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The Evolution of Mining Pools and Miners' Behaviors in the Bitcoin Blockchain

Natkamon Tovanich, Nicolas Soulié, Nicolas Heulot, and Petra Isenberg

***Abstract*—We analyzed 23 mining pools and explore the mobility of miners throughout Bitcoin's history. Mining pools have emerged as major players to ensure that the Bitcoin system stays secure, valid, and stable. Many questions remain open regarding how mining pools have evolved throughout Bitcoin's history and when and why miners join or leave the pools. We investigated the reward payout flow of mining pools and characterized them based on payout irregularity and structural complexity. Based on our proposed algorithm, we identified miners and studied their mobility in the pools over time. Our analysis shows that Bitcoin mining is an industry that is sensitive to external events (e. g., market price and government policy). Over time, competition between pools involving reward schemes and pool fees motivated miners to migrate between pools (i. e., pool hopping and cross pooling). These factors converged toward optimal scheme and values, which made mining activities more stable.**

***Index Terms*—Bitcoin, Bitcoin mining, mining pools, pool hopping, visual analytics**

I. Introduction

BITCOIN mining is an extremely important yet controversial aspect of how the cryptocurrency works. The invention of mining and the accompanying *proof-of-work protocol* was one of Nakamoto's most important inventions that led to the rising importance of blockchain adoption and research with its solution to the double-spending problem [1]. The underlying principle behind the mining protocol has been to offer miners financial incentives in the form of *block rewards* (fixed by the protocol) and *transaction fees* in return for keeping the whole network stable and secure. These financial incentives may be the primary motivation for miners to join the network even though mining income is connected to several uncertainties. Practically, individual miners receive a reward only occasionally, relative to their computational power. As more miners join the network [2] and with faster mining hardware available [3], the total computational power of miners (called the *hash rate*) has been growing rapidly [4]. The *mining difficulty* is constantly adjusted by the protocol relative to the hash rate [5], so the probability of mining a new block with the same hardware becomes lower as the hash rate increases. This phenomenon has created problems on a global scale due to excessive amounts of energy being consumed for mining [6]–[8] but also on a local scale as miners need to live with uncertainty about their expected rewards due to the increasing competition. To combat this uncertainty, mining pools have emerged in which miners combine computational resources to gain a more stable and predictable income. These mining pools now contribute ≈99% of the total hash rate [9] and individual miners have become very rare. Mining pools compete with each other to attract more miners by varying how they pay out rewards to their members. Two factors are generally varied: *pool fees*, which are fees kept by the pool for their services, and *payout schemes* that determine when and how rewards are paid out. This article attempts to address three questions regarding the evolution of mining pools and miners' behaviors: 1) how mining pools have evolved, 2) how mining pools distribute the reward to miners, and 3) how miners choose to join or leave mining pools. A better understanding of the impacts on pools' growth or decline of both external (e. g., market price and regulation) and internal (e. g., payout scheme, pool fee, and the share of transaction fee) factors is necessary to assess the viability and sustainability of Bitcoin mining industry. Documenting the evolution of mining pools is, thus, of significant interest to economists, miners, and pool managers for evaluating the future of Bitcoin and, more generally, of blockchain-based technology that adopts a *proof-of-work* consensus mechanism.

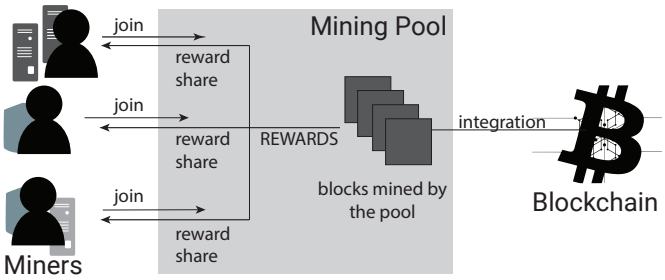

Fig. 1. The overview of Bitcoin mining activity. The diagram shows the interactions between individual miners, mining pools, and the Bitcoin protocol.

Concerning individual miners, we specifically look at *new miners* who decide to enter a pool, *pool hoppers* who migrate from one pool to another, *dropout miners* who stop mining, and *cross-pooling miners* who mine for multiple pools. Analyzing the migration of miners is specifically crucial as migration directly affects mining pools' market shares. Miners decide to join or leave a pool not only to increase their short-term mining rewards but also to counteract the possible domination of pools in the network. In return, migration flows affect how mining pools set their policies (e. g., payout schemes and pool fees) to compete in the market. The combination of mining pool activities and migration behaviors of miners is not yet

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well understood, and few methods exist that allow studying mining pools over a long time period.

This article is an extension of our previous conference paper [10] in which we proposed a new approach to detect individual miners from the reward payout flow and evaluated miners' migration (*pool hopping*) among the top 15 mining pools. In this extension, we contribute additional updated content regarding the evolution of 23 mining pools and miners' mobility behaviors up to Aug. 2021. To our surprise, the landscape of mining competition was still rapidly changing only one year after. We subsequently revised our analysis and included new findings and evidence that pool characteristics and external events impact the competition of mining pools and miners' behaviors. Furthermore, we investigate the reward payout flow of the 23 mining pools in our study and propose the characterization of their payout patterns. Our results show that the competition of mining pools leads towards an optimal reward scheme and a lower fee that converges toward equilibrium. Specifically, we found that: 1) Miners join new pools that provide a lower pool fee and cross-pool with previous ones as a diversification strategy. 2) Miners hopped into pools that shared transaction fee rewards due to the surge of transaction fees in 2017. 3) A significant number of miners hopped out from Chinese mining pools in Apr.–Jul. 2021 showing the impact of government policy on the mining industry. 4) We observed that, in recent years, mining pools started to draw money from other services to pay miners, making it challenging to detect miners with our current heuristic. 5) Finally, we question the sustainability of Bitcoin mining in the long term due to the halving block rewards and market price volatility.

II. Related Work

Bitcoin mining operates under competitive conditions considering the rapid growth of the hash rate, Bitcoin market price, and mining hardware evolution [11]. Game theory is a frequent approach to model the incentive of miners and mining pools as leading players in the consensus process [12]. Yet, data-driven studies on the competition of mining pools and about miner decisions have not emerged extensively in past work.

Early work from Wang and Liu [2] provided evidence that the top mining pools gained a larger market share while the hash rate grew exponentially between Mar. 2013 and Mar. 2014. The authors analyzed the mining profit regarding hardware cost and electricity price and concluded that the profit became negative when the hash rate increased faster than the Bitcoin price. Belotti et al. [13] investigated pool hopping between KanoPool and SlushPool between Apr. 6–20, 2016, and reported that few miners tried to exploit the time difference of reward payout between two pools with diverse strategies to earn more profit from mining. Romiti et al. [14] analyzed the distribution of mining pools from Dec. 2013 to Dec. 2018 and found that 3–4 mining pools controlled >50% of the hash rate. The authors further analyzed the reward payout among the top-3 mining pools and found that a small number of members received >50% of the the total reward from the pool. From Feb. 2016 to Jan. 2019, Wang et al. [15] found that the top mining pools increased their hash rate exponentially to maintain market share. Mining pools were caught in the Prisoner's Dilemma as their hash rate was increased to compete with other pools. However, their mining profit diminished. The authors also confirmed that pools tended to collect transactions with higher transaction fees to maximize their profit. Xia et al. [16] proposed a method to detect migration between pools. This past work is closely related to ours, but we deviate in several areas.

In this work, we propose miners' migration metrics across multiple mining pools. Together with the external data (e. g., payout scheme, pool fees, market price, and news), we explain the evolution of mining pools and the incentive of miners to join or leave the pools. As Bitcoin relies on the mining activity to ensure the security and trustworthiness of the blockchain, this information is crucial to analyze the evolution of mining pools as well as the whole Bitcoin economy in the long term.

