Ethna: Analyzing the Underlying Peer-to-Peer Network of the Ethereum Blockchain

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Abstract—As the communication infrastructure of the blockchain system, the underlying peer-to-peer (P2P) network has a crucial impact on the efficiency and security of the upper-layer blockchain such as Bitcoin and Ethereum. However, current Ethereum blockchain explorers (e.g., the Etherscan) focus on the tracking of block and transaction records but omit the characterization of the underlying P2P network. This work presents the Ethereum Network Analyzer (Ethna), a tool that probes and analyzes the P2P network of the Ethereum blockchain. Unlike Bitcoin that adopts an unstructured P2P network, Ethereum relies on the Kademlia DHT to manage its P2P network. Therefore, the existing analyzing methods proposed for Bitcoin-like P2P networks are not applicable to Ethereum.

In Ethna, we implement a novel method that can accurately measure the degrees of Ethereum nodes; moreover, we design an algorithm that derives the latency metrics of the message dissemination in the Ethereum network. We run Ethna on the Ethereum Mainnet and conduct extensive experiments to analyze the topological features of its P2P network. Our analysis shows that the Ethereum P2P network conforms to the small-world property, and the degrees of nodes follow a power-law distribution that characterizes scale-free networks.

Index Terms—Ethereum, Peer-to-Peer Networks, Scale-free Networks, Small-world Networks.

I. INTRODUCTION

FIRSTLY introduced in Bitcoin by Satoshi Nakamoto, blockchain is a secure, verifiable and tamper-proof distributed ledger for supporting digital asset transactions [1]. Being able to achieve consensus over a permissionless decentralized network [2][3], blockchain then becomes a disruptive technology in the fields of FinTech [4], Internet of Things (IoT) [5], and supply chains [6]. The blockchain of Bitcoin is called Blockchain 1.0 that only implements a distributed ledger to record transactions. In 2014, smart contract is introduced by Ethereum that can fulfill various Turing-complete computing tasks in a decentralized manner [7]. As the representative of Blockchain 2.0, Ethereum greatly expands the application of blockchain by allowing the users to develop various decentralized applications (DApps). The next-generation blockchain will further boost the performance by adopting the cutting-edge technologies such as novel consensus protocols, cross-chain methods, and sharding.

As the communication infrastructure, peer-to-peer (P2P) network is a vital component of the blockchain system [8]. The nodes of a blockchain send and receive messages of transactions and blocks over the P2P network to achieve distributed consensus. The operational stability of a blockchain system thus is affected by the message forwarding protocol, the peer discovery protocol and the topology of its underlying P2P network. As a consequence, it is particularly important to analyze and understand P2P networks of blockchain systems. However, current Ethereum blockchain explorers (e.g., the Etherscan [9]) focus on the tracking of block and transaction records but omit the characterization of the underlying P2P network. Moreover, the existing analyzing methods proposed for Bitcoin-like P2P networks [10][14] are not applicable to Ethereum, since Ethereum manages its P2P network using the Kademlia DHT structure that is very different from the unstructured P2P network adopted by the Bitcoin blockchain.

This work presents the Ethereum Network Analyzer (Ethna), a tool that probes and analyzes the P2P network of the Ethereum blockchain. Unlike other works [15][18] that investigate the Ethereum P2P network, we measure and analyze the degree distribution of Ethereum nodes according to the random selection feature of the message forwarding protocol in the Ethereum P2P network (i.e., randomly selecting some neighbor nodes to forward messages). Since the randomness of message forwarding is closely related to the actual node degrees, our measured node degrees are accurate enough to reflect the characteristics of Ethereum network topology. In addition, we also exploit the message forwarding protocol of the Ethereum P2P network to analyze the transaction broadcast latency, and further obtain the number of hops required for disseminating messages to the whole Ethereum P2P network.

Based on the measured data and analyzed results in Ethna, we obtain the following conclusion about the topological characteristics of the Ethereum P2P network:

- The average degree of the Ethereum P2P network nodes is 47, and there are a few super nodes with very high degrees. Most node degrees are less than 50, and the degree distribution of all the network nodes presents a power-law distribution, which characterizes scale-free networks.
- The average delay of broadcasting a transaction to the whole Ethereum P2P network is around 200 ms. It takes 3-4 hops to broadcast a new block or new transaction to the whole network, which concludes that the Ethereum P2P network conforms to the small-world property.

We now summarize the main contributions of this work as follows:

- We design a novel method that can accurately measure the degrees of the Ethereum nodes with a simple setup

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and feasible complexity.

- We propose an efficient algorithm to analyze the message propagation metrics in the Ethereum network, including the transaction broadcast latency and the number of hops for broadcasting messages.

- We implement Ethna in Go programming language and deploy this tool in the current Ethereum Mainnet. Our experiment results provide some new insights into the network of Ethereum which can help to improve the design of blockchain system.

The rest of this paper is organized as follows. Section II is the related work. Section III presents the background about the Ethereum P2P network. Section IV introduces our network measurement method. Section V analyzes the measured data to investigate the network topology. Section VI concludes this work.

II. RELATED WORK

The P2P network of Bitcoin blockchain adopts an unstructured topology, the gossip message broadcast protocol and a random node discovery protocol [8]. Work [11] investigated the block and transaction propagation in the Bitcoin P2P network and found that the forking over the Bitcoin blockchain is mainly determined by the message propagation latency. Work [11] measured the size, the node geographic distribution, the stability and the propagation delay of the Bitcoin P2P network. Based on the random node discovery protocol adopted by the Bitcoin P2P network, some works [12, 13] measured the degrees of the nodes in the Bitcoin P2P network. These results reveal that the topology of the Bitcoin P2P network conforms to the scale-free network model, i.e., the degree distribution of Bitcoin nodes follows the power-law distribution where a few of the nodes have very large degrees and most of the nodes have very small degrees. The investigation in [14] also measured the P2P network of Monero coin that has a similar network protocol to that of Bitcoin, and it found that the P2P network of Monero coin also conforms to the characteristics of scale-free networks.

