Department of Computer Science

A Secure and Verifiable P2P Storage System with Encrypted Search using Blockchain

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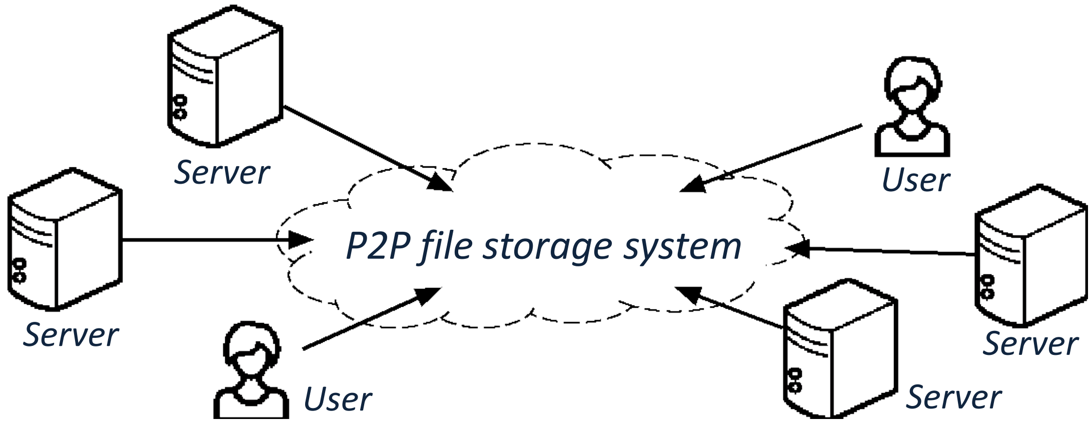
For The World

New demand for P2P storage systems

- **Explosive growth of digital data**
  - fuelled up by e-health, e-commerce, smart cities, IoT, …
- **Mismatch between supply and demand of data storage**
  - a vast amount of under-used storages scattered all over the world
  - high demand from users looking for storage space
- **P2P storage system:**
  - utilize the unused storage space to form a huge global storage system



"centralized proprietary services are being replaced with decentralized open ones;
trusted parties replaced with verifiable computation;
inefficient monolithic services replaced with P2P algorithmic markets."

--- filecoin white paper. 2017.

Failures of traditional P2P file systems

- **Traditional P2P systems, such as BitTorrent or Gnutella, are notorious for their unfairness and lack of security**
  - people are hesitated to contribute their storage resources to or to store their data in the P2P systems
- **No enforced contribution/incentive mechanism**
  - there is no motivation to share services or resources
  - leads to the “free-rider” or the “leecher” problems
- **No enforced security and privacy protection**
  - traditional P2P systems do not offer strong protection of data
  - data stored in the P2P systems are not encrypted by default

Secure P2P file systems

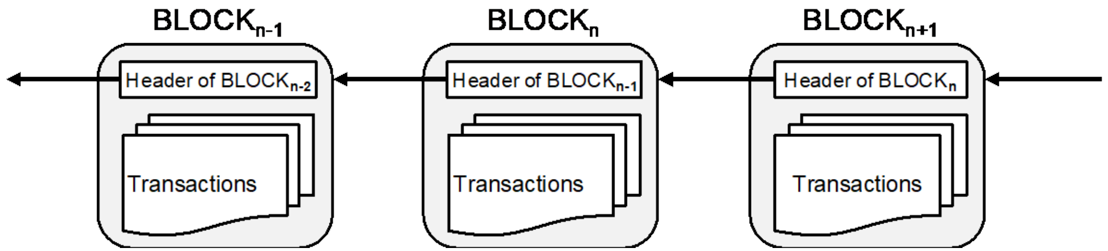
- **The advent of the blockchain brings a new P2P platform**
  - blockchain can enforce the fairness for providing resources/services and receiving respective payments, such as IPFS, Storj, Sia, etc.
- **Strong data protection in the untrusted P2P environment**
  - adopt end-to-end encryption of data, Storj and Sia
- **However, encryption makes search over encrypted data difficult**
  - files can only be accessed via their identifiers, such as in Storj

STORJ Sia Filecoin IPFS

Objective: design a blockchain-based P2P storage system with encrypted search capability

Blockchain technology and PoW

- **Blockchain: a distributed ledger (database) that records all the transactions occurred in the P2P network**
  - all participants in the network hold the same copy of the chain



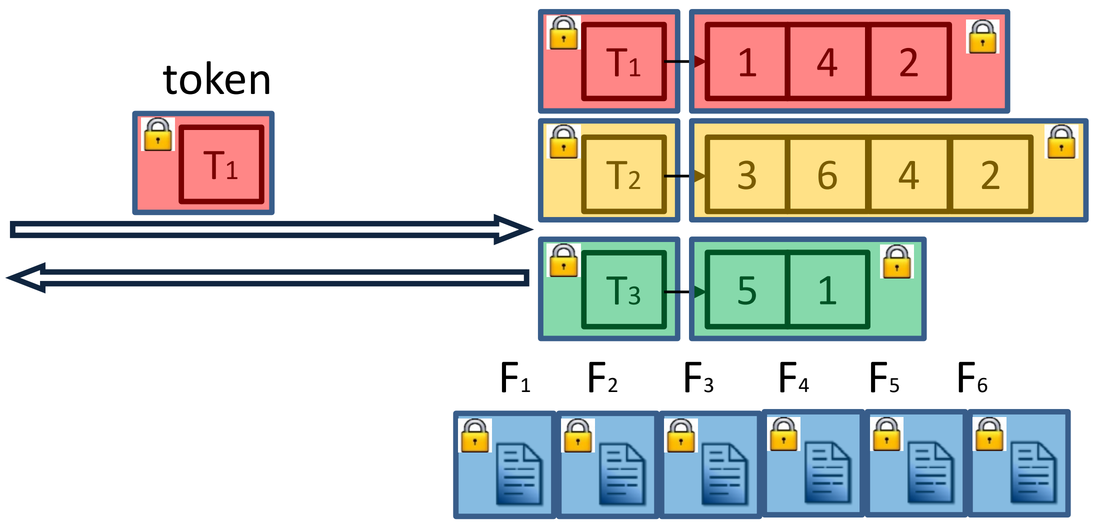
- **Proof-of-Work (PoW): a distributed consensus algorithm**
  - miners (blockchain peers) compete with each other to solve a cryptographic puzzle (Z) in order to generate a new block

$$\boxed{\text{SHA-256\^{}2}(Block_{prev} \,||\, Mr(Tx) \,||\, T \,||\, ticket) \overset{?}{<} Z}$$

- **PoW consumes massive computing resources with no useful value**
  - bitcoin’s annual carbon footprint is bigger than Switzerland’s

Searchable encryption

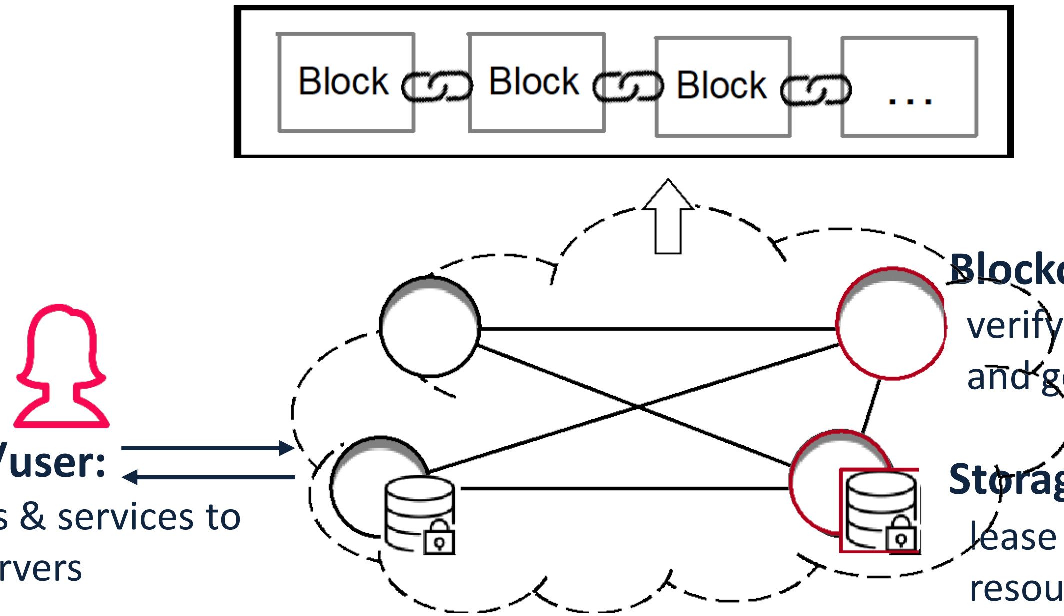
- **Searchable encryption: search encrypted files without decryption**
  - facilitates end-end encryption in client-server model
- **An example of searchable encryption**
  - data owner constructs an encrypted search index and store both the encrypted files and indexes to the server
  - user sends encrypted keyword (trapdoor) to the server to search
  - leaks no more information than search patterns