III. Data Preparation

We extracted members of mining pools and measured pool hopping behaviors over time. Our process included three steps: (A) we obtained the mining reward for each block and attributed it to a known mining pool; (B–C) for each coinbase transaction, we extracted the reward payout flow and detected pool members (miners) of the mining pool; and (D) we identified miners who participated in 23 mining pools and migrated between pools over time. Moreover, we curated panel data on pool characteristics information extracted from external online sources to assess its impact on miners' mobility. The dataset is available in a Zenodo archive [17]

A. Mining pool attribution, market shares, and characteristics

1) Mining pool attribution

When a mining pool mines a block, it receives the mining reward from the *coinbase transaction* of the block. A coinbase transaction combines the block reward from the Bitcoin network and transaction fees from every transaction in the mined block. It also includes a *coinbase string* inserted by the miner. For each coinbase transaction, we attributed the mining pool based on the address matching or coinbase string pattern. We identified the mining pool that mined each block based on Romiti et al. [14] that compiled known mining pool tagging until Dec. 2018. After this block, we continued their procedure and tagged pools until Sep. 2021 with the datasets from Blockchain.info [18] and BTC.com [19]. The blocks that did not match any known mining pool are labeled as "unknown."

2) Mining pool market shares

The market share of a mining pool is the percentage of the blocks it mined compared to the total blocks mined in a month. We calculated each pool's monthly market share and displayed the market share of mining pools that obtained $> 1,000$ block rewards until Aug. 2021 in Fig. 2.

3) Mining pool characteristics

We obtained information about pool characteristics, in particular payout schemes and pool fees, from the Bitcoin Wiki page [20] on the topic. We downloaded the page's edit history and manually cleaned the data for each month by comparing it with the information from the Bitcoin Forum [21], mining pool websites, and other online sources.As a result, we constructed panel data that includes all changes in pool characteristics over time. Mining pools for which we have this panel data

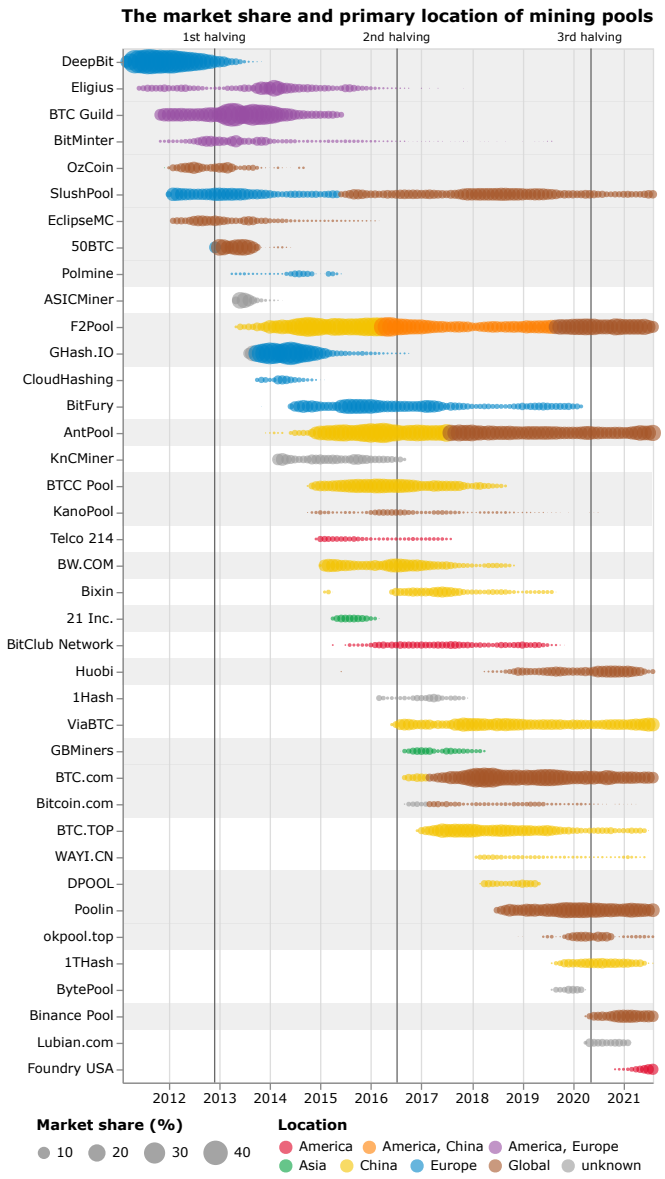

Fig. 2. Market share of mining pools that mined >1,000 blocks. The size of circles indicates the market share for each month. Different colors indicate the primary location of mining pools. Mining pools highlighted in the grey background have pool characteristics information.

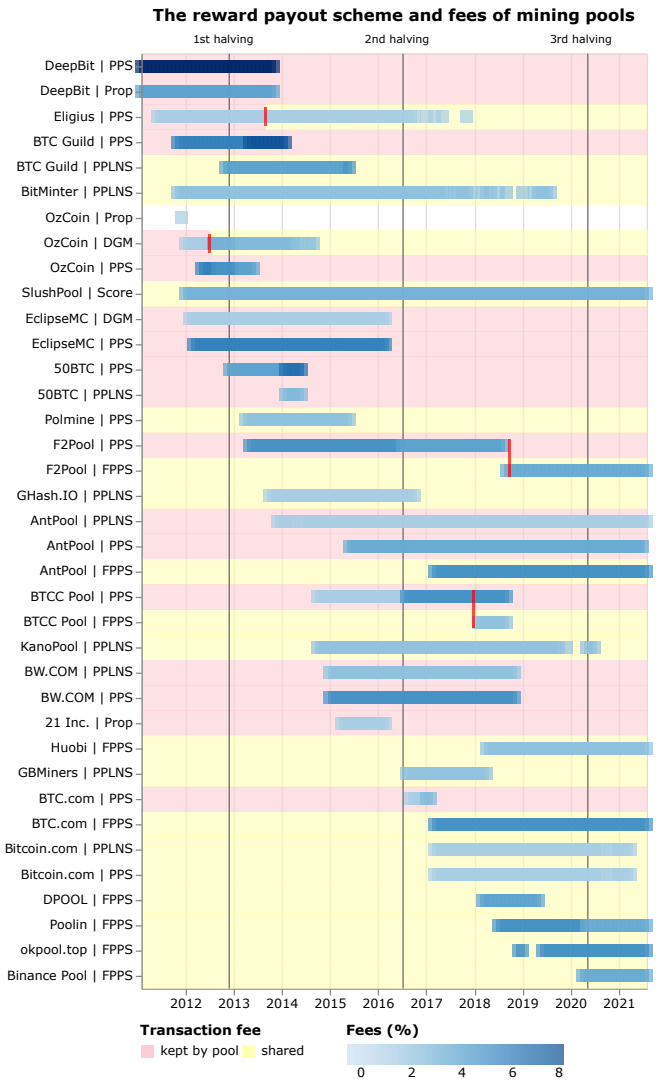

Fig. 3. Reward payout scheme and pool fees. The color scale indicates the pool fee for each mining pool separated by payout scheme, while the background color indicates whether the pool shares the transaction fee with miners.

are highlighted with a grey background in Fig. 2 while pool characteristics, including payout scheme and pool fee, are shown in Fig. 3.

B. Transaction flow and transaction purity

We defined transaction flow graphs and the transaction purity definitions before applying them to our payout flow model and heuristic algorithm.

Definition 1. A *transaction flow* is a directed graph of Bitcoin transactions from a seeding transaction. Each node represents a transaction tx in the transaction flow. A transaction has a timestamp attribute $time$. Each directed edge corresponds to a value transfer from a transaction to another. Therefore, whether it is the input or the output of a transaction depends on the direction of the edge. An edge contains the information about the amount of transferred $value$, and the public-key address of the $owner$. Each edge contains references to the receiving transaction node $receive$ and spending transaction node $spend$.

We adopted a *transaction purity* measure to determine how much Bitcoin value in the transaction is received from the seeding transaction. This measure is commonly used for taint analysis in Bitcoin (e. g., [22], [23]) to track the diffusion of money in the transaction network.

Definition 2. Let $tx.in$ and $tx.out$ be sets of receiving (inputs) and spending (outputs) edges of a transaction tx respectively. The *transaction purity* is recursively defined as being the average purity of the input transactions weighted by their respective values. The purity of a transaction tx can be expressed as follows:

$$purity(tx) = \frac{\sum_{e \in tx.in} purity(e.receive) \cdot e.value}{\sum_{e \in tx.in} e.value} \quad (1)$$

The purity of a transaction without inputs is 1 because it is the root transaction in the transaction flow.