The current Ethereum blockchain explorers (e.g., Etherscan [9], Ethereum Blockchain Explorer [19], and Ethereum Nodes Explorer [20]) focus on the tracking of transaction, block and node records but omit the characterization of the underlying P2P network. Some characteristics of the Ethereum P2P network were studied [15–17], including the scale of the Ethereum P2P network, the delay distribution among nodes and the geographical distribution of nodes. However, no conclusion was made on the characteristics of the Ethereum network topology. By far, the investigations on measuring the degrees of nodes in the Ethereum P2P network and analyzing the Ethereum P2P network topology based on the degree distribution are still inadequate.

The peer discovery protocol of Ethereum is quite different from those of Bitcoin and Monroe coin, because the Ethereum P2P network adopts the K-bucket data structure in the Kademlia DHT protocol [21] to discover network nodes and maintain node information. Thus, it turns out that to measure the degrees of network nodes in Ethereum and to study the Ethereum P2P network based on the distribution of node degrees are not straightforward. For example, work [13] measured the degrees of peers in the Ethereum P2P network by regarding the number of peers stored in K-buckets as the same to the peer degree; however, the peer degrees measured in [13] is far greater than the actual peer degree, since the actual node degree is often much smaller than the number of nodes stored in the K-buckets due to the leaves of nodes over time (we provide experiment results to support this point in Section V).

III. BACKGROUND

The Ethereum network communication is implemented in three protocols, RLPx for node discovery and secure transport, DEVp2p for application session establishments, and the Ethereum subprotocol for application-level communications [22–24]. This section describes the message forwarding protocol adopted by the Ethereum subprotocol for propagating the messages of transactions and blocks over the P2P network, which is exploited by our Ethna to derive useful information for investigating the Ethereum P2P network.

A. Functional Modules of Message Forwarding Protocol

As shown in Fig. 1, the message forwarding processing at each Ethereum node can be divided into several functional modules. These modules interact with each others to complete the whole message forwarding process. The P2P module is responsible for communicating with the underlying P2P network, i.e., it receives and sends various messages with other neighbor nodes, delivers the messages of blocks and transactions to the protocol manager module and keeps the messages related to the P2P network communication within the P2P module for processing (such as ping/pong messages). The protocol manager (ProtocolManager) module processes the received block and transaction messages and delivers them to the transaction pool (TxPool) and block processing (BlockProcess) modules respectively. The TxPool module is used to store the transactions that have not been recorded onto the blockchain. The BlockProcess module is used to process the blocks newly received from the network. Details on the function of each module and the interaction process among the modules are explained as below.

The ProtocolManager module delivers the transactions received from the network to the TxPool module. The transactions in TxPool are arranged according to the accounts they belong to, as illustrated in Fig. 2. Each row in Fig. 2 arranges transactions issued by the same account, and these transactions are sorted by their nonce values in ascending order. According to whether their nonce values are continuous, these transactions are respectively stored in two different subparts of TxPool:

- PendingPool: it maintains the pending transactions that have not been included in the blocks on the blockchain but are ready to be packaged into a new block.

Nonce in each transaction is an integer that is associated with the account that issues this transaction. For each account, the nonce value starts from 0 and it is increased by 1 after a new transaction is issued by this account.
shown in Fig. 2, the blue transactions are pending transactions; the nonce values of these transactions linked to each account are continuous. For each account, the maximal number of pending transactions can be stored in PendingPool is 16. In addition, once a transaction goes to the PendingPool of TxPool, the TxPool module will feedback to inform the ProtocolManager module that this transaction can be forwarded to other neighbor nodes who do not know the transaction yet. Miner nodes can select transactions from its PendingPool to pack them into a new block according to the packing rules of Ethereum.

- Queued: it maintains the “future” transactions after a transaction with a continuous nonce value is absent and these future transactions are not ready to be packaged into a new block. As shown in Fig. 2, the transaction (in green) belonging to Account 3 with the nonce value of 1 is missing due to the network problem or other reasons. Therefore, the later consecutive transactions (in yellow) with nonce value greater than 1 enter the Queued of TxPool. Only after the transaction with nonce value of 1 arrives in TxPool, these transactions with continuous nonce values can enter PendingPool. For each account, Queued can store up to 64 transactions.

When a new block sent from the network is found by the ProtocolManager module, it will be sent to the BlockProcess module for further processing. Firstly, BlockProcess validates the block. Once the block validation is passed, the world state of the local blockchain will be updated, and then a chain head event (ChainHeadEvent) will be sent from BlockProcess to TxPool. ChainHeadEvent contains the latest world state updated by the current new block. After receiving ChainHeadEvent, TxPool will reset itself according to the updated world state. That is, it removes the transactions that are stored in PendingPool/Queued and are already included in the new block; moreover, it adds the transactions included in the new block but not in the PendingPool/Queued to the PendingPool/Queued. During this period of the TxPool resetting, TxPool is temporarily blocked and the transactions sent from ProtocolManager cannot enter TxPool.

Normally, when a new block is received and there is no fork found on the blockchain, the transactions included in the new block will be removed from PendingPool and Queued during the TxPool resetting, as explained above. On the other hand, when two blocks with the same height are received in sequence, i.e., there is a fork observed on the blockchain, the processing of the TxPool resetting is different. The two blocks, which are denoted by FormerBlock and AfterBlock, respectively, are corresponding to two different world states. After receiving FormerBlock, TxPool will be reset according to its world state, i.e., the transactions that are included in FormerBlock and also are existing in PendingPool/Queued are removed from PendingPool/Queued, and those only included in FormerBlock but are not existing in PendingPool/Queued are added to PendingPool/Queued. After receiving AfterBlock, the transactions that are existing in AfterBlock will be removed from PendingPool/Queued. Then, the transactions in FormerBlock and AfterBlock are compared to find the transactions that are not included in AfterBlock but are included in FormerBlock (have already been excluded from PendingPool/Queued). These transactions need to be readded to PendingPool/Queued.

From the above descriptions, we can see that when the TxPool resetting is happening, a large number of transactions may enter PendingPool simultaneously, and then TxPool informs ProtocolManager that these newly coming transactions can be forwarded to other nodes in the network.

B. Block Propagation Strategy

In the Ethereum P2P network, the propagation of blocks and transactions adopts a gossip-type strategy [25]. We consider an Ethereum node that receives a new block sent from one of its neighbor nodes. The node that receives the new block will randomly select some of its connected neighbor nodes to propagate the received new block. We call the neighbor nodes of this node that also do not know the new block as the downstream peers of the node about this block. The number of these downstream peers is denoted by \( N \). After the node receives the new block, it firstly validates the block header,
and then it randomly selects $\sqrt{N}$ downstream peers to forward the new block. After that, it further validates the whole block, and then sends the hash of the block to the remaining $N - \sqrt{N}$ downstream peers if the block validation passes. Fig. 3 illustrates this block propagation process after an Ethereum node receives a new block.