Challenges in the design of blockchain-based P2P storage systems

- **Support efficient search capability over encrypted files**
  - on-chain encrypted search and on-chain verification of search results
- **Enable file updates with forward-security**
  - efficient file update with strong security: forward-security
- **incorporate the data auditing into proof-of-work (PoW)**
  - make some useful value of PoW

Framework of a blockchain-based P2P storage system



Data owner/user: outsource files & services to the storage servers

Blockchain peers: verify the correctness of transactions and generate new blocks

Storage servers: lease out computing/storage resources to users

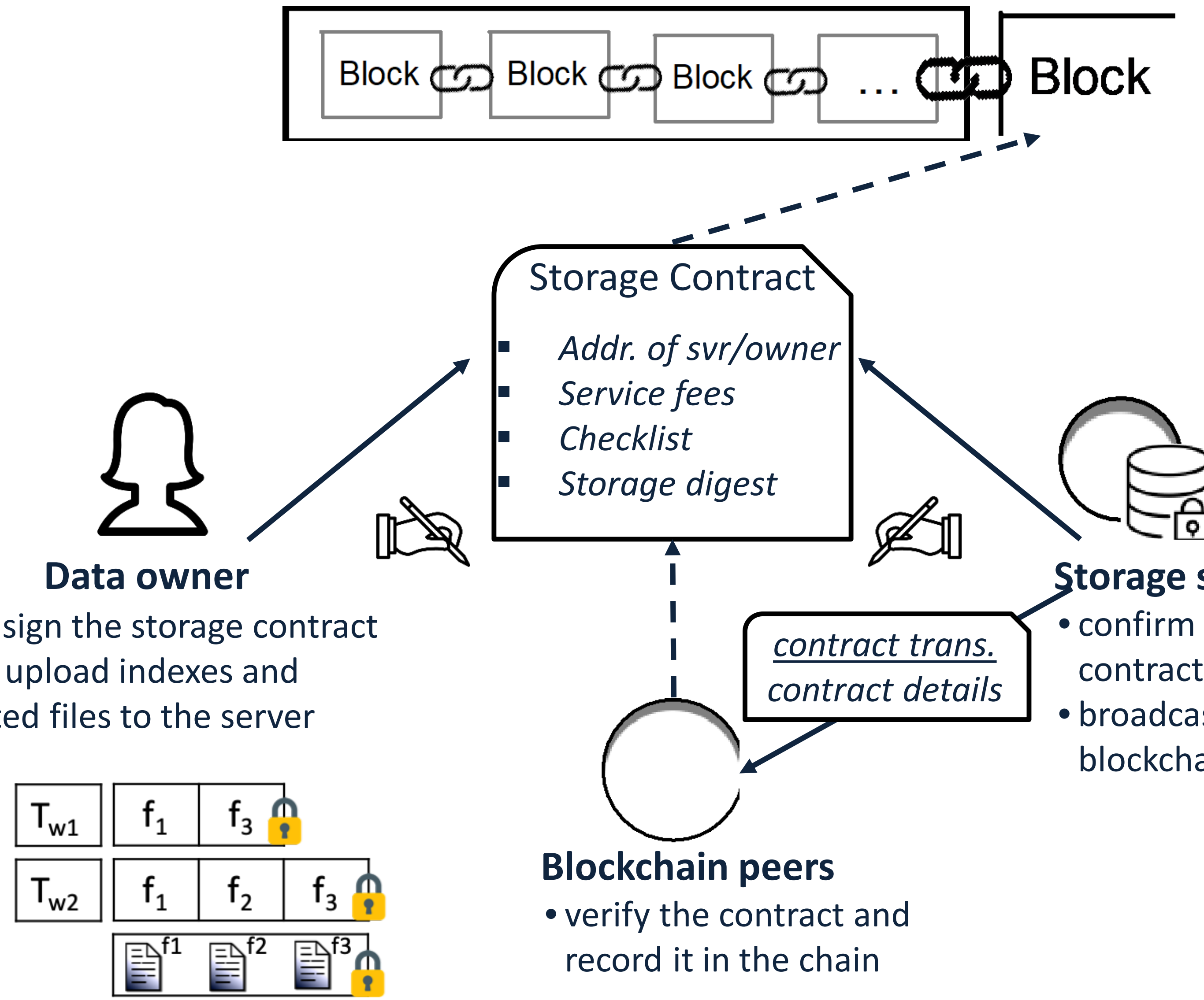
P2P storage network

A secure and fair platform for people to lease computing resources and for users to receive services

Framework of a blockchain-based P2P storage system (cont'd)

- **Blockchain P2P network consists of storage servers and peers**
  - storage servers can be peers
- **Data owners/users interact with storage servers via transactions**
  - data owners bind with servers via smart contracts
  - data and search indexes are stored off-chain at storage servers
  - all operations between owner/user and server are via transactions
    - contract transactions, data search/update transactions, etc
- **Peers verify correctness of transactions and generate new blocks to the blockchain**

Signing a storage contract



Data owner

- draft & sign the storage contract
- build & upload indexes and encrypted files to the server

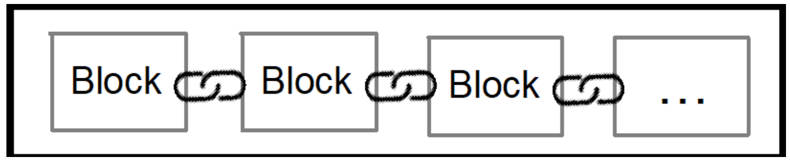
Storage server

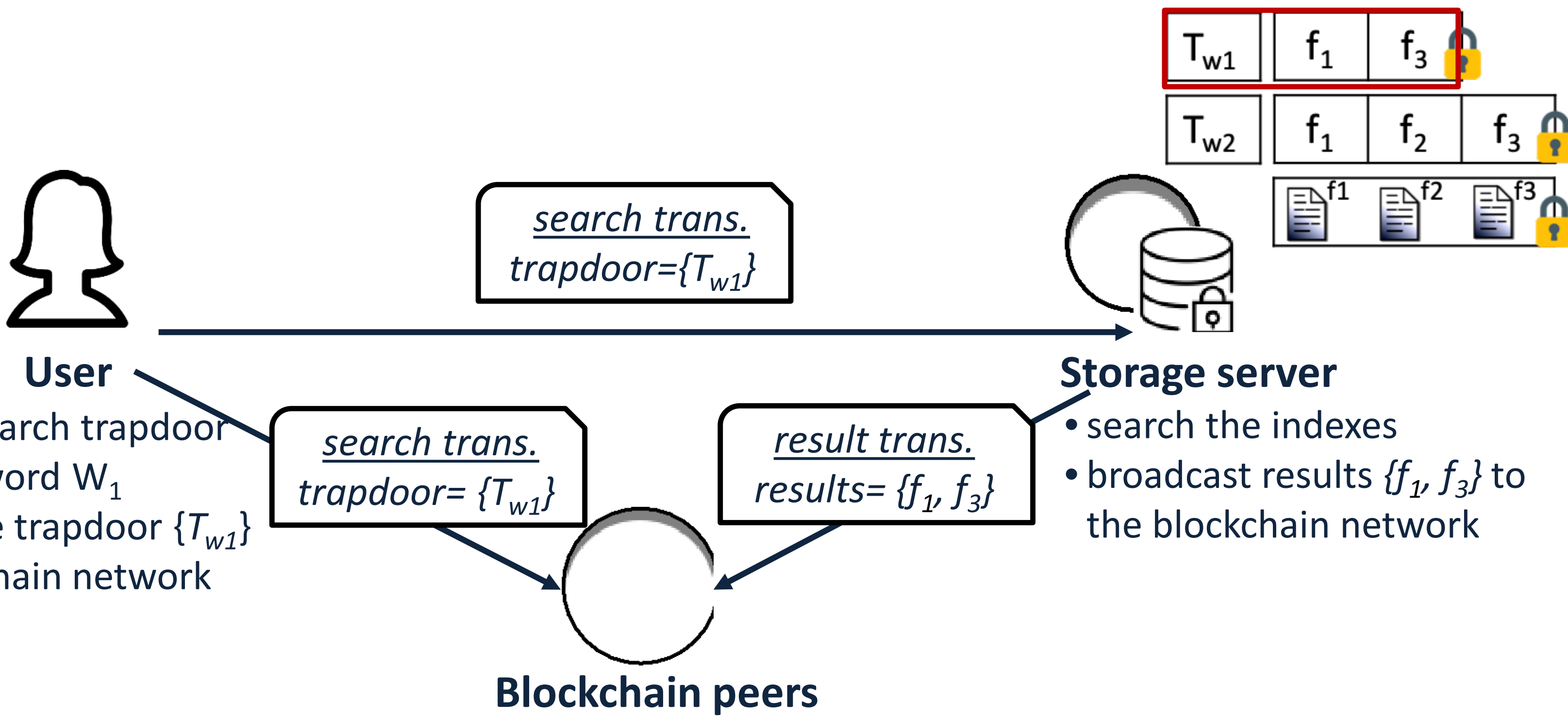
- confirm & sign the storage contract
- broadcast the contract to blockchain network