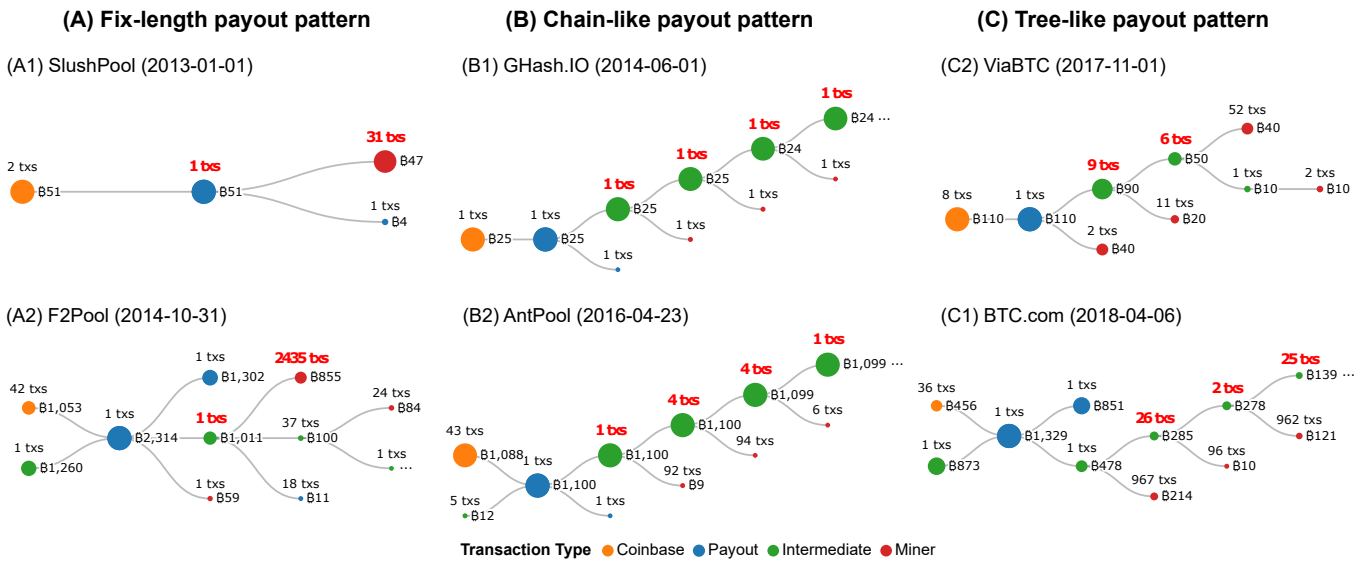

Fig. 4. Representative examples of reward payout flow patterns from the mining pools in our study. Each column shows one type of pattern: (A) fixed length, (B) chain-like, and (C) tree-like payout pattern. The flows were extracted using our algorithm and are represented as node-link diagrams. Here, we sampled the payout flow in the month where the mining pool had the highest market share. Each node represents a transaction type with branches of similar patterns grouped together. The color of the node indicates the transaction type. The total value of transactions in each node is encoded by circle size in proportion to the tx_{payout} value. The number of transactions and their combined value are the top and the right labels for each node respectively.

C. Mining pool payout flows

After a mining pool receives the mining reward from a coinbase transaction, the pool has to distribute the reward to pool members. Past work reported that mining pools distribute the reward to individual miners in different patterns [2], [13], [14], [24]. However, payout flows reported in those works were extracted manually. To assess payout flows more systematically, we introduce the payout flow model as a transaction graph consisting of four transaction types: coinbase (● $tx_{coinbase}$), payout (● tx_{payout}), intermediate (● tx_{inter}), and miner (● tx_{miner}).

1) A mining pool receives mining rewards from coinbase transactions ● $tx_{coinbase}$ and collects them in a payout transaction ● tx_{payout} before distributing it to miners.
2) A mining pool distributes the reward from ● tx_{payout} to intermediate transactions ● tx_{inter} before splitting rewards to pool member (miner) addresses.
3) Pool members receive the reward from ● tx_{inter} and spend it in a transaction we call miner transaction ● tx_{miner}. We assumed that pool members receive the reward from this flow and then combine it with other Bitcoin values outside the flow to spend in ● tx_{miner}. Therefore, the purity of ● tx_{miner} is < 1.

Based on this model, the *reward payout flow* is the Bitcoin transaction flow from a payout transaction ● tx_{payout} to pool members ● tx_{miner} . We considered ● tx_{payout} as the seeding transaction because it collects every mining reward and distributes it to pool members.

1) Extracting reward payout flows

We devised Algorithm 1 to automatically extract payout flows from the coinbase transactions. We used the BlockSci API [25] to access the transaction data. We initiated the list of ● tx_{payout} from all outputs of ● $tx_{coinbase}$ as inputs to the algorithm.

Algorithm 1: Reward payout flow extraction

Input : tx_{payout} is a payout transaction as a seeding node of the payout flow.
Output : $edges$ is the edge list of the payout flow.

```
queue ← PriorityQueue([tx_payout]);
edges ← List();
while queue is not empty do
    tx ← queue.pop();
    if purity(tx) = 1 and valid(tx) = True then
        for edge in tx.out do
            edges.append(edge);
            queue.append(edge.spend);
        end
    end
end
```

For each ● tx_{payout}, we traversed the transaction graph from ● tx_{payout} which has $purity = 1$ until the transaction has $purity_{tx} < 1$ (i. e., ● tx_{miner}). The algorithm returns a directed edge list that represents the payout flow.

We added two additional termination criteria $valid(tx)$ that stop following the current transaction tx flow: 1) when the time difference between ● tx_{payout} and tx is more than one day and 2) when the $tx.value$ is < 0.001 BTC—as most mining pools have a minimum payout value [13], [16].

2) Identifying individual miners.

For each edge list obtained from Algorithm 1, we constructed a payout flow graph using the NetworkX library [26]. Next, we extracted the ● tx_{miner} and derived the list of miners from each payout flow graph.

Definition 3. *Miner transaction* ● tx_{miner} is a transaction

in the payout flow graph that does not have any output in the payout flow graph $|tx_{miner}.out| = 0$. We tagged all input edge(s) of ● tx_{miner} as *owner* edges. The list of miners who received the reward from ● tx_{payout} is defined as $M_{tx_{payout}}$.

Some ● tx_{miner} transactions may be connected to the pool wallet to keep the represented value as profits for the pool or as deposits for the next payout, as illustrated in Fig. 4-A2 and C1. We detected ● tx_{miner} input edges that have the same *owner* addresses as the mining pool and assigned them as ● tx_{payout} to extract further reward payout flows.

Fig. 4 displays representative payout flow patterns that we obtained from the algorithm. We confirmed past work [24] that showed that payout flows of mining pools can be characterized into three patterns. (A) Fix-length pools paid rewards directly to miners within a small path length. (B) Chain-like pools paid a fixed number of miners and sent the remaining shares to their wallets to pay miners in the next step. (C) Mining pools split the reward into multiple intermediate transactions in a tree-like structure before sending them to miners.

D. Miners' migration between mining pools

To analyze miner migration between pools, we compared the list of miners who received rewards from each mining pool in a set time interval and calculated the intersection of miners between pools. We set the time interval to months to be able to analyze detailed patterns for the entire mining pool history.

Definition 4. Let t be a time interval where $t \in T = \{t_0, ..., t-1, t, t+1, ..., t_n\}$. The set of *miners in the mining pool* M^t_{pool} is the summation of the miner list $M_{tx_{payout}}$ for all payout transactions of a mining pool $pool$ at time t.

The miner's migration flow is modelled as a diagram in Fig. 5. For each time interval t, the list of miners that migrate from/to a mining pool $pool$, M^t_{pool}, is divided into 7 *miner groups* as follows:

- *New (Dropout)* miners are miners that enter (exit) the mining activity at time t, annotated as $M_{new|pool}$ ($M_{drop|pool}$).
- *Same before (Same after)* miners are in M^t_{pool} but are also in M^{t-1}_{pool} (M^{t+1}_{pool}).
- *Hopping in (Hopping out)* miners are in M^t_{pool} but move from (to) other pools $M^{t-1}_{others|pool}$ ($M^{t+1}_{others|pool}$).
- *Cross-pooling* miners are in M^t_{pool} but also receive a reward from other pools at the same t ($M^t_{others|pool}$).

