, SA.accounts.dest)$ with $src = u_P$ and $dest = u_C$.
2. The parent SMR system orders and executes the Deposit transaction (provided u_P has enough funds) by transferring amt from u_P 's parent account to the SA (concretely, to u_P 's account representation within the SA). This effectively locks the funds within the SA smart contract, until the SA smart contract transfers it back to u_P 's account during withdrawal (see Section 4.1.2).
3. When the parent's replicated state that includes the transaction becomes final (for some SMR-system-specific definition of finality), the

⁷If u_P does not run these processes, u_P contacts a trusted participant that does and that performs the deposit on u_P 's behalf.

local parent replica notifies the local IPC agent, potentially attaching a proof of finality of $PoF(tx)$ to the notification.⁸

4. The IPC agent constructs a transaction $tx' = Deposited(\langle src, amt, SA.accounts.dest \rangle, PoF)$ and submits it to the child SMR system.
5. Upon ordering tx' , the replicated logic of the child SMR system mints amt new coins and adds them to u_C 's account.

We show in Figure 2 the events being produced and consumed by the deposit functionality and in Algorithm 3 the pseudocode per component to implement the functionality.

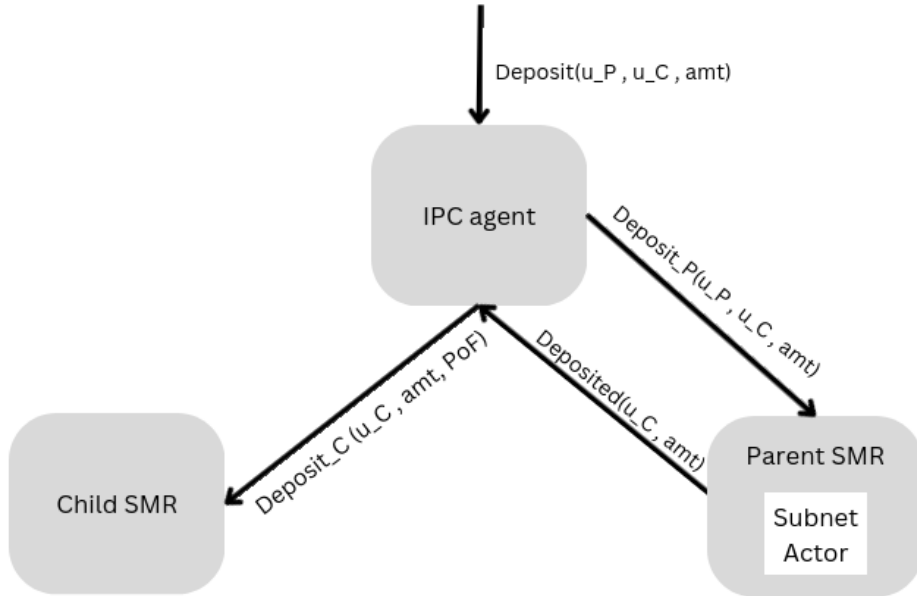


Figure 2: Events produced and consumed during a deposit.

⁸The exact content of $PoF(tx)$ depends on the implementations of the SMR systems. It might contain, for example, a quorum of replica signatures, a Merkle proof of inclusion, or even be empty.

Algorithm 3: Deposit operation

input: *src* account in parent, *dest* account in child, amount *amt*

```
1 ▶ IPC agent:
2   └─ submit  $tx = Deposit(src, amt, SA.accounts.dest)$  to parent SMR replica
3 ▶ Parent SMR replica:
4   └─ upon  $tx$  do
5       └─ move amt from src to SA.accounts.dest           // "lock" at parent
6       └─ notify agent ParentDeposited( $tx$ )
7 ▶ IPC agent:
8   └─ upon notification of ParentDeposited( $tx$ ) from parent SMR do
9       └─ create PoF that  $tx$  is final at parent SMR           // see Sec. ? for
10          └─ details
11          └─ submit Deposited =  $\langle tx, PoF \rangle$  to child SMR
12 ▶ Child SMR replica:
13   └─ upon Deposited do
14       └─ assert PoF for  $tx$ 
15       └─ increase dest account by amt
```