Blockchain peers

- verify the contract and record it in the chain

Search transaction





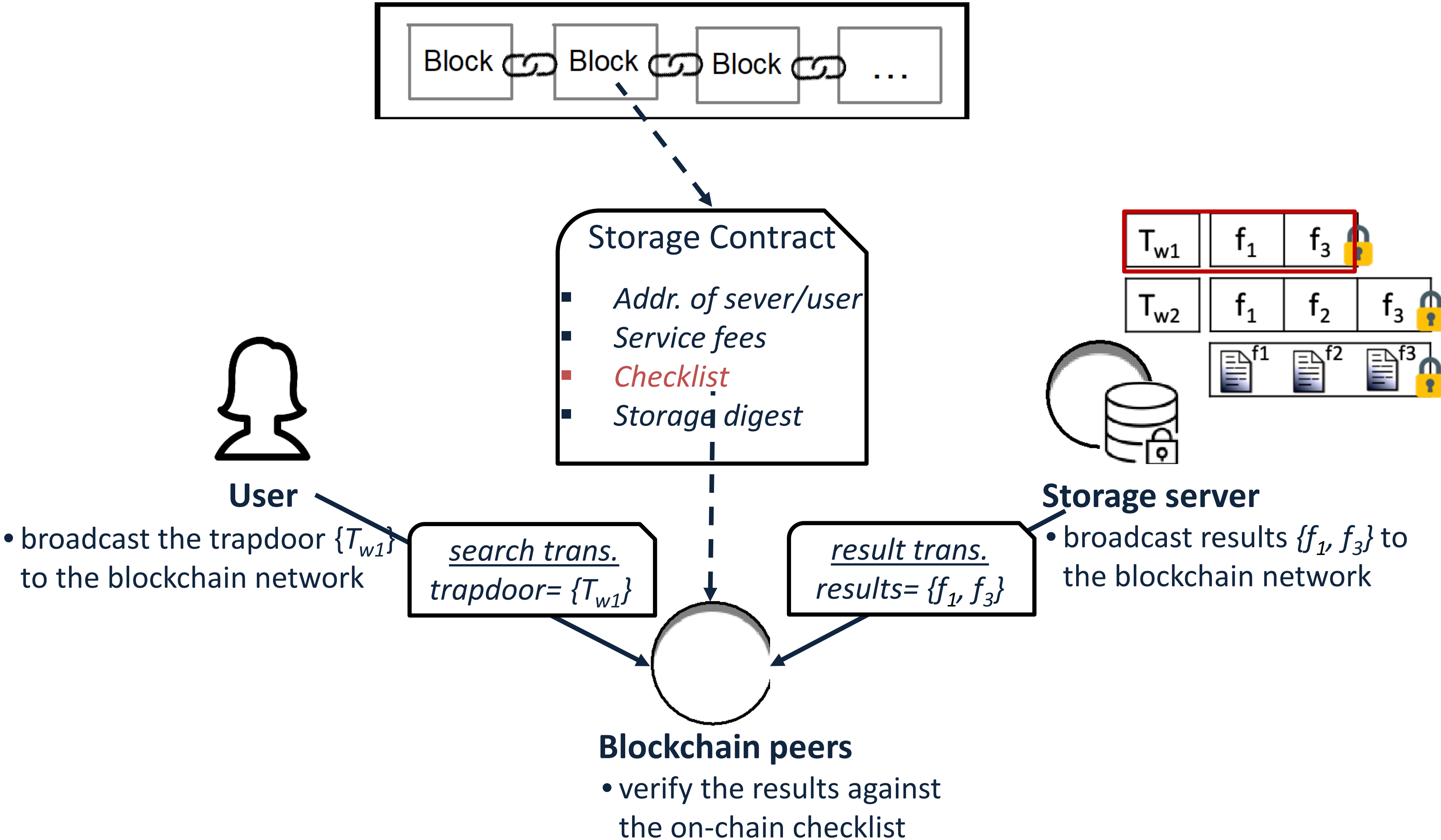
User

- generate a search trapdoor $\{T_{w1}\}$ for keyword W_1
- broadcast the trapdoor $\{T_{w1}\}$ to the blockchain network

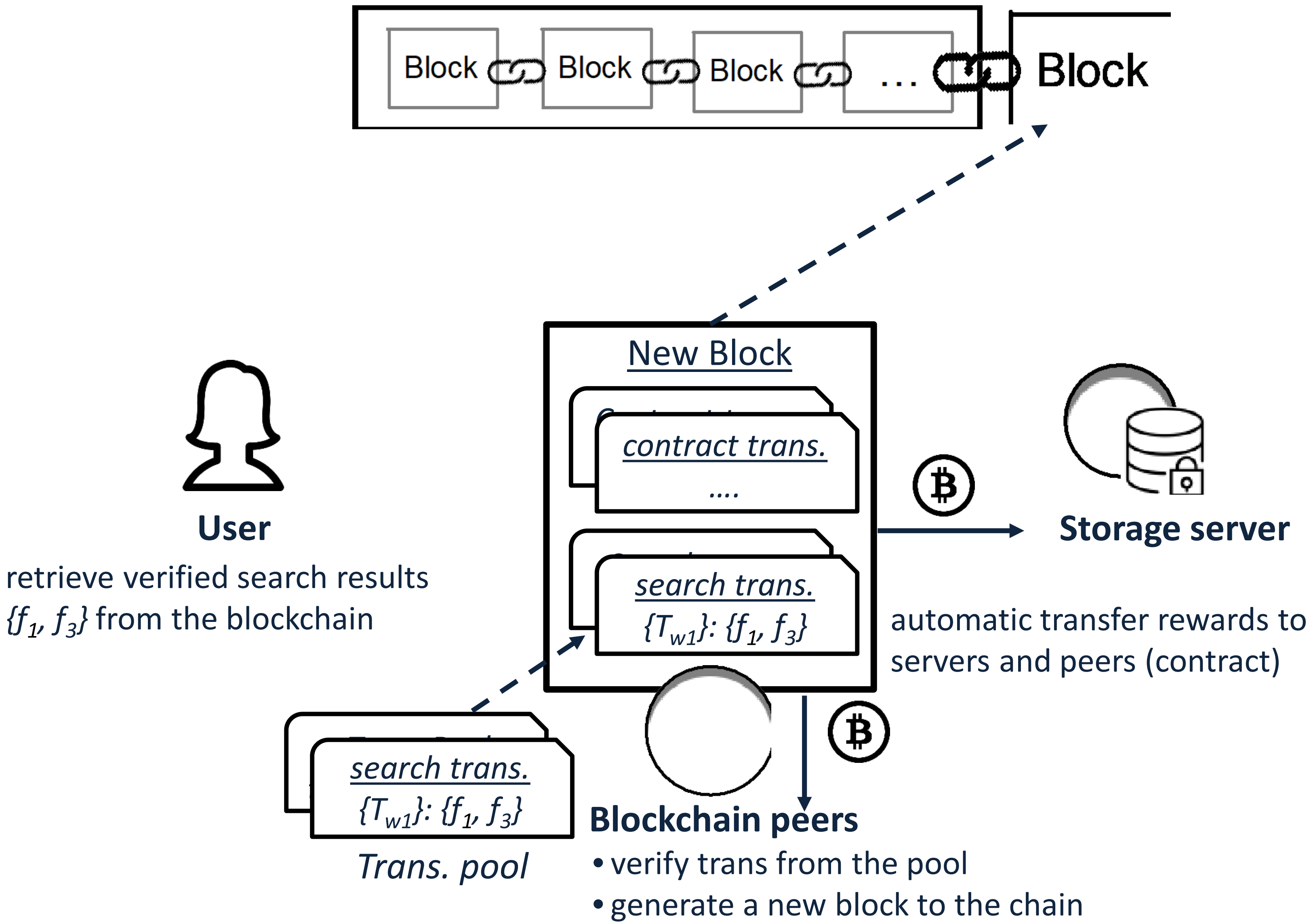
Storage server

- search the indexes
- broadcast results $\{f_1, f_3\}$ to the blockchain network