We next explain how an Ethereum node acquires a new block when the node receives the block hash from some of its neighbor nodes. Fig. 4 illustrates the process of acquiring a new block at an Ethereum node that receives a block hash. When an Ethereum node has received the new block hash, this node first waits for 400 ms; and then randomly selects one node from the neighbor nodes that already know the new block (i.e., the neighbor nodes that have already sent the block or the block hash to this node). After that, this node sends GetHeader information to request the header of the new block from the selected neighbor node. After receiving the block header returned by the selected neighbor node, the node will wait for 100 ms, and then randomly select a neighbor node from the set of the neighbor nodes that know the new block to obtain the body of the new block. In the end, the received new block body and the new block header will be assembled into a new block and appended to the tail of the local blockchain after the validation of this block is passed. Usually, an Ethereum node connects with multiple neighbor nodes in the Ethereum P2P network. As shown in Fig. 4, it is a long process for a node to obtain the block through the hash of this block. As a consequence, during the process, it is possible that other neighbor node may send the new block to this node. Once the node receives the block sent from other neighbor node, it will stop the process of obtaining the block through the block hash.

### C. Transaction Propagation Strategy

The nodes in the current Ethereum Mainnet run different protocols, such as the les protocol which provides light node service and the eth protocol that provides full node service [26]. For the nodes running the les protocol, only the block header information will be synchronized; the transaction information in block body will be synchronized from other nodes when it is necessary. For the nodes running the eth protocol, all block information including transactions will be synchronized all the time. We aim at exploiting the transaction propagation process to measure the Ethereum P2P network. Thus, we will focus on the nodes running the eth protocol.

The eth protocol has different versions, such as eth62, eth63, eth64 and eth65 [27]. The nodes running different versions of the eth protocol have slightly different transaction propagation strategies. Note that the transaction propagation strategy of eth64 and its earlier versions are completely different from that of eth65 and its later versions. Moreover, most of the eth protocols currently used by the nodes in Ethereum Mainnet are eth64 or eth65. Therefore, the transaction propagation strategies of eth64 and eth65 will affect our measurement method. In the following, we call the nodes running the eth64 protocol as eth64 nodes, and the node running the eth65 protocol as eth65 nodes. The transaction propagation strategies of eth64 and eth65 are described as below.

For an eth64 node, when receiving a new transaction, the ProtocolManager module first sends the new transaction to TxPool for validation. The validated new transactions are stored into the PendingPool or Queued following the rules discussed in Section III.A. When a new transaction enters the PendingPool of the TxPool module, the TxPool module will inform the ProtocolManager module that a new transaction is available to forward. In the end, the ProtocolManager module forwards the new transaction to the neighbor nodes who are unknown about this transaction.

For an eth65 node, the transaction propagation processing executes two different actions according to the version of the eth protocol adopted by the forwarding target neighbor node: forwarding the transaction itself or forwarding the transaction hash to the target neighbor node. We illustrate the transaction propagation process of an eth65 node in Fig. 5. When an eth65 node receives a new transaction, its ProtocolManager module first sends the new transaction to TxPool for validation. When
the validation of the transaction is passed and the transaction is stored in the PendingPool of TxPool, TxPool notifies the ProtocolManager module that there is a new transaction that can be forwarded to other neighbor nodes. Then, the ProtocolManager randomly selects $\sqrt{N}$ downstream peers that do not know the transaction as the targets to forward this transaction. For the remaining $N - \sqrt{N}$ downstream peers, if the version of the eth protocol run by the downstream peer is eth65, the transaction hash will be forwarded; if the version of the eth protocol run by the downstream peer is eth64, then the transaction will be forwarded.

As explained above, eth65 nodes will receive transaction hashes from its neighbor eth65 nodes. When an eth65 node receives the hash of a new transaction, the process of obtaining the new transaction is illustrated in Fig. 6. After receiving the new transaction hash, the eth65 node waits for 500 ms. During this period, if there is no other neighbor node sending the new transaction to it, the eth65 node randomly selects one of the neighbor nodes that have sent it the new transaction hash, and sends a GetTx information to the selected neighbor node for requesting the new transaction. After the requested neighbor node returns the new transaction, the eth65 node validates the new transaction. If the validation of the transaction is passed, the transaction is added to TxPool of this eth65 node.

### IV. NETWORK MEASUREMENT

In this section, we introduce the Ethereum network nodes that are set up by Ethna to probe the Ethereum P2P network. Then, using these probing nodes, we propose methods to measure the time instants when nodes propagate transactions, and the numbers of transactions propagated by other Ethereum nodes.

#### A. Setting up Probing Nodes

To probe the running Ethereum P2P network, we set up two different nodes on Ethereum Mainnet:

- **NetworkObserverNode**: it is an Ethereum node that operates under the fast-synchronizing mode. When the state of the local blockchain at a node is far from the world state of the current blockchain, the node will execute the fast-synchronization mode to rapidly synchronize to the current world state. The node operating under the fast-synchronizing mode only validate the world states contained in the blocks downloaded from other nodes and skips the validating and forwarding of the transactions included in the blocks. Thus, the fast-synchronization mode could reduce the synchronization time [28]. NetworkObserverNode under the fast-synchronization mode will randomly connect with other neighbor nodes on Ethereum Mainnet. Although its neighbor nodes will inform NetworkObserverNode new blocks and new transactions, NetworkObserverNode under the fast-synchronization mode will not forward those blocks and transactions after receiving them. Therefore, NetworkObserverNode only plays the role of an observer on Ethereum Mainnet. NetworkObserverNode runs the Ethereum software with version v1.9.15 [29] that adopts the eth65 protocol. We set up NetworkObserverNode using an AliCloud server located in Shenzhen, China, whose IP address over the public internet is 8.129.212.167.