We estimated the quantity of miners' migration as the percentage of the total value for each miner group. We report the percentage of value rather than the number of addresses because it gives more weight to miners that have a high contribution to the pool and therefore the measure is more robust regarding small or occasional miners.

Definition 5. The *percentage of the total value of miners* (X) is the total value of M^t_{pool} associated with M_x, where x is a set of miners from miner groups. We defined this measure as:

$$X(M^t_{pool}, M_x) = \frac{\sum_{m \in M^t_{pool} \cap M_x} m.value}{\sum_{m \in M^t_{pool}} m.value} \quad (2)$$

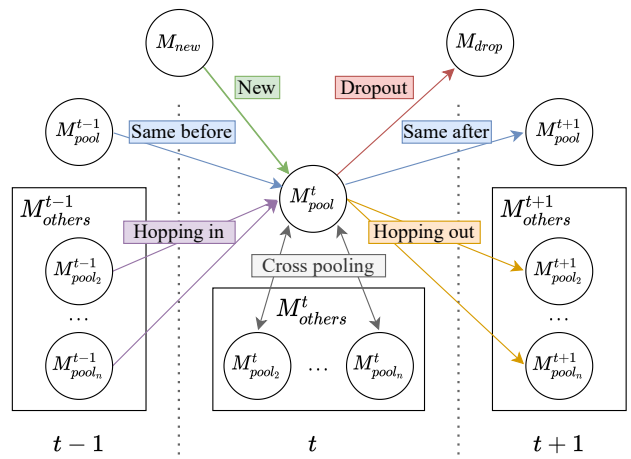

Fig. 5. The miners' migration flow model of $pool$ at time interval t. $t-1$ ($t+1$) is the time interval before (resp. after) t. M_{new} (M_{drop}) is the list of miners not in any pool at $t-1$ (resp. is not found in any mining pool at $t+1$). The union of the list of miners from other pools is M_{others}.

For example, the percentage of *hopping in* (*hopping out*) miners is annotated as $X(M^t_{pool}, M^{t-1}_{others|pool})$ (resp. $X(M^t_{pool}, M^{t+1}_{others|pool})$).

For each mining pool, we obtained the monthly percentage of miners' migration for each miner group. To understand the flow of miners in a mining pool, we summarized *miners' migration flows* into a net gain or loss metric for the pool from different flow types with 1) *New and dropout flow:* the percent difference between new and dropout miners; 2) *Hopping in and out flow:* the percent difference between hopping in and hopping out miners; and 3) *Cross-pooling:* the percentage of cross-pooling miners.

Additionally, we calculated *the percentage of cross miners' rewards from the pool* as the total reward that cross miners received from the pool divided by the total reward that cross miners received from all mining pools. A higher percentage implies that miners dedicated more computational resources to this particular pool. It also indicates the attractiveness of the pool compared to other pools at the same time interval.

E. Assumptions and limitations of payout flow extraction

Our approach rests on the assumption that individual miners who receive a reward share will spend it in a transaction that includes input transactions from outside the flow. The algorithm will make a false classification when a miner forwards the reward using a transaction without further inputs. In this case, the algorithm will calculate that the transaction purity is 1, assign it as ● tx_{inter}, and follow all outputs from ● $tx_{inter}.out$. We provided an evaluation to justify that our approach can be used to detect miners' addresses in our previous article [10].

Another important assumption is that mining pools spend only the mining reward from ● $tx_{coinbase}$ to distribute among their miners. Therefore, the purity of ● tx_{payout} and ● tx_{inter} is assumed to be 1. However, if the mining pool also uses bitcoin values to pay miners from an external source outside the flow, the algorithm will stop following the payout flow and falsely assign ● tx_{miner} instead of ● tx_{inter}.

Nonetheless, some mining pools distribute the reward to miners that violates two assumptions in our approach. As a result, those mining pools tend to have a small number of miners for each payout flow. We calculated the median number of miners for each mining pool. We removed 16 pools which we could only extract less than five miners per payout: 21 Inc., ASICMiner, Binance Pool, BitClub Network, BitFury, Bixin, BTCC Pool, BW.COM, DPOOL, Foundry USA, GBMiners, KnCMiner, Lubian.com, OzCoin, Poolin, and Telco 214. We found that these pools sent a large amount of reward to a few addresses, likely to be their own addresses. BitFury and Foundry USA were likely to be private pools that keep the reward in their wallets and do not show an obvious payout pattern. BW.COM and Binance Pool also provide wallet and exchange services, and therefore they can draw the money to pay miners from other sources outside the reward payout flow. Other dismissed pools were small and tended to operate only for a short period.

For these mining pools, the purity threshold could be adjusted to less than 1 in cases where mining pools add bitcoin values from other sources. We tried the lower purity threshold and found it to be computationally much slower. The algorithm tended to classify ● tx_{miner} as ● tx_{inter} and continued following the flow because miners could also combine the reward with other sources of money to spend in Bitcoin marketplaces and services. We found that this approach is inefficient in extracting payout flows on a large scale.

IV. Reward Payout Flow Patterns

Previous work has reported the payout patterns for a few mining pools in a limited time interval. Romiti et al. explored the payout flow pattern of three miners: BTC.com, AntPool, and ViaBTC [14]. Liu et al. reviewed payout patterns from previous studies and classified them into *direct* and *indirect* distributions and furthermore to *tree-like* and *chain-like* payout structures [24]. In this work, we studied the payout flow pattern of more mining pools over the entire Bitcoin history. We propose a new characterization of payout flows based on two measures:

1) **Payout irregularity** is measured from the correlation between the number of blocks mined and the number of payouts per month. Mining pools that *pay per block*(s) (or per round) to miners should have a high positive correlation since they distributed rewards to miners when they obtained a reward from a coinbase transaction. Mining pools that *pay miners regularly* (also called *regular payout*) should have a fixed number of payout transactions per day regardless of the block mined. Therefore, we expect no correlation or weak correlation among those regular payout pools.
2) **Path length to miners variability** determine the structure and complexity of reward payout flows. Mining pools distribute rewards to miners either directly from the payout transaction or forward them to intermediate addresses before paying to miners in multiple steps. We calculated the path length for each miner to see how many steps it took for miners to receive a reward from the payout transaction. The median absolute deviation (MAD) of path lengths describes the payout pattern for each mining pool. We will refer to this measure as "variability" of miners' path lengths. A high MAD implies that miners received rewards with diverse path lengths (i. e., some miners received reward shares with the path length of 2, 3, 4, and so on). A low MAD means that all miners receive a reward with the same path length.

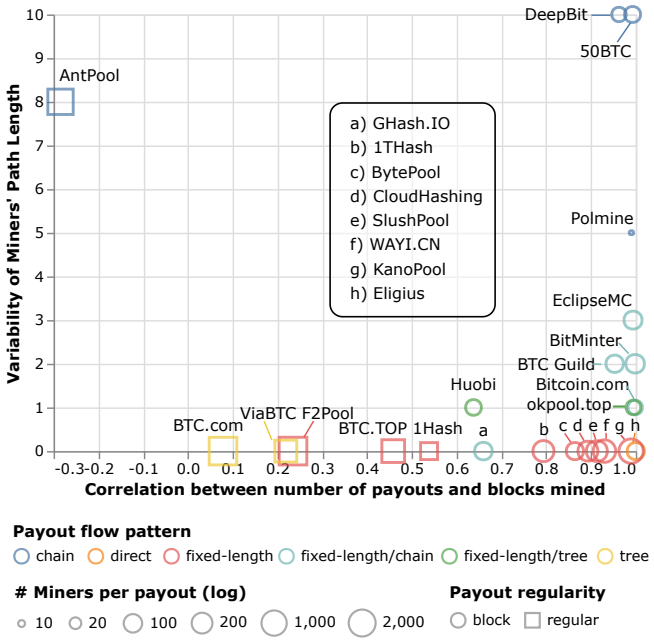

Fig. 6. The scatter plot shows the characteristics of payout flow patterns of mining pools regarding payout irregularity (y-axis) and payout flow structure (x-axis). The color indicates the payout flow structure and shape indicates whether a mining pool pays per block (round) or regularly (e. g., daily). The area of each point is proportional to the median number of miners per payout on the logarithmic scale.