Search result verification



Generating new blocks to the blockchain



Key techniques

- **Efficient verification of search results on the blockchain**
  - design an efficient and secure on-chain checklist
- **Efficient file updates with forward security**
  - design a file index structure that can efficiently support both file update and search operations
- **Data integrity auditing: a useful proof-of-work (PoW)**
  - design a data auditing protocol that is incorporated into PoW

Verifying search results in P2P systems

- **Verification of correctness usually requires a third-party authority to make an unbiased judgement**
  - storage servers may not return a complete or accurate set of search results for saving computational cost or other reasons
  - vice versa, users may mis-accuse the honest servers in order to deny the payment
- **However, there is no central authority in the P2P network**
  - rely on peers to verify search results in the blockchain network

An efficient on-chain checklist

- **Store pre-defined search results on the blockchain for verification**
  - verification of search results can be done by any peers
- **Explore the incremental set hash technique to reduce the size of the checklist on blockchain**
  - incremental set hash can map multi-sets of arbitrary sizes to fixed length strings
  - generate one hash digest (4 bytes) for each pre-defined search result

kwd	checklist
w_1	f_1, f_3
w_2	f_1, f_2, f_3

Compressed checklist →

kwd	compressed checklist
$H(w_1)$	$H(f_1 \cup f_3)$
$H(w_2)$	$H(f_1 \cup f_2 \cup f_3)$

A secure on-chain checklist

- **However, simply using this on-chain checklist would leak result distribution, leading to inference attacks**

kwd	compressed checklist
$H(w_1)$	$H(f_1 \cup f_3)$
$H(w_2)$	$H(f_1 \cup f_2 \cup f_3)$
$H(w_3)$	$H(f_1 \cup f_2 \cup f_3)$

attacker's view
kt6gUXGWgL
TRxZDzVYjV
TRxZDzVYjV

Match them up

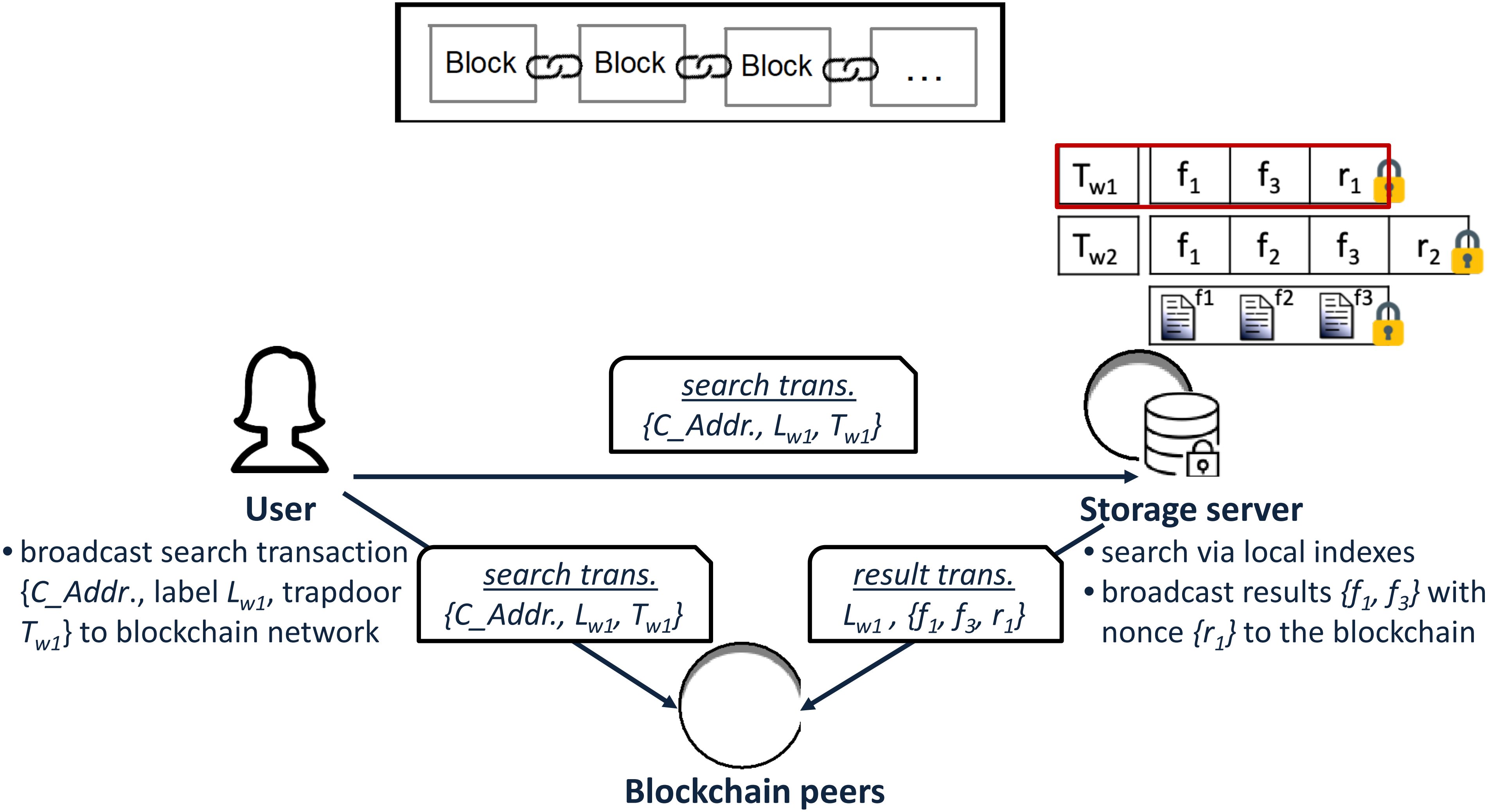
auxiliary info.	
f_1, f_3	w_1
f_1, f_2, f_3	w_2
f_1, f_2, f_3	w_3

- **Embed random masks (nonce r) into compressed checklist to hide the result distribution**

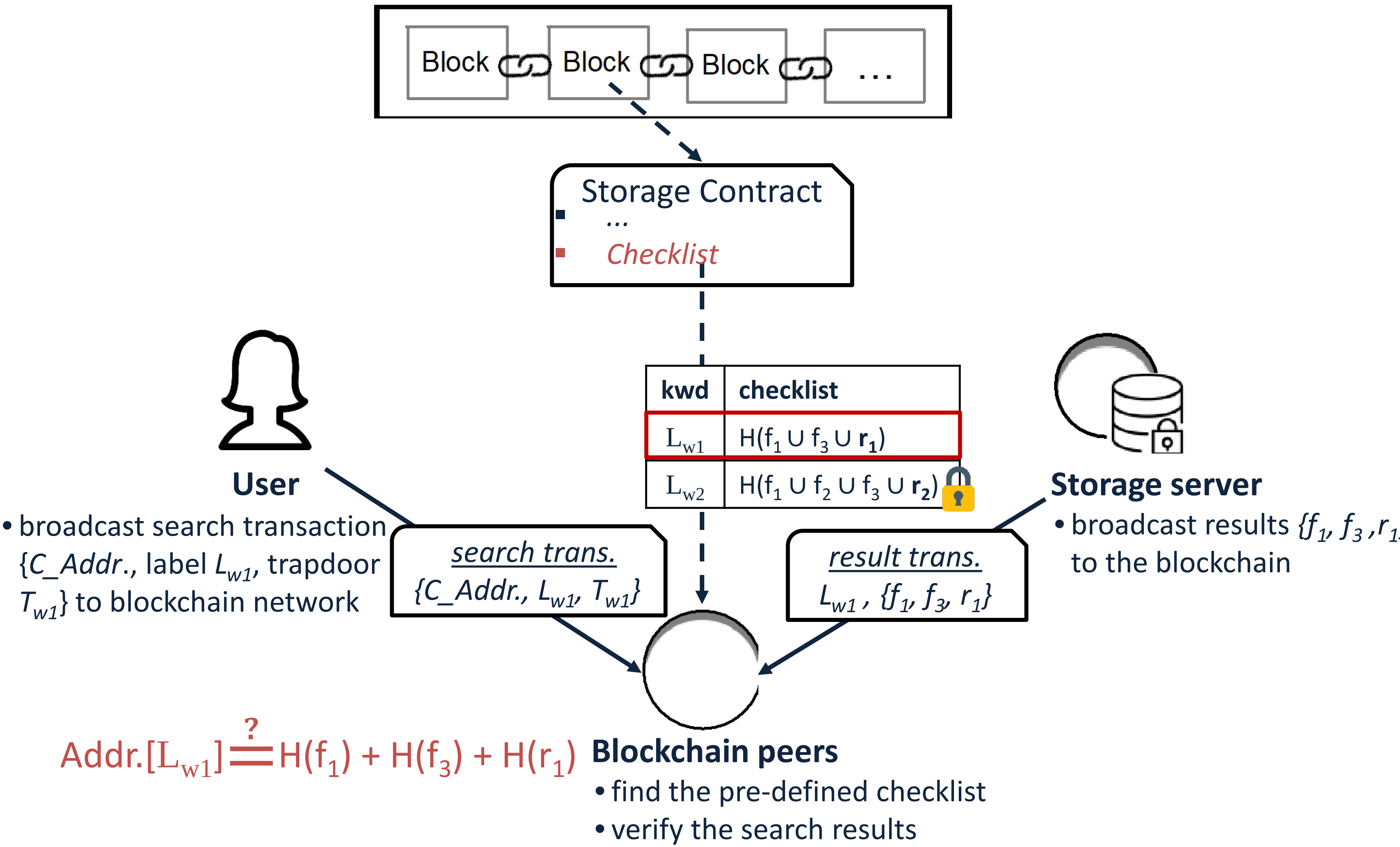
kwd	compressed checklist
$H(w_1)$	$H(f_1 \cup f_3 \cup \mathbf{r_1})$
$H(w_2)$	$H(f_1 \cup f_2 \cup f_3 \cup \mathbf{r_2})$
$H(w_3)$	$H(f_1 \cup f_2 \cup f_3 \cup \mathbf{r_3})$