- **LocalFullNode**: it is an Ethereum node that has synchronized to the latest word state of the blockchain. LocalFullNode will receive, verify and forward new blocks and new transactions. LocalFullNode runs the Ethereum software with version v1.9.15 that adopts the eth65 protocol. We set up LocalFullNode over the LAN of Shenzhen University in Shenzhen, China. LocalFullNode has no own public internet IP address, and it uses NAT protocol to communicate with other nodes on Ethereum Mainnet.

With these two Ethereum nodes, we can probe the Ethereum P2P network to measure transaction-propagation time instants, and the number of transactions forwarded by each node within a certain observation time window, as explained in the following.

#### B. Network Measuring Method

1) **Measuring transaction-propagation time instants:**
As discussed in Section III, when Ethereum nodes join the network, they will choose suitable nodes to connect with
and exchange blocks and transactions with these connected neighbor nodes. To find the cost time for broadcasting a new transaction to most nodes in the Ethereum P2P network is one of the key objectives of Nhna. To achieve this objective, we first measure the transaction-propagation time instants at the neighbor nodes of NetworkObserverNode using the following measuring method. We utilize NetworkObserverNode to collect transactions sent from its connected neighbor nodes. We know that acting as a network observer, NetworkObserverNode will not change the states of TxPool at each of its neighbor nodes, because it only receives transactions but will not forward transactions.

Usually, a transaction or a transaction hash is propagated over the network in a packet solely consisting of this transaction or this transaction hash. For some cases, a number of transactions or transaction hashes will be encapsulated into one packet and propagated over the network. Whenever NetworkObserverNode receives a packet of transactions or transaction hashes from a neighbor node, we record the useful information about these transactions into a database called TxMsgPool. For each transaction or transaction hash contained in each received packet, we first record a raw-data record, tempTxMsg, that is given by the following form:

\[
\text{tempTxMsg } \{\text{PeerID, TxHash, Timestamp, GasPrice, PacketSize}\}
\]

where the fields are explained below: PeerID is the peer identification of the neighbor node who sends the packet of transactions/transaction hashes to NetworkObserverNode; TxHash is the transaction hash; Timestamp is the local time stamp when NetworkObserverNode receives the packet of transactions/transaction hashes; GasPrice is the service charge of this transaction paid to the miner; PacketSize is the number of total transactions/transaction hashes contained in the received packet (e.g., when the neighbor nodes sends a transaction to NetworkObserverNode and this transaction is separately encapsulated into a packet, the value of PacketSize is 1).

All raw-data records, tempTxMsg, are stored into the database, TxMsgPool. The Timestamp filed in each raw-data record tempTxMsg is the local time stamp when NetworkOb-

\[2\]Since the local blockchain state of NetworkObserverNode that is configured to execute the fast synchronization is far from the current world state of the blockchain, the recently issued transactions in Ethereum do not conform to the local blockchain state NetworkObserverNode and NetworkObserverNode will discard these new transactions when it fails to validate the transactions during the fast-synchronization process.

\[3\]A eth65 node will create two cache queues for each of its neighbor eth65 nodes, namely TxQueued and TxHashQueued. TxQueued is used to cache the corresponding transactions that are ready to be propagated to this neighbor node, and TxHashQueued is used to cache the corresponding transaction hashes that are ready to be propagated to this neighbor node. After the eth65 node selects a neighbor eth65 node for propagating a transaction or a transaction hash, it will immediately feed the transaction or the transaction hash into the TxQueued or TxHashQueued of this neighbor node. When the thread resources for processing the neighbor node are free, it will package all the transactions in the TxQueued into a transaction packet, and forward this transaction packet to the neighbor node. In the same way, the transaction hash needs to be cached in TxHashQueued of the neighbor node before forwarding. When the thread resources are free, all transaction hashes in the TxHashQueued are packaged into a transaction hash packet and then forwarded to the corresponding neighbor node.

\[4\]The GasPrice filed of tempTxMsg should be no less than 18 Gwei. The value of GasPrice is an indicator to know whether this transaction is normally propagated over the network. When an Ethereum node starts with the geth client, the minimal value of the GasPrice that determines whether transactions can enter its TxPool can be set. Only transactions with GasPrice values that are no less than the set value can enter TxPool and be forwarded later. If the GasPrice of a newly received transaction is too small, it will be discarded by the node immediately. As a consequence, the propagation time of that transaction will be longer; even worse, some nodes may fail to receive the transaction. The default minimal value of GasPrice in the current version of Ethereum software is 1 Gwei, and in the older versions it is set to be 18 Gwei. We performed a simple experiment to investigate the impact of GasPrice on transaction propagations. We first crawled 1528 transactions from the website on October 14, 2019. These transactions were propagated over the Ethereum P2P network. We then collected the propagation results of these transactions at our NetworkObserverNode. There are eight neighbor nodes (in different geographic locations) connected to

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\[t\]: Time instant of receiving tx from the neighbor node

\[x\]: The ping time from NetworkObserverNode to the neighbor node

\[t+x\]: The time instant when the neighbor node forwards tx

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Fig. 7. The measuring method for transaction propagation time instants between two neighbor nodes.
TABLE I
THE IMPACT OF GASPRICE ON TRANSACTION PROPAGATIONS

| Location     | Received | Missed | GasPrice < 18 | 18 <= GasPrice <= 50 | GasPrice > 50 |
|--------------|----------|--------|---------------|---------------------|--------------|
| Beijing1     | 1520     | 8      | 8             | 0                   | 0            |
| Beijing2     | 1521     | 7      | 5             | 0                   | 2            |
| Nuremberg    | 1505     | 23     | 23            | 0                   | 0            |
| Hangzhou     | 1528     | 0      | 0             | 0                   | 0            |
| Shenzhen1    | 1519     | 9      | 9             | 0                   | 0            |
| Shenzhen2    | 1506     | 22     | 22            | 0                   | 0            |
| Shijiazhuang | 1503     | 25     | 23            | 0                   | 2            |
| Lille        | 1521     | 7      | 7             | 0                   | 0            |

NetworkObserverNode. These neighbor nodes forward their received transactions to NetworkObserverNode. We can check at NetworkObserverNode to see whether all 1528 transactions are propagated from the eight neighbor nodes to NetworkObserverNode. The propagation results of the 1528 transactions are shown in TABLE I. We can see that the numbers of these transactions received by NetworkObserverNode from each of its neighbor nodes are all less than 1528. This indicates that some transactions got lost. To look into these lost transactions, we find that most of the lost transactions have GasPrice less than 18 Gwei. Thus, we can conclude that these transactions are discarded because of their small GasPrice. Hence, in order to investigate the transactions that are propagated normally, we only select the raw-data records, tempTxMsg, whose GasPrice filed is no less than 18 Gwei for analysis.