Fig. 6 shows scatterplot of payouts positioned according to payout irregularity (y-axis) and miners' path length variability (x-axis). For each mining pool, we examined samples of payout flows and annotated what we found as the shape (payout regularity) and color (payout flow patterns).

A. Payout irregularity

Mining pools in the early years between 2011 and 2013 commonly distributed reward shares to miners directly after they successfully mined a block. DeepBit is the first mining pool that dominated the market and distributed the reward to miners for each block is mined. After the inception of DeepBit, other mining pools also adopted the same policy to pay miners per block, such as Eligius, BTC Guild, BitMinter, and SlushPool. Over the active period of each mining pool, the correlation between payouts and blocks mined is close to 1, implying that mining pools pay miners as much as they receive from coinbase transactions.

The *pay-per-block* policy is risk-free for mining pools because they do not need to hold any funds to pay miners [27]. Instead, miners accept uncertainty regarding the constancy of income as the expected reward time is inversely proportional to the market share of the pool [27]. This policy incentivizes some miners to move between pools (cross-pool) to maximize their reward. After the first halving day, mining pools that adopted

a *pay-per-block* policy tended to be less successful according to market share and eventually disappeared from the mining competition. Even though new *pay-per-block* mining pools emerged, they tended to be short-lived (e. g., Polmine, 50BTC, and CloudHashing). In contrast, mining pools that provided a more stable income to miners (e. g., F2Pool and AntPool) dominated the mining competition from 2014. SlushPool is an exceptional *pay-per-block* pool that is still active and constantly mined new blocks from 2012 until now.

Since 2013, new mining pools have offered miners a more *regular payout* to attract miners. These mining pools collect mining rewards to their addresses before distributing them to miners regularly (i. e., daily). Therefore, the number of payout transactions should remain constant over time. We found that mining pools that provide a *regular payout* to miners tend to have a low correlation between the block mined and the number of payout transactions per month in the range of -0.3 and 0.6. F2Pool and AntPool were early pools that implemented this policy from 2013 to 2014. BTC.com and ViaBTC emerged around the second halving day in mid-2018 and adopted the same *regular payout* policy. Nowadays, these four mining pools are the top pools in the mining market.

With the *regular payout* policy, mining pools guarantee to pay a predictable income to miners. Mining pools need to cope with financial risk due to the uncertainty of mining a block. They, therefore need funds to pay miners when they do not manage to obtain enough reward before the next payout [27]. These mining pools, therefore, tend to pose higher fees to miners. The domination of regular payout pools shows that miners prefer to join mining pools that provide a steady income. Nowadays, the top mining pools distribute rewards to miners regularly, indicating that mining has become an industry as mining pools are able to reserve funds and manage their risk.

B. Payout flow structure

The variability of path length to miners (y-axis on Fig. 6) implies the payout flow structure. Mining pools distribute the reward to miners using direct to more complex patterns, making it harder to identify miners.

A median path length variability (MAD) of 0 implies that mining pools were likely to distribute rewards to all miners with the same path length. We call this a *"fixed-length"* payout pattern. This pattern has been used by pools that started operating between 2011 and 2014: SlushPool (Fig. 6-A1), CloudHashing, and KanoPool. Eligius is an exceptional pool that paid miners *directly* from the output of coinbase transactions. Mining pools applying this pattern send all mining rewards from coinbase transactions to their own addresses and distribute the rewards to all miners in the same payout transaction. Due to the simplicity of this payout flow, it minimizes the number of transactions for each payout. However, miners' addresses can be easily inferred from the flow. Despite this concern, the pattern is widely used among recent small-size pools, such as KanoPool and WAYI.CN, and 1THash. Exceptionally, F2Pool (Fig. 6-A2) offers a regular income to miners and uses this *fixed-length* pattern to pay miners.

Mining pools that distribute rewards to miners in a *"chain-like"* pattern have a path length variability > 1. DeepBit and GHash.IO (Fig. 6-B1) paid reward shares to a single miner per step and kept the change to pay other miners in subsequent transactions as the payout chain grows. Three pools that emerged after GHash.IO, EclipseMC, 50BTC, and Polmine, also utilized the same payout pattern. With this pattern, mining pools create as many transactions as the number of contributing miners and, therefore, have high path length variability. However, this payout pattern was only feasible in the early periods of mining pools due to the small number of miners, high block rewards, and negligible transaction fees. Many mining pools from 2012 to 2013 adopted this payout pattern but payed to multiple miners at each step, including ElicpseMC, BTC Guild, BitMinter, and Bitcoin.com. This pattern helps reduce the number of intermediate transactions, and therefore, the total transaction fees to distribute reward shares. The variability of their payout flow dropped to around 1–3 path lengths. AntPool (Fig. 6-B2) is the only regular payout mining pool that adopts this payout structure.

As more miners participate in mining pools, ViaBTC and BTC.com (Fig. 6-C) switched to a *tree-like* payout structure to distribute rewards to more miners in a few steps. They are currently the top mining pools with 12% and 9% of market share, respectively (as of Aug. 2021). For each payout flow, a mining pool splits rewards into multiple intermediate transactions before sending them to miners' addresses. These pools have a low miners' path length variability (MAD = 0–1) because miners receive reward shares from different intermediate transactions but with the same path length.

From this analysis, we witnessed the development of payout flow structures from a *chain-like* structure used by the first mining pools to *fixed-length* patterns that have been used more recently. Most mining pools adopt simple payout flow patterns (e. g., *direct* and *chain-like*). Nowadays, active large mining pools deploy *tree-like* distributions to pay a large number of miners with short path lengths. A *tree-like* pattern is commonly found in current pools because it reduces transaction fees with lower path lengths. These three patterns make miners easy to trace using our heuristic. To make miners less detectable, mining pools should mix the reward with money outside the flow and miners should change addresses which they receive rewards from the pool.

V. Economic Analysis of Mining Pools Evolution and Miners' Migration Behavior

We present miners' migration flows over time in Fig. 7 and explore whether the collective behavior of miners affect the evolution of market share and pool characteristics (i. e., payout schemes and pool fees).

A. Convergence to Full-Pay-Per-Share (FPPS) payout scheme

In the competition to attract miners, payout schemes and pool fees are major pool characteristics that directly impact miners' income. Fig. 7-A illustrates that fee and payout schemes exhibit the usual economic evolution observed in the competition context. The Proportional payout scheme was used at the beginning of Bitcoin and disappeared in 2013 [28]. Over time, mining pools switched progressively to Pay-Per-Share (PPS) and Pay-Per-Last-N-Shares (PPLNS) payout schemes. As PPS and PPLNS are more robust to pool hopping than