attacker's view
XGkt7gUW8A
LKGM8EUnGd
IgDwwF64cl

Search transaction with result verification



Verifying search results with on-chain checklist



File updates in blockchain-based systems

- **Blockchain is “append-only” and the data stored on the chain cannot be modified**
  - store encrypted indexes off the chain
    - make the blockchain light-weighted
- **Two issues for file updates: efficiency and security**
  - the efficiency of search often conflicts with the efficiency of update in encrypted search
  - achieve forward-security for file updates

Index structures for encrypted search

secure index structures

Direct index (file index)	Inverted index (keyword index)

File IDs	**Keywords**
$H(f_1)$	$Enc(w_1)$; $Enc(w_2)$
$H(f_2)$	$Enc(w_2)$

- file-update time complexity: sub-linear
- kwd-search time complexity: linear

Keywords	**File IDs**
$H(w_1)$	$Enc(f_1)$
$H(w_2)$	$Enc(f_1)$; $Enc(f_2)$

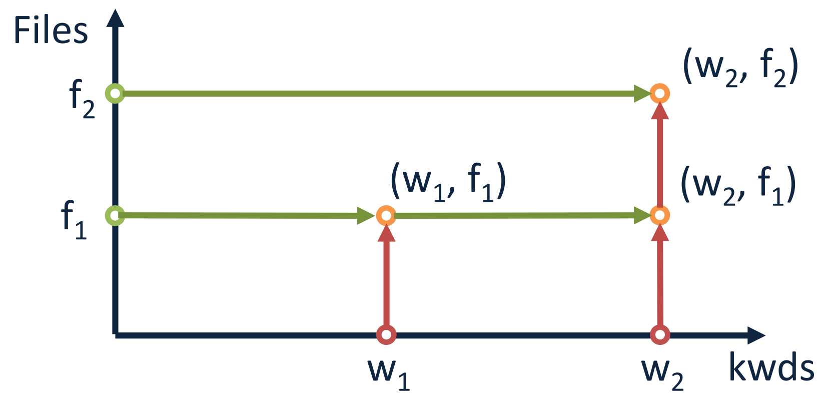
- kwd-search time complexity: sub-linear
- file-update time complexity: linear

How to design an index structure efficient for both search and update operations?

File indexes vs. keyword indexes

- **Relationship between file indexes & keyword indexes**

kwd	file IDs
w_1	f_1
w_2	f_1, f_2



- **To make both search and update efficient, we need**
  - keep both file and keyword indexes (dual indexes)
    - optimal search and update complexity: O(1)

Building encrypted dual indexes

- Extract each keyword-file pair (w, f) from the original data set
- Assign an index pointer (ptr) to each keyword-file pair

Original DB

Kwd	file IDs
w_1	f_1
w_2	f_1, f_2

Indexing pointer

KV pairs

ptr_1	w_1	f_1
ptr_2	w_2	f_1
ptr_3	w_2	f_2

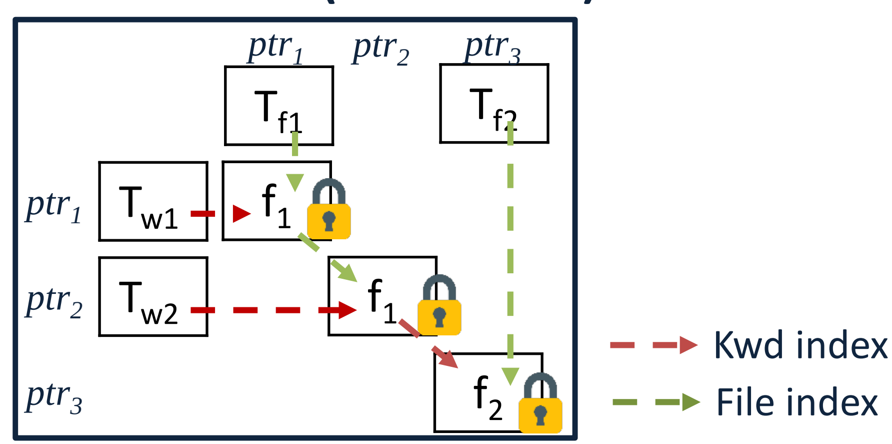
- Build the dual indexes (kwd index and file index) and store at the server-side
- Keep the local kwd and file states (pointers to the dual-index entries)

Local states (pointers)