The PacketSize filed of tempTxMsg should have a value of 1. The value of PacketSize is a key indicator to determine whether the TxPool of the neighbor node who sends the transactions/transaction hashes to NetworkObserverNode is reset during the process of this transaction/transaction hash propagation. According to Section III, if there is no TxPool resetting that occurs at the neighbor node, the neighbor node can store this transaction into its TxPool and forwards the transaction itself or the hash of this transaction to NetworkObserverNode promptly after this neighbor node receives the transaction and finishes its validation. In this case, the time cost used to validate and store this transaction is very short (around 1 ms) and it can be regarded as negligible. However, if there is a TxPool resetting that occurs at the neighbor node, a lot number of transactions enter the TxPool simultaneously and then these transactions or the hashes of these transactions are forwarded together in one packet. Therefore, the propagation time of transactions is severely enlarged by the TxPool resetting process that usually leads to PacketSize > 1, and we only select the raw-data records, tempTxMsg, whose PacketSize filed is 1 for analysis.

Thus, using each raw-data record tempTxMsg{PeerID, TxHash, TimeStamp, GasPrice, PacketSize} where PacketSize = 1 and GasPrice > 18 and the corresponding Delay, we can obtain a transaction-propagation record, TxMsg, for this transaction propagation. The form of the transaction-propagation record TxMsg is given by

\[
\text{TxMsg}\{\text{PeerID}, \text{TxHash}, \text{ForwardTime}\}
\]

where ForwardTime = TimeStamp − Delay. All the transaction-propagation records, TxMsg, are stored into the database TxMsgPool for the following analysis.

2) Measuring the number of transactions forwarded by each eth65 node:

According to Section III, when an eth65 node propagates a new transaction, it will forward both of the transaction and the transaction hash to some of its neighbor nodes, respectively. Based on the transactions and transaction hashes received by NetworkObserverNode during a certain measuring period, we can create a node-propagation record, denoted by PeerPacketMsg, for each node that connects with NetworkObserverNode to store the numbers of the transactions and the transaction hashes sent out by this node. This node-propagation record is written as

\[
\text{PeerPacketMsg}\{\text{PeerID}, \text{TxPacketCount}, \text{TxHashPacketCount}, \text{StartTime}, \text{CurrentTime}\}
\]

where PeerID is the node identification, TxPacketCount is the number of the transaction packets sent by this node, TxHashPacketCount is the transaction hash packets sent by this node, StartTime is the time instant that the first transaction or transaction hash packet sent by the node is received at NetworkObserverNode, CurrentTime is the local time that the latest transaction or transaction hash packet sent by the node is received at NetworkObserverNode.

So far, we have set up probing nodes over Ethereum Mainnet to collect transaction-propagation records, TxMsg, and the records of the transactions forwarded by each node, PeerPacketMsg from the Ethereum P2P network. In next section, we utilize these propagation records to analyze the topological features of the Ethereum P2P network.

V. ANALYSIS OF NETWORK TOPOLOGY

This section presents algorithms used by Ethna to analyze the topological features of the Ethereum P2P network, i.e. the distribution of node degrees, the latency cost to broadcast a transaction to most of the nodes, and the number of hops required to broadcast a message over the Ethereum P2P network. We implement Ethna in Go programming language and deploy
it into the current Ethereum Mainnet to experimentally verify Ethna.

A. The analyzing method for the node degree distribution

We first propose a novel and simple method for analyzing the degree distribution of Ethereum nodes.

As described in Section III, whenever an eth65 node receives a new transaction, it forwards the transaction to \( \sqrt{N} \) neighbor nodes that are randomly selected from the \( N \) downstream peers that are unknown about this transaction, and forwards the transaction hash to the remaining \( N - \sqrt{N} \) downstream peers. When a node receives a new transaction from one of its neighbor nodes, it needs to validate the transaction before forwarding it to other neighbor nodes. During the period from validating to forwarding, it could happen that its other neighbor nodes also forward the same transaction to this node. As a result, these neighbor nodes that also forward the transaction will not be treated as the downstream peers when this node forwards the transaction. Therefore, strictly speaking, the number of the downstream peers of this node should be smaller than the degree of the node. Moreover, for different transactions, the downstream peers and the numbers of the downstream peers may be different. In the Ethereum P2P network, the average processing time of a transaction after it is received by a node and before it can be forwarded by this node is around 1 ms. Compared with the average transaction propagation time between two neighboring nodes of 200 ms (see our measured result provided in Section V.B), this processing time is negligible. Therefore, for each node, we treat the numbers of the downstream peers about all of its forwarded transactions as a same number \( N \), and use \( N + 1 \) as the approximation of the node degree.

In Section IV, for each of its connected nodes, NetworkObserverNode has obtained a node-propagation record, PeerPacketMsg, which stores the number of the transaction packets forwarded by this node and the number of the transaction hash packets forwarded by this node. Note that when forwarding each transaction, a node will randomly select \( \sqrt{N} \) neighbor node from the \( N \) downstream peers to forward the transaction and the remaining \( N - \sqrt{N} \) downstream peers to forward the transaction hash. Therefore, the ratio of the number of the transactions received by NetworkObserverNode from a node over the number of the transactions plus the transaction hashes received by NetworkObserverNode from the same node is \( \frac{\sqrt{N}}{N} \). Based on the above analysis, we can establish the following formula for each node using the TxPacketCount and TxHashPacketCount data contained in its corresponding PeerPacketMsg record:

\[
\frac{\sqrt{N}}{N} = \frac{\text{TxPacketCount}}{\text{TxPacketCount} + \text{TxHashPacketCount}} \tag{1}
\]

which is statistically hold when the number of transactions and transaction hashes forwarded by this node is large. Using the data contained in PeerPacketMsg for each node, we can solve (1) to find the number of the downstream peers \( N \) and use \( N + 1 \) to as the approximation of the degree of this node. The computation of \( N \) from (1) is rather feasible and the setup of collecting data records used in the computation is also very simple, i.e., we only need to have a node of NetworkObserverNode as the network observer on Ethereum Mainnet. Next, we will conduct experiments to verify whether this analyzing method of node degrees in our Ethna is accurate.