One thing that differs a downward transaction (e.g., deposit) from an upward transaction (e.g., checkpoint) is that any participant that operates the child SMR replica also has visibility into the state of the parent SMR (albeit stale) through its local parent SMR replica. This enables the **local validity check** method to assert the finality at the parent (which may or may not be preferred over others).⁹

4.1.2 Withdrawals

A withdrawal is a transfer of funds from user u_C 's wallet in the child subnet to some user u_P 's wallet in the parent subnet. We assume that u_C is a participant running a parent replica, a child replica and an IPC agent. The withdraw is performed as follows:

1. u_C triggers the $Withdraw(u_C, u_P, amt)$ event at the local IPC agent.
2. The local IPC agent submits the corresponding (properly signed) transaction $tx = Withdraw_C(u_C, u_P, amt)$ to the child SMR system.
3. The child SMR system orders and executes the Withdraw transaction, burning *amt* funds in u_C 's account (provided u_C has enough funds).

⁹**local validity check** (simpler, efficient, *weaker guarantees*): *PoF* contains a pointer to the block containing tx at the parent, together with the height h of that block. To assert that tx is final, the child queries the parent about TX , if it exists – return valid, else – return invalid. If invalid but the parent is still below height h , then query again when parent reaches height h . This is a test inside the child SMR process. Therefore, if we want this method (and I believe we do), we should widen the interface so that a child SMR can ask the agent to get data from the parent. However, this optimization comes at the expense of the encapsulation of components, that is, it entails tinkering with the child SMR code.

4. When the child's replicated state that includes the transaction becomes final (for some SMR-system-specific definition of finality that has been defined in the SA), the local child replica notifies the local IPC agent, potentially attaching a proof PoF that this state is final.
5. The IPC agent constructs a transaction $tx' = Burned(u_P, amt, PoF)$ and submits it to the parent SMR system.
6. Upon ordering tx' , the replicated logic of the parent SMR system updates the state of the SA transferring the funds from SA (concretely, to u_P 's account representation within the SA) to u_P 's account.

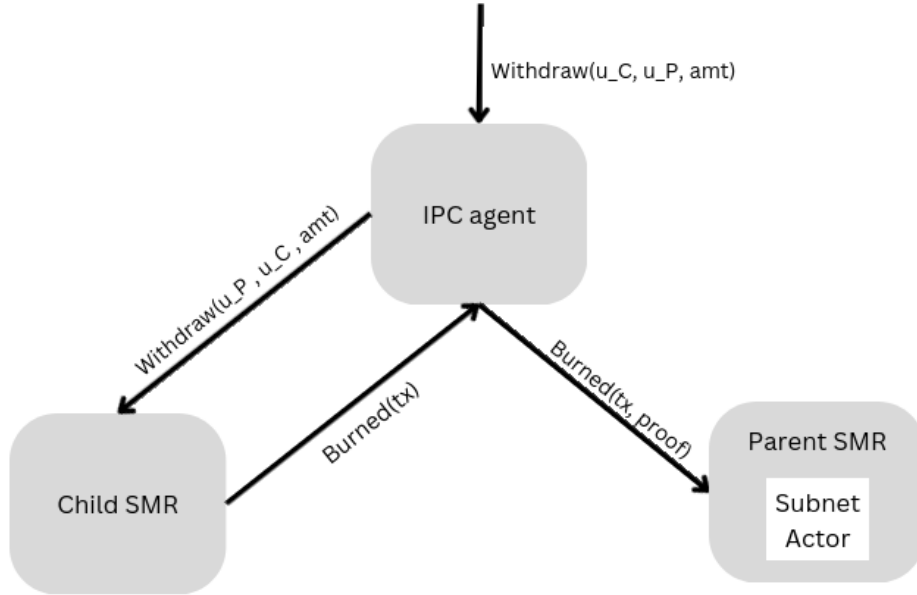


Figure 3: Events produced and consumed during a withdrawal.