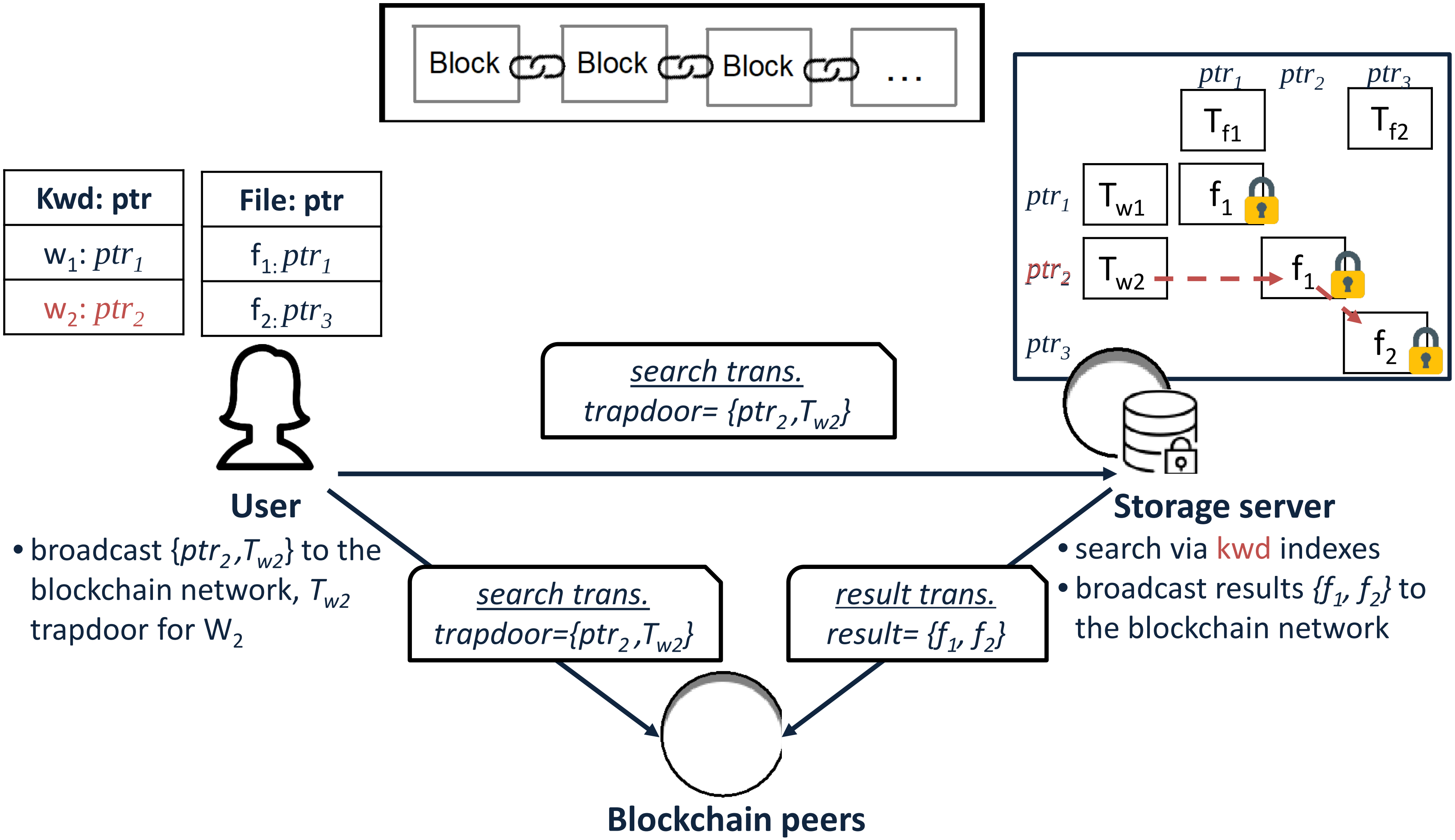
Kwd: ptr
w_1: ptr_1
w_2: ptr_2

File: ptr
$f_{1:}$ ptr_1
$f_{2:}$ ptr_3

Dual indexes (server-side)

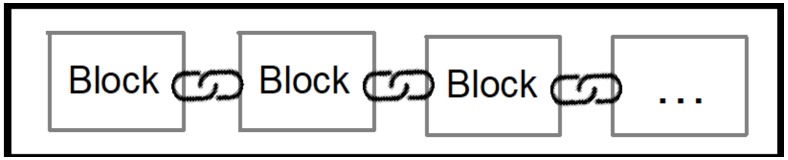


Search by using dual indexes



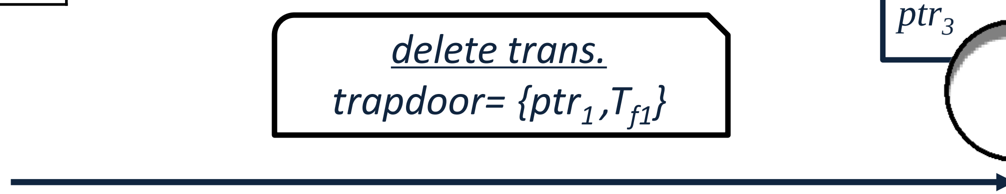
O(1) complexity for encrypted search

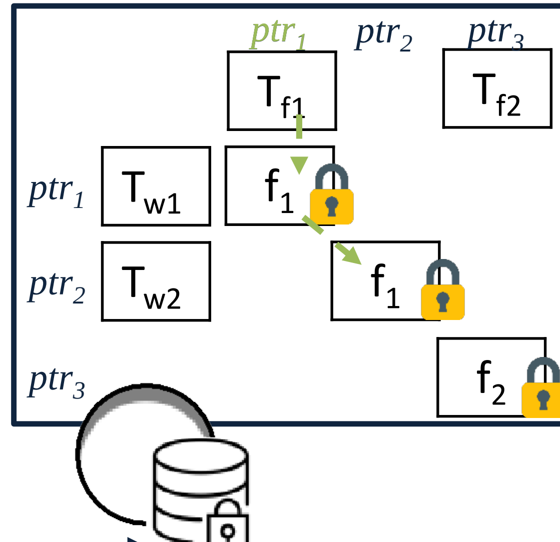
Deleting files from dual indexes



Kwd: ptr
w_1: ptr_1
w_2: ptr_2

File: ptr
f_1: ptr_1
f_2: ptr_3



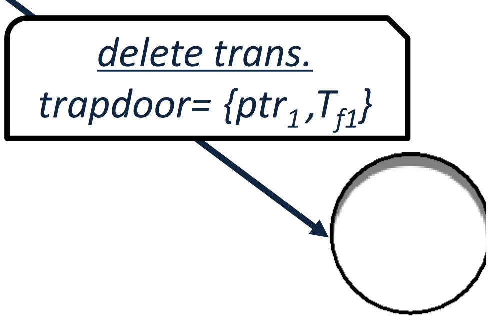


User

- generate a delete trapdoor {T_{f1}} for file f_1
- broadcast {ptr_1,T_{f1}} to the blockchain network

Storage server

- search via file indexes
- delete the file-pointers from indexes

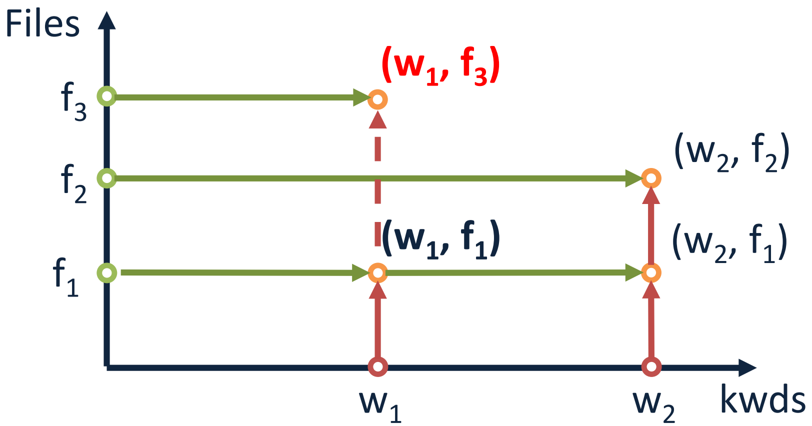


Blockchain peers

O(1) complexity for file delete

Forward security

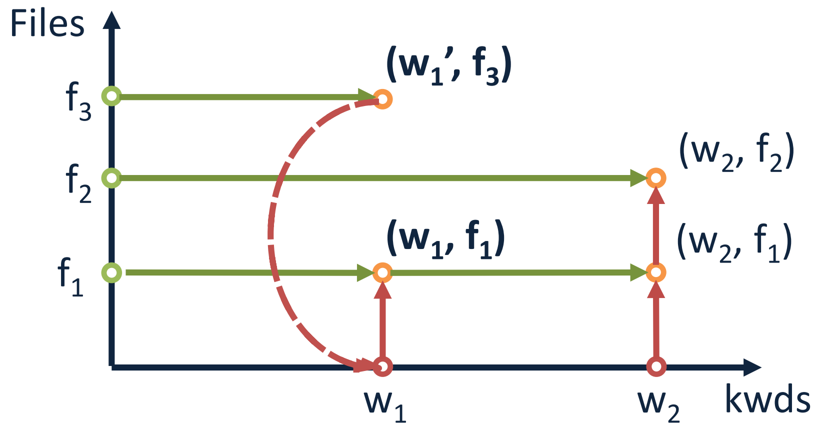
- **Forward-security** is a security property, requiring that the newly added files shall not have any link to the previous search results
- **Example:** Suppose to add the new file f_3 with pair (w_1, f_3), and w_1 was searched before, the server shall not learn that f_3 contains a previously searched kwd w_1

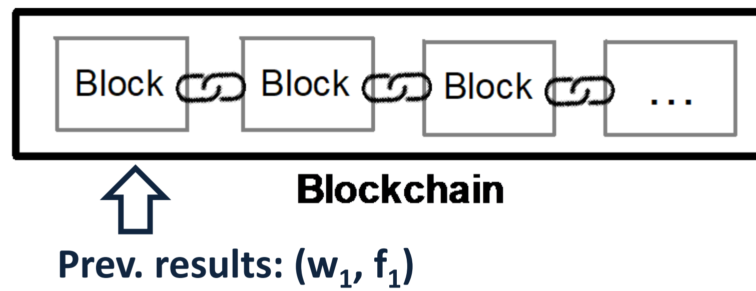


However, by directly adding new entry (w_1, f_3) to the indexes, it will reveal that f_1 and f_3 share the same kwd w_1!