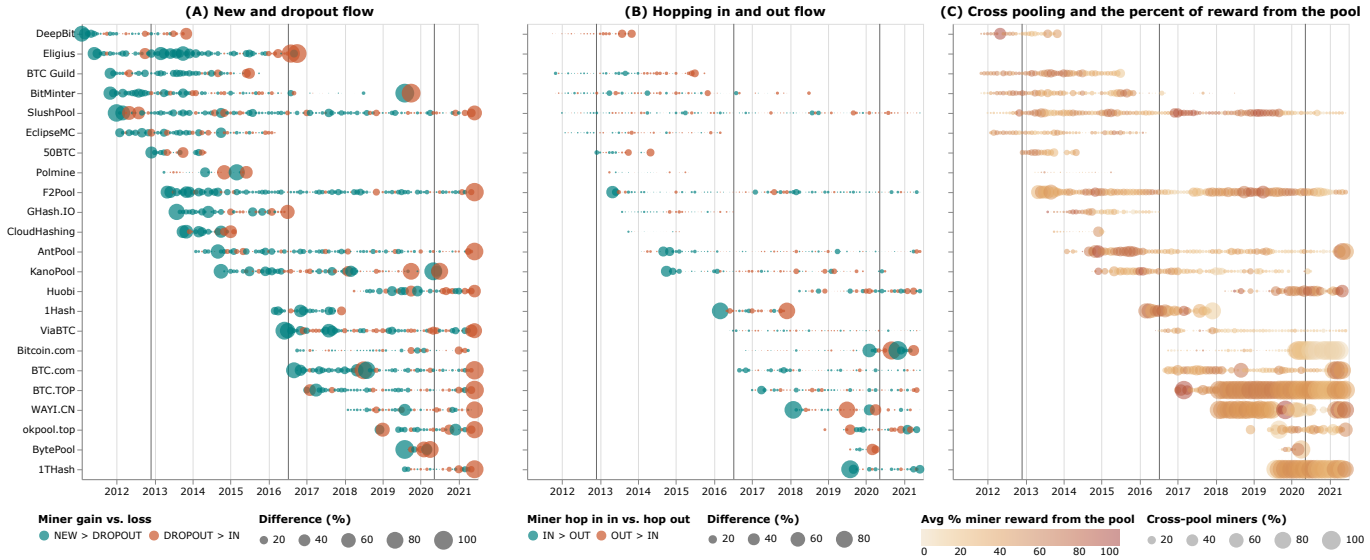

Fig. 7. Miners' migration flow statistics. (A) New and dropout flow. The size of the circle represents the absolute difference between new and dropout miners. New miners' positive (or negative) flow is encoded with green (or red) color. (B) Hopping in and out flow. Circle size represents the absolute difference between hopping in and hopping out miners. The color indicates more hop-in miners than hop-out miners (green) or vice versa (red). (C) Cross pooling. Circle size corresponds to the percentage of cross-pooling miners. The percentage of reward that cross-pooling miners obtained from the pool is encoded using a brown color scale. Three grey vertical lines in each chart indicate halving days on Nov. 28, 2012, Jul. 9, 2016, and May 11, 2020.

the proportional reward [27], these payout schemes are more attractive for pool managers.

A second explanation for the growing use of PPS and PPLNS relies on their different but complementary risk/return ratios. PPS pools pay miners in proportion to their contribution to the pool, thus providing risk-free, low income. All the risk is carried by the pool, which needs to create a reserve of money to pay the miners during "bad luck" periods. PPLNS pools pay only those miners who contributed to the last N shares in a given time window. Miners who contribute but leave the pool before a block has been mined might not get any reward. Therefore, PPLNS leaves all the risk to the miners, and the expected reward variance is higher compared to PPS [27].

PPS and PPLNS can be viewed then as two different *financial assets*. For this purpose, it is noticeable that the fees applied to these two financial assets follow the classical *two-parameter financial asset pricing model* [29]. In financial markets, risky assets must have a higher expected return to be attractive. In the case of Bitcoin mining, Fig. 7-A is consistent with this scheme as the more risky asset (PPLNS) is likely to have a lower fee (≈0%) compared to the risk-free one (PPS, ≈2-3%).

After the 2nd halving day, PPS mining pools increasingly switched to FPPS (Full-Pay-Per-Share) payout schemes, notably BTC.com and F2Pool in 2017 and 2018, respectively (Fig. 3). From 2019, FPPS became the dominant payout scheme with more than 50% of the total market share. It implements the same PPS protocol to share a constant income to miners while also sharing transaction fees with miners. AntPool is the only top pool that still offers the PPLNS payout scheme in addition to FPPS. This result implies that miners prefer to receive a regular payment, and mining pools have become an industry since they need to manage the risk from mining activity. New mining pools have more difficulty competing in Bitcoin mining as they need more reserved funds to cope with the risk when they start to operate. Nonetheless, the FPPS payout scheme makes the mining market more stable as it demotivates miners to hop between pools [27] and gain more profit from arbitrage.

B. *Cross-pooling and new pools discovery*

Even though we focus on mining pools that mined > 1,000 blocks, Fig. 2 shows that new pools constantly appear in the mining competition. When a new pool begins its business, it uses popular forums (e. g., Bitcointalk.org, Reddit, or Twitter) and its websites to advertise information about the pool (e. g., payout schemes, pool fees, and node addresses) to attract miners. Most mining pools did not have a formal legal existence, especially during the first years of Bitcoin. Therefore, miners needed to rely on the honesty of pool managers. Scams such as the Ponzi scheme involving dishonest pools have been observed, such as with the BitClub Network [30]. This uncertainty about pool honesty can lead miners to implement "trial and error" mechanisms to learn about the reliability and profitability of a new pool [31]. For this purpose, they can dedicate some of their computational resources toward these new pools to check if the pool's operations (e. g., payout frequency, minimum payout threshold, and shared transaction fee) and outcomes are in line with those advertised.

Consistent with this behavior, Fig. 7-C shows that from 2013 cross-pooling tended to be very important at the beginning of many new pools. This cross-pooling occurs from incumbent pools toward the new pools, especially if the latter offers similar or better-than-expected income. For instance, F2Pool proposed remunerating miners using a PPS payout scheme with 4% fee when entering the mining market in 2013. At that time (May 2013), the three biggest pools were BTC Guild (PPS, 5% fee), 50BTC (PPS, 3%), and SlushPool (Score, 2%). The entry of F2Pool is associated with an important cross-pooling between those pools, and especially with BTC Guild, which provides lower payouts (see Fig. 8-A). The same dynamic can be observed in Fig. 8-B with the entry in 2014 of AntPool

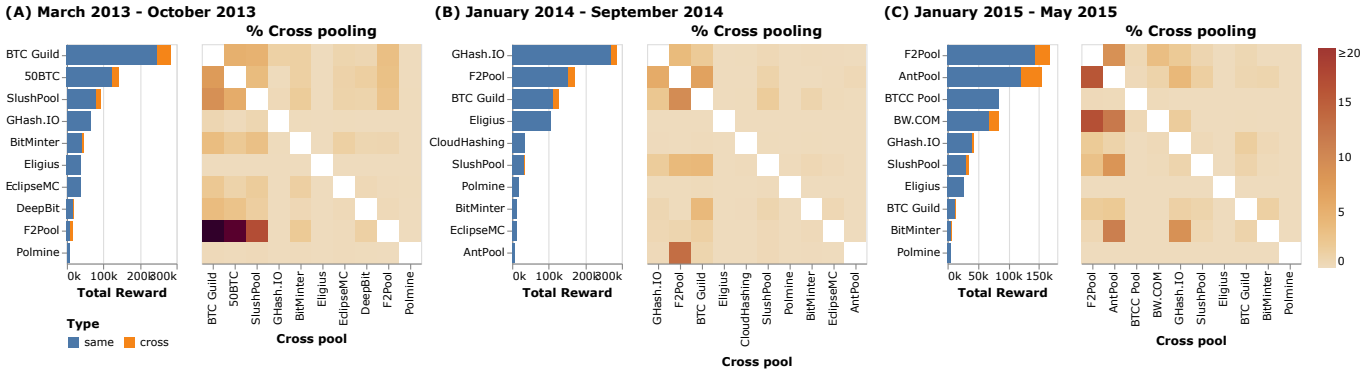

Fig. 8. Cross-pooling among mining pools during three periods: (A) Mar.–Nov. 2013, (B) Jun.–Dec. 2014, and (C) Nov. 2016–Feb. 2017. The stacked bar chart shows the total reward distributed from each mining pool during the period as a proxy for the pool size. Mining pools are sorted from the highest to the lowest value. Each bar is separated by the total amount of non-cross-pooling miners (in blue) and cross-pooling miners (in orange). The heatmap shows the percentage of cross-pooling miners from a mining pool in the row to another mining pool in the column. For instance, the dark cells in (A) indicate a large cross pooling of miners from F2Pool (row) to BTC Guild and 50BTC (column).

(PPLNS, 0%). It generated large cross-pooling with the main existing pools: GHash.IO (PPLNS, 0%), F2Pool (PPS, 4%), and Eligius (PPS, ~0%). In Fig. 8-C, BW.com (PPS, 4%; PPLNS, 1%) is also associated with cross-pooling with the current largest pools—F2Pool (PPS, 4%) and AntPool (PPLNS, 0%)—when it entered the market in 2015.