Algorithm 4: Withdraw operation

input: *src* account in child, *dest* account in parent, *amt* amount of coins

```
1 ▶ IPC agent:
2   └ submit  $tx = \text{Withdraw}(src, amt, dest)$  to child SMR
3 ▶ Child SMR replica:
4   └ upon  $tx = \text{Withdraw}(src, amt, dest)$  do
5     └ deduct amt from src account at child // “burns” amt in child
6     └ notify agent Burned(tx)
7 ▶ IPC agent:
8   └ upon notification of Burned(tx) from child SMR replica do
9     └ create PoF that tx is final at child SMR // see Sec. ? for details
10    └ submit  $tx' = \text{Burned}(tx, PoF)$  to parent SMR replica
11 ▶ parent SMR replica:
12   └ upon  $tx' = \text{Burned}(tx, PoF)$  do
13     └ assert SA.verifyGlobalFinality(PoF, tx)
14     └ move amt coins from SA.accounts[src] to dest
```

4.2 Enhanced Functionality

[arp: From here below we need to add the gateway actor and refine the functionality, leave out till round of feedback for GW] We show here a list of desirable functionalities that build upon the basic withdrawals and deposits.

4.2.1 Checkpointing

A checkpoint contains a representation of the updated state of the child SMR system to be included in the parent SMR system. A checkpoint can be triggered by predefined events (i.e. periodically after a number of state updates, triggered by a specific user or set of users, etc.). As such, the checkpoint functionality may or may not be triggered by a user request on the child SMR. A checkpoint is performed as follows:

1. If the predefined checkpoint trigger is met, then the IPC agent queries the child SMR replica for the updated state to be represented in this checkpoint.
2. The IPC agent creates a proof *PoF* that this updated state of the child SMR system is final, possibly compressing its representation of the state.
3. The IPC agent submits a transaction $tx' = \text{Checkpoint}(state, PoF)$ to the parent SMR replica
4. Upon ordering tx' , the replicated logic of the parent SMR system updates the state of the SA according to the checkpoint state, if necessary.

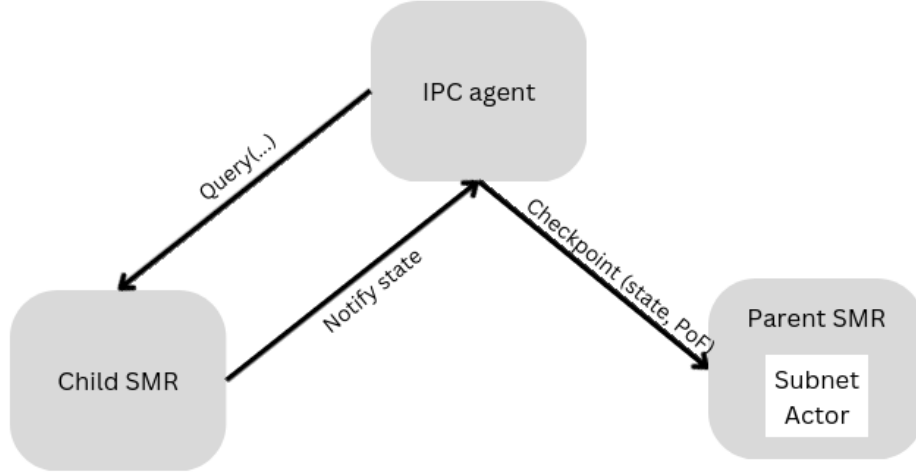


Figure 4: Events produced and consumed by the checkpointing functionality.