Forward secure search in blockchain

- Only the keywords that are searched before may cause the forward-security problem: utilize prev. search results in the chain

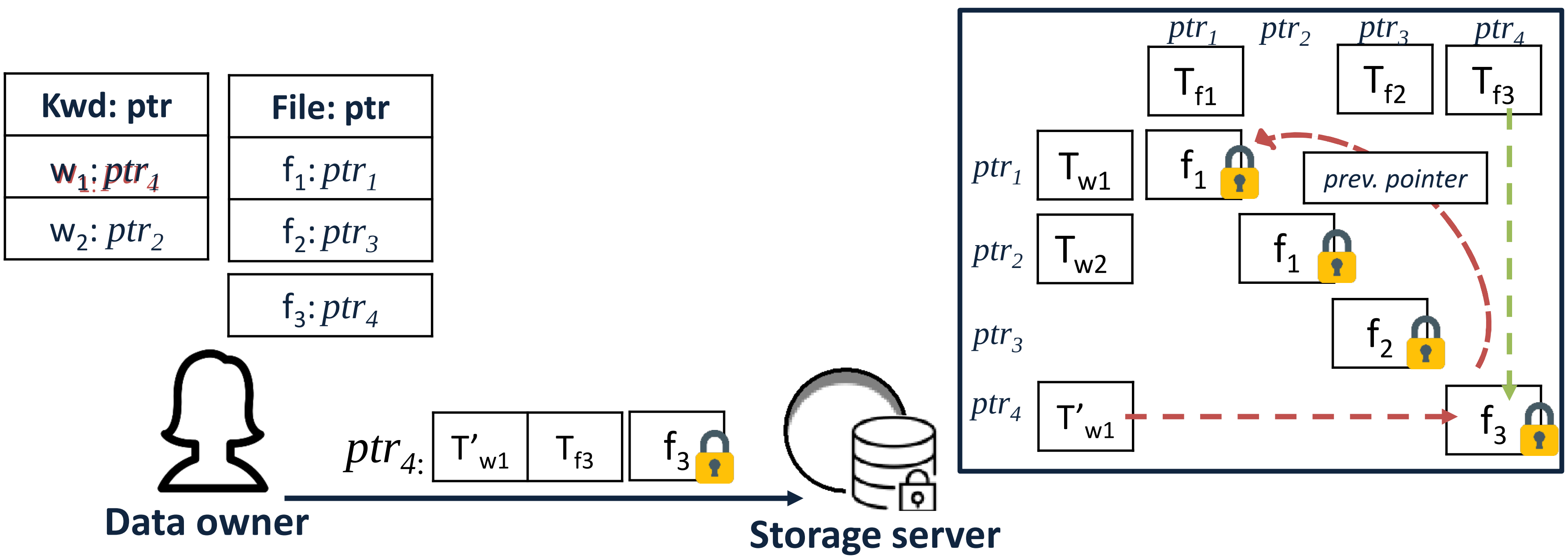




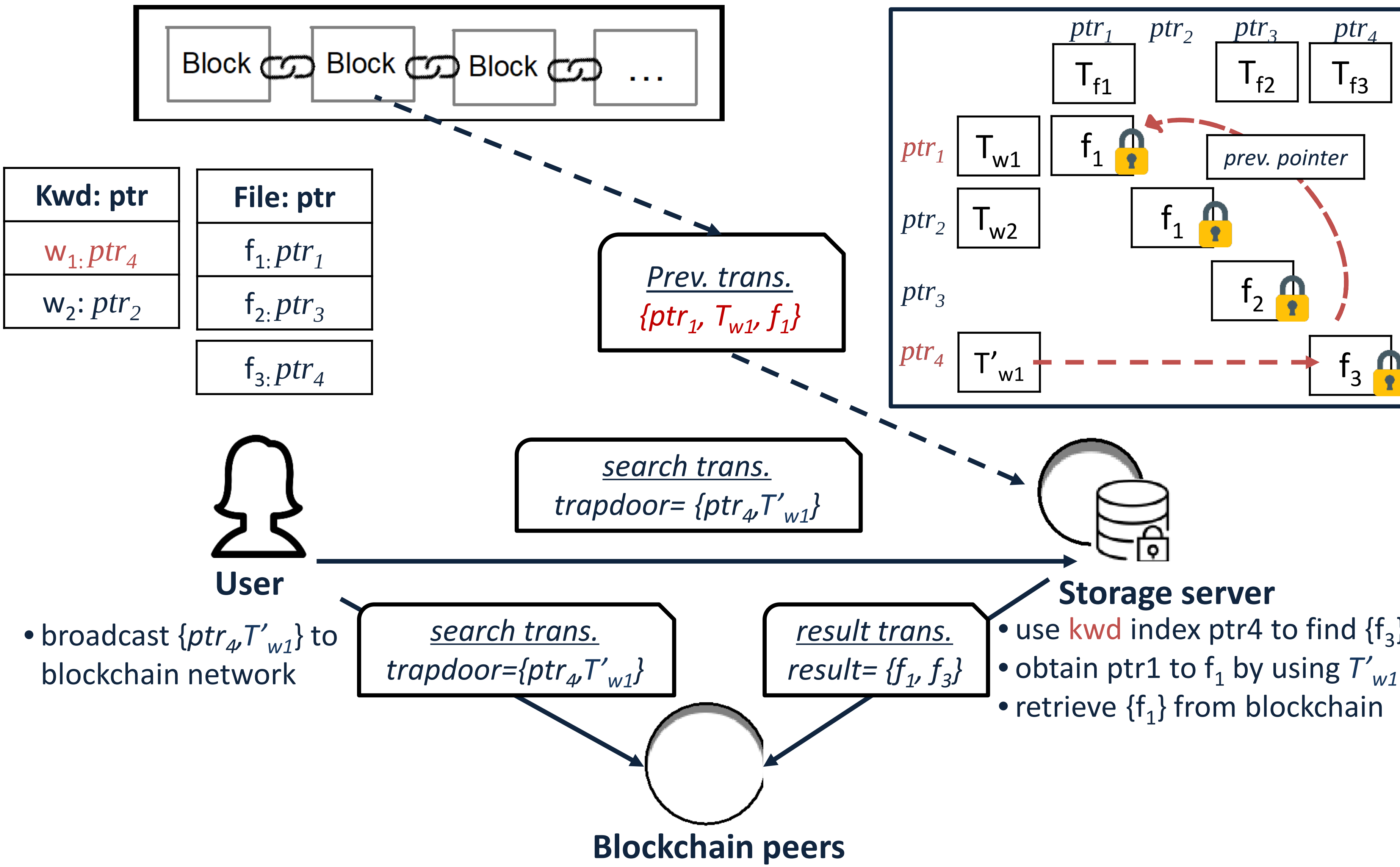
- **Add an entry with new trapdoor w_1' to the front of the kwd index chain**
  - the new entry points to the previous trapdoor (kwd) entry
- **Use the new trapdoor w_1' to search for kwd w_1**
  - update the local states to the new trapdoor
- **Retrieve the previously searched results from the blockchain**
  - previously searched results are recorded in the blockchain

Update indexes for adding a new file

- **Example:** when add a new kwd-file pair (w_1, f_3), i.e., w_1: $f_3 \rightarrow f_1$
  - add new pointer ptr_4 (f_3: ptr_4) and (w_1: ptr_1) -> (w_1: ptr_4) in the local states
  - generate a new trapdoor T'_{w1} for w_1 and request the server to add a new index-entry for T'_{w1}, which further links to f_1 with the old trapdoor T_{w1}
- Need to enter a new contract with the updated checklist