1) The experimental verification of analyzing node degrees:

We run NetworkObserverNode and LocalFullNode on Ethereum Mainnet to conduct the experiments of measuring the degrees of Ethereum nodes. We only use eth65 nodes as the targets to measure the node degrees of the Ethereum P2P network but do not use eth64 nodes. The reason for not using eth64 nodes to measure node degrees is explained in Appendix. We employ the network measuring method proposed in Section IV to count the packets of transactions and transaction hashes sent by each of the eth65 nodes that are stably connected with NetworkObserverNode to obtain the PeerPacketMsg records. With the data contained in PeerPacketMsg records, we can solve the formula in (1) to obtain \( N \) and use \( N + 1 \) to approximate the node degree for each eth65 node. After that, we can derive the degree distribution of Ethereum nodes.

We first conduct experiments to verify the measure method of node degrees in our Ethna. Our NetworkObserverNode and LocalFullNode were connected to each other on Ethereum Mainnet during the measure period from July 04, 2020 to August 09, 2020. Since LocalFullNode has completed the blockchain synchronization, it will propagate transactions and transaction hashes to NetworkObserverNode. Therefore, NetworkObserverNode is used to collect the transaction packets and the transaction hash packets forwarded by LocalFullNode to obtain the PeerPacketMsg record of LocalFullNode. Then, the number of the downstream peers of LocalFullNode, \( N \), is calculated by using the formula expressed in (1). We measure the network and compute \( N \) for LocalFullNode on a daily basis, i.e., each day, we recount the numbers of transaction/transaction hash packets to obtain PeerPacketMsg and recalculate \( N \) for LocalFullNode. In addition, we also count the numbers of block packets and block hash packets and calculate \( N \) by using them to replace the numbers of transaction packets and transaction hash packets in (1). We then treat \( N + 1 \) as the measured degree of LocalFullNode in our Ethna. We also measured the degrees of LocalFullNode using the K-bucket based scheme proposed in [18]. Fig. 8 presents the measured degrees of LocalFullNode and its actual degrees for comparisons. It can be seen from Fig. 8 that the measured node degrees using the method of our Ethna are very close to the actual node degrees. The measured node degrees using the K-bucket based scheme [18] are far larger than the
actual node degrees. The measured results using our Ethna method with the numbers of transaction packets are closer to the actual node degrees than the measured results using our Ethna method with the numbers of block packets (the reason is explained in Appendix). We can see that the mismatches between the measured node degrees using our Ethna method with transaction packets and the actual node degrees range over [2, 4]. Therefore, it is regarded quite accurate to use the value of $N + 1$ measured by our Ethna to approximate the node degree. Based on the measured degrees of the nodes that are stably connected with our NetworkObserverNode, we then can infer the degree distribution of all the nodes in the Ethereum P2P network.

2) The experiment for deriving the degree distribution:

With the measured node degrees, we can analyze the degree distribution of nodes in the Ethereum P2P network. The right way to analyze the topology of P2P networks, such as the degree distribution of nodes, should be performed by taking a snapshot of the states of all nodes in the whole P2P network at the same time. When the Ethereum P2P network operates stably, the degrees of its nodes vary within a narrow range without significant fluctuations. And the varying range is related to MaximumPeerCount (the maximum number of neighbor nodes allowed to connect with when starting the node) and the local network configuration. We can observe the degrees of our NetworkObserverNode and LocalFullNode to verify whether the degrees of Ethereum nodes are stable over time within an acceptable range.

Fig. 9 presents the observed degrees of NetworkObserverNode and LocalFullNode during the period from June 9, 2020 to June 17, 2020. The MaximumPeerCount of the NetworkObserverNode and LocalFullNode is set to 50. From the results in Fig. 9, we can see that during the observation period, the degree of NetworkObserverNode fluctuated within the range of [25, 30] and that of LocalFullNode fluctuated within the range of [10, 14]. This shows that the node degrees of NetworkObserverNode and LocalFullNo both are rather stable over time. Therefore, we believe that when analyzing the degree distribution of Ethereum nodes, the degree of eth65 nodes measured at different time instants can be used to derive the degree distribution of the nodes in the Ethereum P2P network.

We next run NetworkObserverNode to measure the degrees of the eth65 nodes that establish stable connections with NetworkObserverNode (if a node propagates more than 1000 packets of transactions or transaction hashes to NetworkObserverNode, it is regarded as a node that establishes a stable connection). During the measurement period from June 9, 2020 to June 17, 2020, we found that there were 555 eth65 nodes having stable connections with NetworkObserverNode, and we analyze their degrees using the method of Ethna. Fig. 10 shows the empirical probability density function (pdf) and Fig. 11 shows empirical cumulative distribution function (cdf) of the node degrees, respectively. From Fig. 10 and Fig. 11, we can see that there are a small number of super nodes (nodes have very high degrees) in the network; the average degree of the 555 eth65 nodes is 47; and the degree distribution of the nodes likes a power-law distribution. The version of Ethereum software is updated to v1.9.0 on June 12, 2020, which sets the default maximum degree of nodes to 50. From the results in Fig. 10 and Fig. 11, we can see that the degrees of the 78% of the nodes are smaller than MaximumPeerCount and the degrees of 22% of the nodes are greater than MaximumPeerCount. This indicates that the degree distribution of Ethereum nodes conforms to the pareto’s principle. It reveals that most nodes started from MaximumPeerCount, and only a few nodes modify MaximumPeerCount to act as super nodes. Since the characteristics of scale-free networks conform to the pareto’s principle and the node-degree distributions of scale-free networks are power-law distributions, we can conclude that the Ethereum P2P network has the feature of scale-free networks.