C. Mining pool fees and the attractiveness of the pool

Pool fees are used as a competitive advantage for mining pools. Within each payout scheme type, new pools tend to apply a lower fee than the incumbents. For instance, DeepBit applied a relatively high fee for PPS (10%) as the first dominant mining pool between 2011–2012. In 2012, mining pools, such as BTC Guild, applied lower PPS fees (5%) to attract new miners (Fig. 7-A) and hopping-in miners (Fig. 7-B), probably from DeepBit, which had more hopping-out miners in the same period. Still focusing on PPS pools, we see the same pattern in 2013 when F2Pool (4%, named Discus Fish at the time) or 50BTC appeared (3%), then in 2014 with AntPool (2.5%), and in 2016 with BTC.com (1.5%). This competition led to a decrease in pools' average PPS fees, which stabilized around 2% from 2016. The same dynamics occurred for PPLNS pools. While BTC Guild has applied a 3% fee since 2011, 50BTC created in 2012 applied a lower fee (2.5%). This trend got stronger with GHash.IO (0%) in 2013 or AntPool (0%) in 2014. When these pools appeared with lower fees, new miners were attracted by those pools (Fig. 7-A) and hopped out from older pools (Fig. 7-B).

Over this period, the dynamics of market shares of mining pools are mainly driven by new and dropout flow (Fig. 7-A). Mining pools that gain market share tend to attract new miners while miners drop out from pools that lose market share. This feedback loop probably explains the domination of a few mining pools at a time. We observed a small number of pool-hopping miners when there is competition for lower pool fees (Fig. 7-B). New successful pools adopted lower fees to attract miners while the older ones declined or stopped operating if they did not follow this trend.

After 2015, pool fees tended to converge to similar levels for both the PPS and PPLNS payout schemes (followed by FPPS in 2018) that pays constant income to miners. Moreover, pool fees tended to converge to the lowest fee possible for each available scheme. As a result, pool-hoping miners decreased as there was no incentive for miners to perform pool hopping to maximize their income (Fig. 3).

D. Sharing transaction fees to attract miners

Block rewards were high before the 2nd halving day (50 BTC and 25 BTC accordingly). At the same time, transaction fees were relatively low and were probably irrelevant for miners when choosing a pool (Fig. 9-A). Mining pools in this period usually shared block rewards with miners and kept transaction fees to themselves. After the 2nd halving day, transaction fees steadily increased, partially to compensate miners for losing block rewards. We saw two critical peaks of transaction fees in 2017: the first one from February to June and the second one from October to December (highlighted with grey backgrounds). For these two periods, we are interested in studying whether the policy of mining pools to share transaction fees or not impacted the pool hopping behavior of miners.

The first peak illustrates the rising trend of top mining pools to share transaction fees with miners. First, three mining pools (AntPool, BTC.COM, and Bitcoin.com) switched from not sharing to sharing transaction fees during the beginning of the rise (Fig. 9-A). Secondly, mining pools that still did not share transactions fees (F2Pool and BW.COM) saw their market shares decrease (see Fig. 2). Conversely, mining pools that already shared transaction fees before this period (ViaBTC) or started to share (AntPool and BTC.com) sustained or improved their market shares (see Fig. 2). The second peak at the end of October exhibited the same patterns. The most dynamic pools already shared transaction fees (e. g., BTC.com, ViaBTC, and SlushPool). BTCC Pool that did not share transaction fees started to do so. We noticed that mining pools that did not share transaction fees tended to face a decline in market shares (e. g., BW.COM).

Moreover, we also observed that miners were hopping out from mining pools that did not share transaction fees to miners. During the first peak, Fig. 7-B shows that miners hopped out from F2Pool and BTCC Pool to join pools that shared transaction fees such as AntPool and BTC.Com. The same dynamic also happened during the second peak of transaction

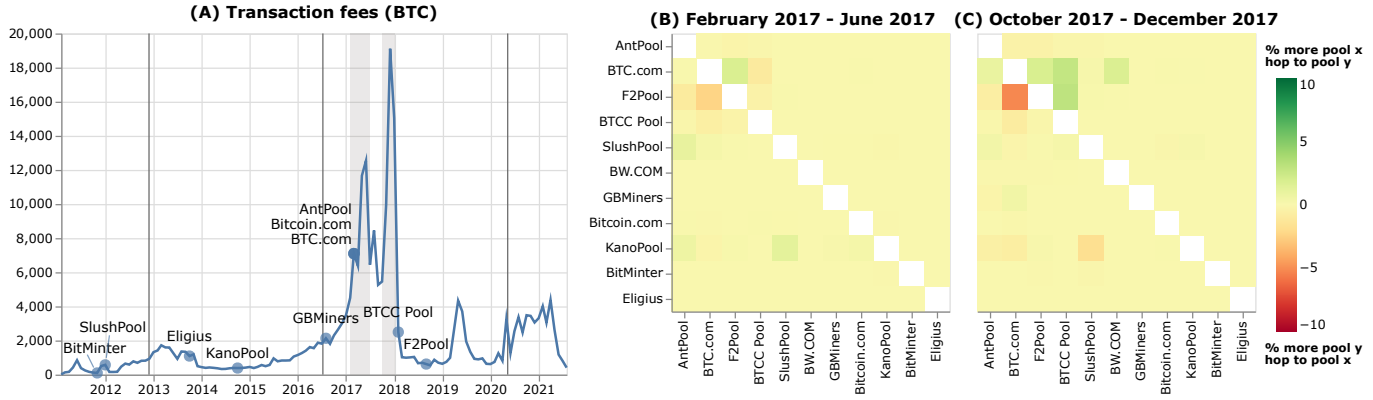

Fig. 9. The evolution of transaction fees and pool hopping behavior. (A) Transaction fee over time with an annotation on the first month that mining pool changed their policy to share transaction fees. The grey background highlights two periods with a peak in transaction fees. The heatmaps in (B) and (C) display hopping in and out flows from mining from two periods in Feb.–Jun. 2017 and Oct.–Dec. 2017, respectively. The color scale encodes the percentage of mining pools for each row hopping in to (positive value) or hopping out from (negative value) the pools listed on the column.

fees (see Fig. 7-C), during which miners from F2Pool and BTCC Pool hopped out toward BTC.com and AntPool probably to benefit from shared fees policy. The migration of miners from BTCC Pool and F2Pool might motivate their decisions to share transaction fees in 2018. Nonetheless, the effect of pool hopping in these two periods was not obvious because more miners were joining the mining activity.

These trends highlight the growing role of transaction fees in pools' competition. As long as transaction fees have been low, mining pools tend not to share them. Once transaction fees represented significant money, it became a competitive advantage between pools. Mining pools that already shared them became more attractive, involving competitors to follow them or see otherwise their market shares decreasing. From 2017, sharing transaction fees seemed to become the norm for pools (Fig. 3). New pools and incumbent ones shared transaction fees with miners either using the PPS or PPLNS.

E. High percentages of cross-pooling in recent mining pools

In Fig. 7-C, we observed a high percentage of cross pooling among mining pools operating from 2018. To investigate further, Fig. 10 illustrates the cross pooling view in our MiningVis tool [32] for each year from 2018–2020. Considering the percentage of cross pooling and the amount of cross-pooling flow, we found a consistent cross-pooling behavior between three Chinese-based mining pools: BTC.TOP, WAYI.CN, and 1THash. BTC.TOP is a private pool while WAYI.CN and 1THash offer cloud mining services. All of 1THash and WAYI.CN miners are from BTC.TOP. We suspect that these miners come from the same entity or use the same wallet, private pool (BTC.TOP) or mining platform (e. g., Bitdeer [33]) to increase their income by joining mining cloud services.

In 2020, we saw cross-pooling between Huobi and okpool.top miners. Both of them provide broad services to miners, including pool, cloud computing, wallet, and exchange. Miners may use the wallet associated with any or both pools to receive the reward and, therefore, collectively may produce additional flow between both pools that may not be related to mining. This current practice of mining pools to operate together with wallet and exchange service, thus, poses a new challenge to track miners. Mining pools can draw from other sources of money kept in Bitcoin services (e. g., from wallet and exchange services) to pay reward shares to miners. Miners may not receive their reward share directly from coinbase transactions, and therefore we cannot trace them directly on payout flows.