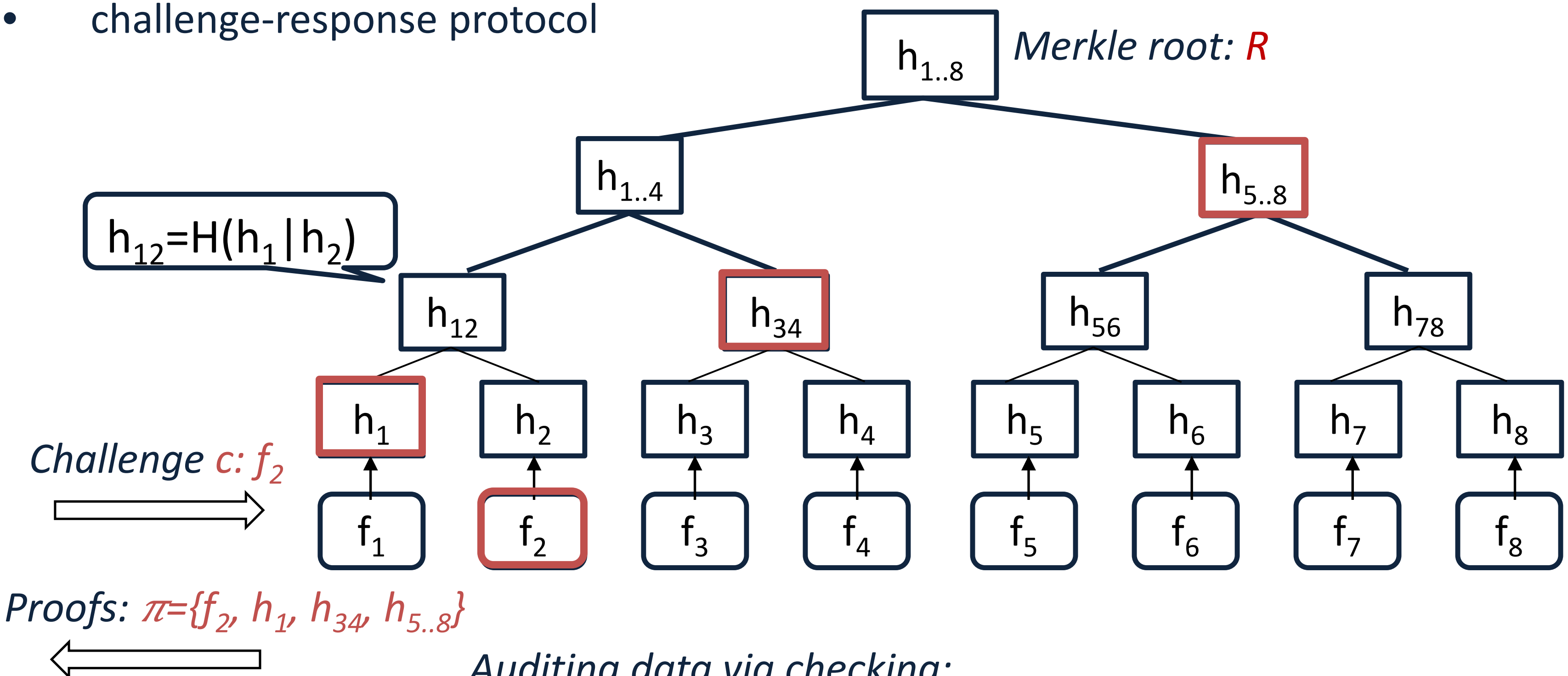


Search for new files via dual indexes



Data auditing: A useful PoW

- **Data auditing is to check the integrity of data stored at servers**
  - ensure the data at the servers are not missing, corrupted, …
- **Merkle Hash Tree for data auditing**
  - challenge-response protocol



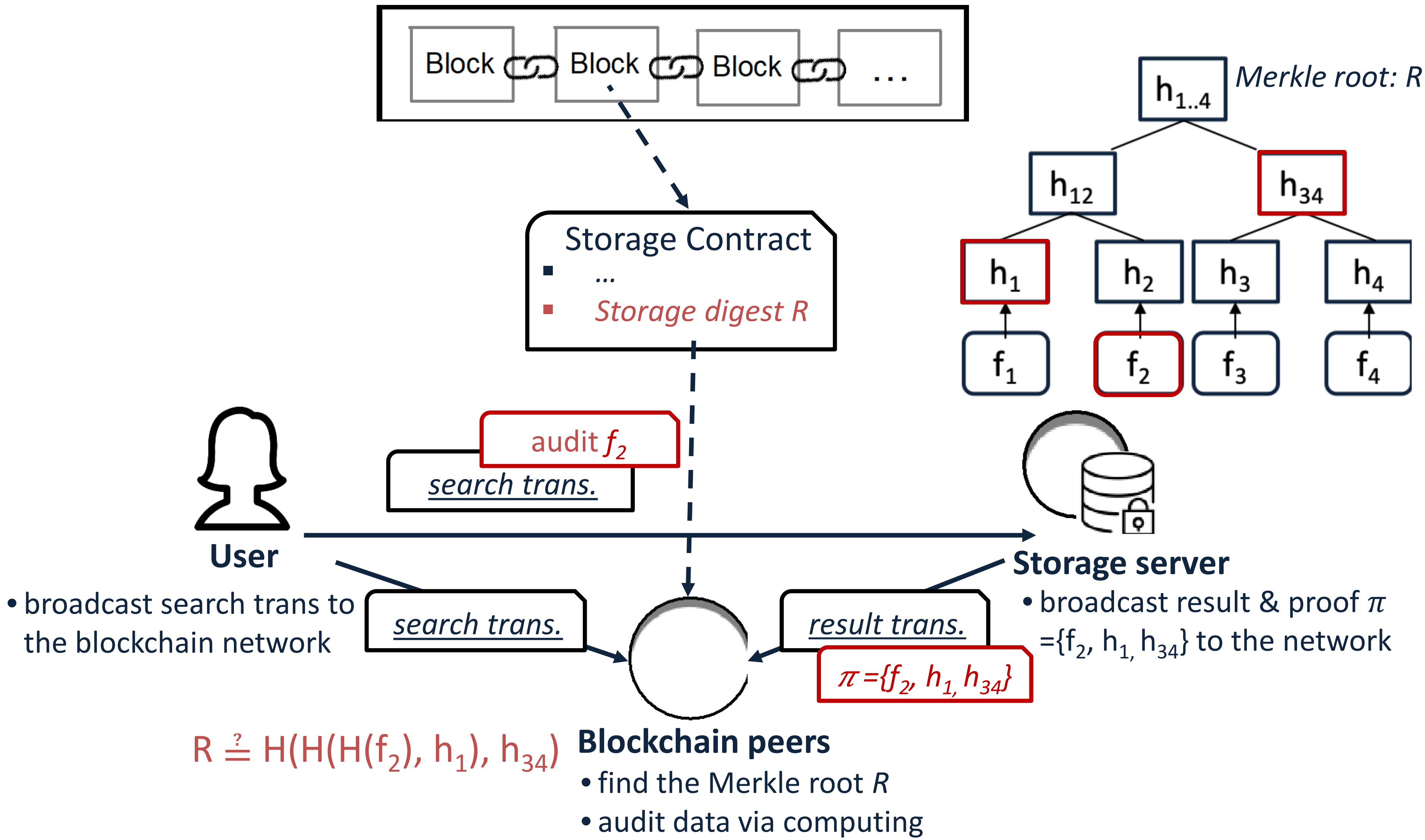
Auditing data via checking:

$$R \stackrel{?}{=} H(H(H(H(f_2), h_1), h_{34}), h_{5..8})$$

Design strategies

- **An auditing challenge is generated from each search transaction**
  - the storage server generates an auditing position (a file ID) out of the incoming search transaction
  - it broadcasts the auditing proof, together with search results
- **Data auditing is part of the PoW by the peers**
  - blockchain peers can verify auditing proofs and the search results
- **Ensure the integrity of data throughout the life time of the system**

Data auditing within the blockchain



A new consensus protocol

- **Verification of a search result transaction includes:**
  - verifying the search results, and
  - auditing the integrity of the stored file
- **Peers compete with each other to generate new blocks**

$$\boxed{\text{SHA-256}^\wedge 2(\underbrace{pk}_{\textit{peer ID}} \,||\, \underbrace{T}_{\textit{ticket}} \,||\, \underbrace{Mr(Tx)}_{\textit{transitions}} \,||\, \underbrace{H(\pi)}_{\textit{file-proofs}} \,||\, \underbrace{Block_{pre}}_{\textit{Prev. block}}) \overset{?}{<} Z \times \underbrace{B_{stc}}_{\textit{peer's stake}}}$$

$Mr(Tx)$: the Merkle-tree root of validated transactions in the new block

$H(\pi)$: the hash value of validated file-proofs

B_{stc} : the peer's stake (amount of deposit it has in the system)

A hybrid method of proof-of-stake and proof-of-work

- **Proof-of-stake gives more advantage to peers with higher stake, reducing the average time for generating a new block**
  - a trade-off between randomness and deterministic in block mining
  - increase the throughput of generating new blocks
- **Peers perform data auditing as a useful PoW**
- **The longest chain rule still holds the global consensus among the peers**

Summary

A secure and verifiable blockchain-based P2P storage system

- **support secure search over encrypted files**
  - off-chain storage of files and search indexes:
    - make the blockchain light-weighted
  - on-chain verification of search results
- **support file updates with forward security**
  - both search and update operations are in sub-linear complexity
  - leverage the property of blockchain to preserve the forward-security for file updates
- **data auditing as a useful PoW**
  - ensure data integrity in the P2P systems
  - a hybrid method of proof-of-stake and proof-of-work:
    - increase the throughput of the blockchain

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