Algorithm 5: Checkpoint operation

```

1 ▶ IPC agent:
2   if trigger for checkpoint then
3      $state \leftarrow$  query the child SMR replica for the state
4     create PoF that state is final at child // Possibly compress state
5     submit  $tx' = \text{Checkpoint}(state, PoF)$  to parent SMR replica
6 ▶ parent SMR replica:
7   upon  $tx' = \text{Checkpoint}(state, PoF)$  do
8     assert  $SA.verifyGlobalFinality(PoF, state)$ 
9      $SA.latestCheckpoint \leftarrow state$ 

```

4.2.2 Slashing

[**gg:** This section is immature for review (even a preliminary one)]

We show here the events produced and consumed by the slashing functionality. Given specific misbehavior from participants that is identified as Proofs of Fraud (PoFs), e.g. gathering signed equivocating messages, the child SMR reports the PoFs to the IPC agent, which immediately forwards a slash a request to the parent SMR. [**arp:** Extend with need to verify if child SMR can continue, needs to remedy its depleted collateral or should be killed with latest checkpoint/state update].

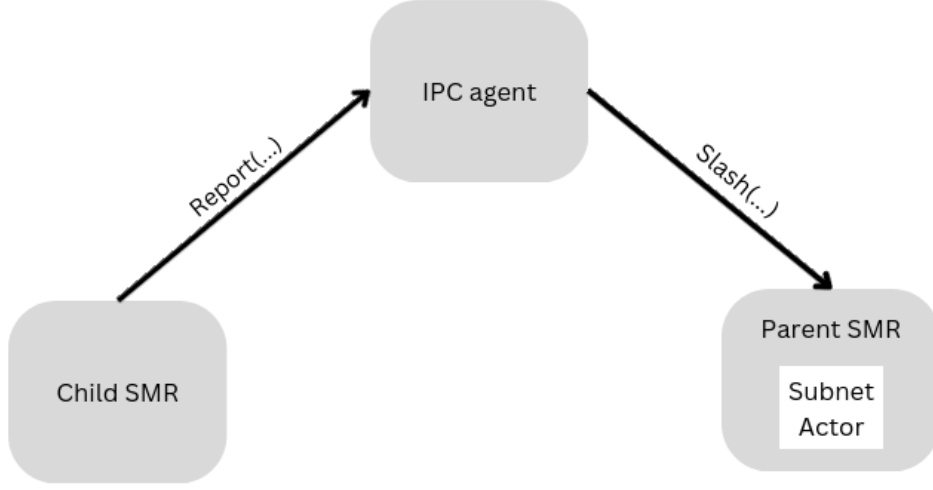


Figure 5: Events produced and consumed by the slashing functionality.

Algorithm 6: Slash Functionality

```

input: -
1 ▶ Child SMR:
2   upon Proofs of fraud pofs generated do
3     [ Notify  $\langle \text{report}, \text{pofs} \rangle$  to IPC agent ]
4 ▶ IPC agent:
5   upon  $\langle \text{report}, \text{pofs} \rangle$  notified by child SMR do
6     [ Submit  $\langle \text{slash}, \text{pofs} \rangle$  to parent SMR ]
7   upon [arp: State updated after slashing] do
8     [ arp: Check child SMR rules are still satisfied, remedy/close otherwise? ]
9 ▶ Parent SMR:
10  upon  $\langle \text{slash}, \text{pofs} \rangle$  submitted by IPC agent do
11    [ Update SA state slashing/excluding participants ]
    [ Notify SA update to IPC agent ]

```

4.2.3 post-office

The POST-OFFICE functionality is an inter-subnet transaction service. The main motivation for this functionality comes from a “potential clients” request: enable a smart contract in one subnet to interact with a smart contract in a different subnet.