B. The analyzing method for transaction broadcast latency

This part presents how Ethna analyzes the latency of broadcasting a transaction to most of the nodes in the Ethereum P2P
According to Section IV.B, we write the propagation information of each transaction contained in each packet received by NetworkObserverNode into a transaction-propagation record, $TxMsg\{PeerID, TxHash, ForwardTime\}$, and all $TxMsg$ records are stored in $TxMsgPool$. Since NetworkObserverNode is connected with multiple neighbor nodes at the same time, multiple nodes will forward a same transaction to NetworkObserverNode. Therefore, there will be more than one $TxMsg$ in $TxMsgPool$ that are corresponding to the same transaction, i.e., the $TxHash$ fields of these $TxMsg$ records are the same. Therefore, we can extract all $TxMsg$ records corresponding to the same transaction from $TxMsgPool$, and select them to construct a set of the transaction-propagation records for the same transaction:

$$TxMsgSet = \{ TxMsg[1], TxMsg[2], ..., TxMsg[n] \}$$

where $TxMsg[i]\{PeerID[i], TxHash[i], ForwardTime[i]\}$ is the $i$-th transaction-propagation record for this transaction. In the set $TxMsgSet$, the $TxHash[i]$ of all $TxMsg[i]$ are the same, and the $ForwardTime[i]$ of each $TxMsg[i]$ is the time instant that the corresponding neighbor node forwards this transaction to NetworkObserverNode.

Based on the transaction-propagation records $TxMsg$ in $TxMsgPool$, the set $TxMsgSet$ can be built for each transaction. With all the $TxMsgSet$ sets for the recorded transactions, we propose an algorithm to compute the latency cost to broadcast a transaction to most of the nodes in the Ethereum P2P network. The algorithm for computing the transaction broadcast latency is explained as below:

1) First, for each neighbor node that forwards transactions to NetworkObserverNode, we build an empty set called $PeerTimeDiffSet[PeerID]$, where $PeerID$ is the network peer identification of the corresponding neighbor node.

2) We select a transaction and fetch the set of the transaction-propagation records, $TxMsgSet$, for this selected transaction. Then we calculate the minimum value of the $ForwardTime$ fields of all the transaction-propagation records, $TxMsg$, in $TxMsgSet$ and name this minimum value as $minTime$ that is the earliest time instant that this transaction is forwarded by a neighbor node to NetworkObserverNode.

3) For each and every $TxMsg[i]\{PeerID[i],TxHash[i], ForwardTime[i]\}$ in $TxMsgSet$, we first calculate the difference between $ForwardTime[i]$ in $TxMsg[i]$ and $minTime$, i.e., $ForwardTime[i]-minTime$; then, we put the time difference, $ForwardTime[i]-minTime$, into the corresponding set $PeerTimeDiffSet[PeerID[i]]$ according to the node’s peer identification, $PeerID[i]$.

4) We repeat step 2) and step 3) for each and every recorded transaction to get the time difference sets, $PeerTimeDiffSet[PeerID]$, for all neighbor nodes that forward transactions to NetworkObserverNode.

5) We calculate the average value of all entries in the set of $PeerTimeDiffSet[PeerID]$ and denote this average value by $PeerTimeDiffMean[PeerID]$ for each neighbor node with peer identification, $PeerID$.

6) By averaging all $PeerTimeDiffMean[PeerID]$, we can get the estimated average latency for broadcasting a transaction to most of the nodes in the Ethereum P2P network.

1) The experiment for finding the transaction broadcast latency:

We use the above algorithm with the collected transaction-propagation records to analyze the average transaction broadcast latency. However, when doing that, we need to ensure that we only utilize the propagation records of newly issued transactions that are firstly broadcasted over the network other than some previous transactions that are repeatedly broadcasted over the network due to some problems. Therefore, it’s necessary to identify the new transactions of Ethereum in our analyzing process. The website [9] publishes new transactions observed from Ethereum Mainnet in real time according to its historical records. Therefore, while running NetworkObserverNode to measure transaction propagation records, we use a crawler to collect the information about the new transactions published by the website. When we analyze the transaction
broadcast latency, we only utilize the propagation records of the new transactions.

To ensure that the transaction-propagation records collected by NetworkObserverNode can reflect the feature of the Ethereum network as much as possible, when the data analysis is conducted each time, we ensure that NetworkObserverNode is connected with more than 20 neighbor nodes that are distributed all over the world. We conducted the network measurement on a daily basis from June 09, 2020 to June 17, 2020 over Ethereum Mainnet to get the transaction-propagation records and estimate the average transaction broadcast latency within each day. Fig. 12 presents the results of the analyzed average transaction broadcast latency. We can see that the transaction broadcast latency of the Ethereum P2P network is relatively stable during the measuring period and it is slightly fluctuated around 200 ms. Therefore, we treat the average transaction broadcast latency of the Ethereum P2P network as 200 ms in our later analysis.

C. The analyzing method for the number of hops required to broadcast messages

In this part, we propose a model for the transactions and blocks broadcast delays in the Ethereum P2P network and use the proposed model and the measured results about the message broadcast delays to analyze the number of hops required to broadcast transactions and blocks over the Ethereum P2P network. The delays of broadcasting a transaction and a block to most of the Ethereum nodes can be mathematically modeled as

\[
T_{\text{BlockDelay}} = P_{\text{HashBlock}}x(T_{\text{GetHeader}} + T_{\text{GetBody}} + T_{\text{Process}}5y) + (1 - P_{\text{HashBlock}})xy \quad (2)
\]

\[
T_{\text{TxDelay}} = P_{\text{eth65}}P_{\text{HashTx}}x(T_{\text{GetHash}} + 3y) + (1 - P_{\text{eth65}}P_{\text{HashTx}})xy \quad (3)
\]

where the meanings and the used values of the variables are described as below:

- \(T_{\text{BlockDelay}}\) is the average transaction broadcast delay of the Ethereum P2P network. In Section V.B, we have already found that its value was around 200 ms during the measuring time of June 09, 2020 and June 17, 2020.
- \(T_{\text{BlockDelay}}\) is the average block broadcast delay of the Ethereum P2P network. Currently, some institutions and teams have measured the average block broadcast time and published the results in real time on the website [32]. We can find from the website [32] that the average block propagation time is 477 ms between June 09, 2020 and June 17, 2020.
- \(x\) is the number of hops required to broadcast transactions and blocks from a neighbor node of NetworkObserverNode to most of the nodes in the Ethereum P2P network.
- \(y\) is the average time to propagate a transaction or a block over one hop. In (2), \(5y\) represents that a node needs 5 times of message propagations to obtains the block after receiving a block hash, as shown in Fig. 4. Similarly, \(3y\) in (3) represents that a node needs 3 times of message propagations to obtains the block after receiving the block hash, as shown in Fig. 6.
- \(T_{\text{GetHeader}}\) is the waiting time of a node to obtain the block header after receiving the block hash. Its value is 400 ms.
- \(T_{\text{GetBody}}\) is the waiting time of a node to obtain the block body after receiving the block hash. Its value is 100 ms.
- \(T_{\text{GetHash}}\) is the waiting time of an eth65 node to obtain a transaction after receiving the transaction hash. Its value is 500 ms.
- \(T_{\text{Process}}\) is the average time of processing a block at a node. Fig. 13 indicates the block processing time of LocalFullNode during the measuring period where it fluctuated around 200 ms. Therefore, we treat the value of the variable \(T_{\text{Process}}\) as 200 ms in our analysis.
- \(P_{\text{eth65}}\) is the proportion of eth65 nodes in the current network. From June 9, 2020 to June 16, 2020, we observe that there are totally 1380 nodes connected with NetworkObserverNode and LocalFullNode, of which 40% were eth65 nodes. Thus, \(P_{\text{eth65}}\) is set to be 0.4.
- \(P_{\text{HashBlock}}(P_{\text{HashTx}})\) is the proportion of the blocks(transactions) received by a node after first receiving the hashes of these blocks(transactions) and then requesting these blocks(transactions) to all of the blocks(transactions) received by the node. We have discussed in Section III that nodes can receive a block/transaction directly from their neighbor nodes or request a block/transaction after receiving the hash of the block/transaction from their neighbor nodes. The values of \(P_{\text{HashBlock}}\) and \(P_{\text{HashTx}}\) are determined by two factors: i) how long the node will wait after receiving the hash of a block/transaction and before requesting the block/transaction; ii) how many nodes are selected to forward the hash of the block/transaction. As discussed in Section III, these two factors are the same for the propagations of blocks and transactions. Therefore, we can assume that the values of \(P_{\text{HashBlock}}\) and \(P_{\text{HashTx}}\) are the same in the Ethereum P2P network. We conducted experiments to measure the value of
We found that messages can be broadcast to the broadcast message over the network with collected message broadcast latencies and analyze the number of hops required of scale-free networks. In addition, we model the message P2P network fulfills a power-law and has the characteristics as Bitcoin and Monero, the degree distribution of the Ethereum 1000; similar to the P2P network of blockchain systems such and there are a few of super nodes with a degree greater than measured that the average degree of the Ethereum nodes is 47 of the Ethereum message forwarding protocol to analyze the message propagation records and exploits the random feature Ethna sets up probing nodes on Ethereum Mainnet to collects and analyze the P2P network of the Ethereum blockchain.

NetworkObserverNode to the whole Ethereum network needs no more than 6 hops to reach another node. has the small world effect [33, 34], i.e., one node in the 3.7 hops. This result indicates that the Ethereum P2P network

We proposed Ethna, an Ethereum network analyzer, to probe and analyze the P2P network of the Ethereum blockchain. Ethna sets up probing nodes on Ethereum Mainnet to collects message propagation records and exploits the random feature of the Ethereum message forwarding protocol to analyze the topological characteristics of the Ethereum P2P network. We measured that the average degree of the Ethereum nodes is 47 and there are a few of super nodes with a degree greater than 1000; similar to the P2P network of blockchain systems such as Bitcoin and Monero, the degree distribution of the Ethereum P2P network fulfills a power-law and has the characteristics of scale-free networks. In addition, we model the message broadcast latencies and analyze the number of hops required to broadcast message over the network with collected message propagation records. We found that messages can be broadcast to most of the Ethereum nodes within 6 hops. This result indicates that there is a small-world effect in the Ethereum P2P network.

APPENDIX

1) The reason why we cannot use the transactions forwarded by eth64 nodes to analyze the degrees of eth64 nodes:

This appendix first explains why we cannot use the transactions forwarded by eth64 nodes to analyze the degrees of eth64 nodes. When the number of downstream neighbor nodes \( N \) for an eth64 nodes is smaller than 16, the formula in (1) does not apply. Each time, an eth64 node will randomly selects \( m \) nodes from its \( N \) downstream neighbor nodes to forward the block and the value of \( m \) is given by

\[
m = \begin{cases} \sqrt{N} & N > 16 \\ 4 & 4 \leq N \leq 16 \\ N & 0 < N < 4 \end{cases}
\]

After that, the eth64 forwards the block hash to the remaining \( N - m \) downstream neighbor nodes. As indicated in (4), when \( N \leq 16 \) for an eth64 node, we cannot know whether the eth64 nodes select 4 or \( \sqrt{N} \) nodes to forward blocks, so it is hard to construct a formula like (1) to measure the value of \( N \), i.e., we cannot measure the node degrees that are smaller than 16. Due to this restriction in the block forwarding strategy of eth64 nodes, we cannot measure the degrees of eth64 nodes with low degrees using the transactions forwarded by eth64 nodes.

2) The reason why we cannot use the forwarding of blocks to analyze the node degrees for eth65 nodes or eth64 nodes:

This appendix then explains why we cannot use the number of block packets (BlockPacketCount) and the number of block hash packets (BlockHashPacketCount) to analyze the node degrees for eth65 nodes or eth64 nodes, i.e., why we cannot replace TxPacketCount in (1) with BlockPacketCount and replace TxHashPacketCount in (1) with BlockHashPacketCount.
to compute the number of neighbor downstream nodes for each eth65 or eth64 node. The numbers of block packets and block hash packets sent by eth64 nodes or eth65 nodes are too small during the measuring period. According to the website [9], currently there are 30-50 new transactions generated per second in Ethereum, and one block generated in every 15 seconds. If NetworkObserverNode or LocalFullNode keeps a stable connection with a node for 1 hour, NetworkObserverNode or LocalFullNode can receive approximately 240 block and block hash packets from this node, and NetworkObserverNode or LocalFullNode can receive about 108000 transaction and transaction hash packets from this node. Moreover, the NetworkObserverNode or LocalFullNode usually connect with each node for less than 1 hour, so the value of BlockPacketCount and the value of BlockHashPacketCount for each node are even smaller than 240. Since the formula in (1) is hold only when a large number of messages are randomly forwarded to ensure the statistical property, it is inaccurate to use BlockPacketCount and BlockHashPacketCount to measure the degrees of nodes.

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