[**gg:** Edge case: a leaf subnet does not have a *SA* and, therefore, no POST-OFFICE. We can consider removing the POST-OFFICE functionality from the *SA* and to deploy it as an independent smart contract that will appear only once per subnet. In this case, it needs permissions to call *SA.verifyGlobalFinality(tx,PoF)* function.]

Algorithm 7: POST-OFFICE Functionality

```
input:  $tx = \langle data, src, dest, PoF \rangle$ 
1  ► SA.POST-OFFICE:
2  │ upon POST-OFFICE.propagate( $tx$ ) do
3  │ │ case dest in current subnet do
4  │ │ │ POST-OFFICE.propagateHERE( $tx$ )
5  │ │ case dest requires going up the tree do
6  │ │ │ POST-OFFICE.propagateUP( $tx$ )
7  │ │ case dest requires going down the tree do
8  │ │ │ POST-OFFICE.propagateDOWN( $tx$ )
9  │ upon POST-OFFICE.propagateUP( $tx$ ) do
10 │ │ if src not from this subnet then
11 │ │ │ assert(SA.verifyGlobalFinality( $tx, PoF$ ))
12 │ │ src.append(SA's subnet id)
13 │ │ emit event POST-OFFICE.UP( $\langle data, src, dest \rangle$ )
    │ // propagateDOWN(tx) is analogous to propagateUP(tx)
    │ // propagateHERE(tx) is trivial
14 ► parent SMR process:
15 │ upon event POST-OFFICE.UP( $\langle data, src, dest \rangle$ ) do
16 │ │  $tx \leftarrow \langle data, src, dest \rangle$ 
17 │ │ notify agent on POST-OFFICE.UP( $tx$ )
18 ► IPC agent:
19 │ upon notification of propagateUP(tx) from child SMR do
20 │ │ create PoF that UP(tx) is final at child SMR
21 │ │  $tx_{new} \leftarrow \langle UP(tx), PoF \rangle$ 
22 │ │ submit SA.POST-OFFICE.propagate( $tx_{new}$ ) to parent SMR
```

4.2.4 Atomic Execution

TODO Discuss in Lanzarote?

4.3 Future

5 An Instance of IPC

Here we describe the particular choices implemented by the Consensus Lab team.

The current implementation considers Filecoin as the root subnet[[gg: I wrote it but I'm not sure this is the case...](#)], and Trantor as child subnets. For our interest it is important to note that Trantor is a BFT consensus protocol with immediate finality, and Filecoin is a longest chain style protocol with probabilistic finality. Therefore, as a *PoF* that a child subnet finalized a state we use a multisig on that state, the multisig must correspond to more than 2/3 of the child's validators voting rights as reflected by *SA* at the

time.¹⁰ To verify the finality of a state at the parent, we use the fact that a participant has view in to a version of the parent blockchain (through its local parent replica process). In this case, *PoF* contains the block height h (and pointer to that block) at the parent subnet. A child replica then asserts with its parent that the state is final by checking with its local version of the parent blockchain at height h . If the the local version at the parent replica did not reach height h yet, the child replica considers the state non-final/non-valid currently and checks again when the parent reaches height h .

6 Verifying the Finality of tx

A main ingredient in any Interplanetary Consensus implementation is the creation and verification of a finality proof for a given tx in some subnet. In the previous sections we left these functions opaque. For example, *SA.verifyGlobalFinality(tx, PoF)* was used by the parent replica to verify the finality at the child subnet of tx . The creation of *PoF* and the verification method at the child replica (for transactions of that occur at the parent subnet), are only hinted by plain text. There are multiple ways to implement these functionalities, each with its own trade-offs. Below we propose several such implementations.

References

- [1] IPC Glossary. <https://docs.google.com/document/d/15pA7ahjeA-HY0l8Pxj0n6PxEsWYlRVrZ112MJuRR0fY/edit?usp=sharing>.

¹⁰A next step in the implementation road-map is to offer a threshold signature mechanism instead of using a multisig. For now, multisigs serve the purpose of an MVP implementation.