F. Impact of Chinese government policy on mining pools

Chinese mining pools (e. g., AntPool and F2Pool) emerged in the market around 2013 and increasingly became the dominant source of Bitcoin mining power. According to our previous analysis [28], the total market share of Chinese mining pools exceeded the 51% majority attack threshold in Mar. 2015 until early-2017. At this point, the mining community raised concerns that Chinese pools had relatively too much computational power [34], [35] and could collectively pose a threat to the Bitcoin network [36], [37].

The Chinese authorities monitored activities in Bitcoin closely [38]. The People's Bank of China banned cryptocurrency trading, and peer-to-peer lending in Sep. 2017 [39]. Compared to our pool characteristics information in Fig. 2, many Chinese pools in this period transformed themselves into global pools, including three top mining pools: BTC.COM (Mar. 2017), AntPool (Aug. 2017), and F2Pool (Sep. 2017). Two Chinese pools, BTCC Pool and BW.COM, disappeared from the mining competition.

In May 2021, Chinese authorities shut down Bitcoin trading and mining by shutting electricity supply to mining farms [40]. The total hash rate suddenly dropped in this month (Fig. 11-A). From the miners' migration flow in Fig. 7-A, we found a large number of dropout miners for most of the active pools, such as BTC.COM, BTC.TOP and okpool.top. Interestingly, the market shares of Chinese pools (e. g., Huobi, 1THash, and BTC.TOP) suddenly dropped after this event (Fig. 11-B). Between Apr. and Jun. 2021, we observed some evidence that more miners from Chinese mining pools hopped to global pools (Fig. 11-C): 1) BTC.TOP and 1THash miners migrated to AntPool; 2) Huobi miners hopped in to F2Pool; 3) WAYI.CN miners moved to BTC.com. At the same time, we saw a positive flow from WAYI.CN to AntPool. However, the WAYI.com pool size was tiny, and the percentage varies widely from only a few miners. Nowadays, miners moved their facilities to America and Central Asia [41], making the total hash rate gradually

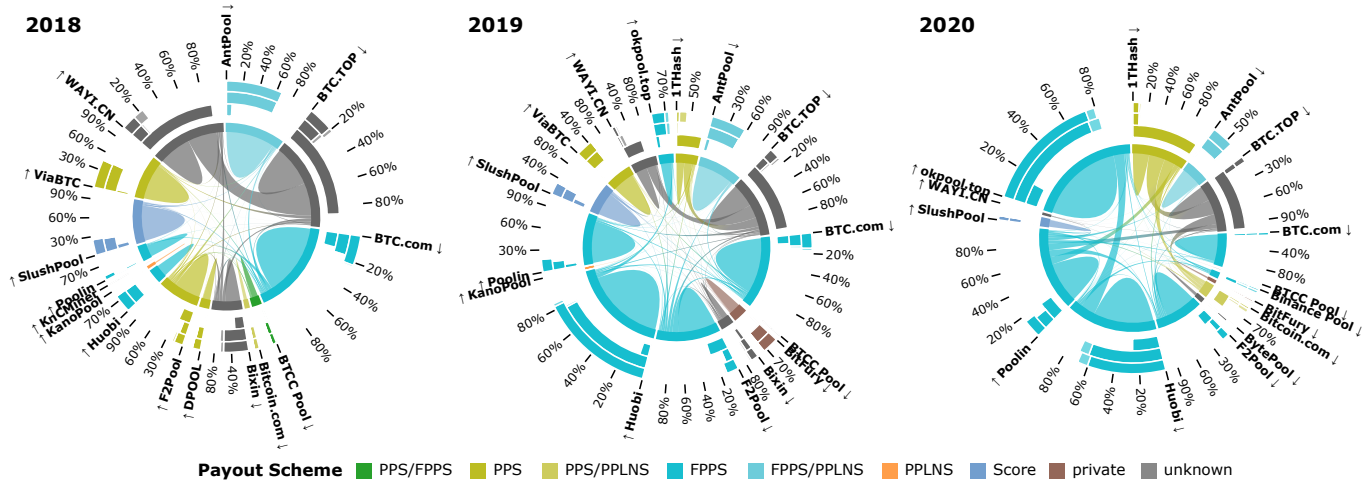

Fig. 10. The chord diagram displays the cross-pooling between mining pools from 2018–2020. The flow size is proportional to the amount of bitcoin currency miners received between two pools. The circular bar charts above each pool indicate the percentage of miners in each category, from top to bottom: 1) new/hopping in, 2) dropout/hopping out, and 3) cross pooling. The colors of hopping in and out miners are more transparent in the 1st and 2nd row, respectively.

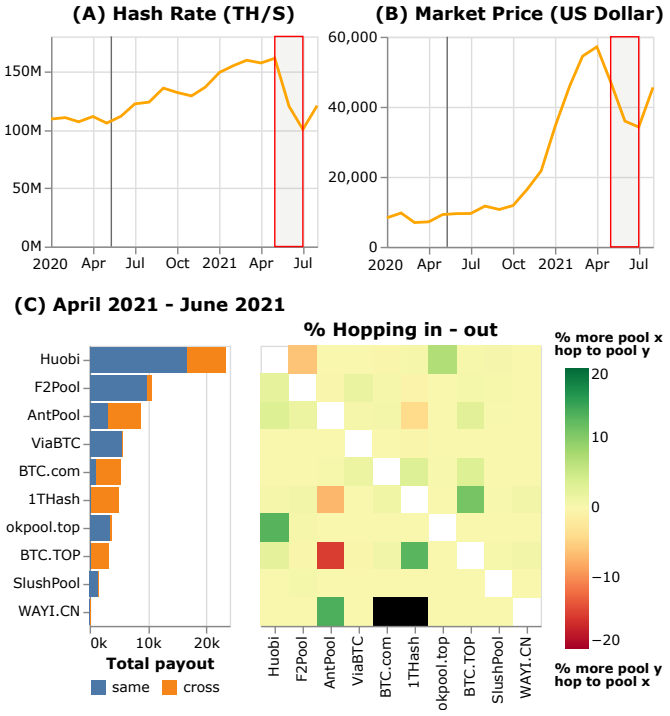

Fig. 11. (A) The total hash rate (in TH/S) and (B) the market price (in US Dollar) of Bitcoin. The time period in which the Chinese government shut down mining farms between Apr.–Jun. 2021 is highlighted in the red box. (C) The hopping in and out flow of mining pools over that period.

recover (Fig. 11-A).

VI. Summary and Conclusion

We proposed a characterization of payout flow patterns and revised our findings on pool hopping behavior among 23 mining pools until Aug. 2021. Mining pools distribute reward shares to miners in the transaction graph we call the *reward payout flow*. Payout flow patterns can be categorized using two quantitative measurements: variability of path length to miners and payout irregularity. We reported the evolution of payout flow patterns from fixed-length and long-chain structures to more complex patterns like tree-like ones. The result provides evidence that Bitcoin mining has become a competitive industry. Most current pools guarantee a regular income to miners and cope with the uncertainty of financial revenue during bad luck periods.

We curated extensive datasets on the market shares of mining pools and pool characteristics over time. The data is available in a public repository [17]. We analyzed the impacts of both Bitcoin internal factors and external ones on miners' mobility (i. e., *cross pooling* and *pool hopping*). The results demonstrate that internal (e. g., pool fees, halving day, and transaction fees) and external (e. g., market price, news, and regulations) factors impact the evolution of the mining pool competitions. Miners consider those factors deciding to enter, hop, cross-pooling, or drop out from/to the pools. The rise of Bitcoin mining prices encouraged more miners to join the pool. Moreover, critical events in Bitcoin mining influenced miners' decision to enter or leave mining activities. In particular, we found that a recent Bitcoin mining ban in China had a significant and immediate impact on mining activity but gradually recovered a few months later. These findings provide evidence that mining pools' competition is still changing and needs to be monitored constantly with all relevant factors.

In the foreseeable future, the sustainability of Bitcoin mining will become critical as mining reward is expected to be halving in early 2024. Until now, the rise of the Bitcoin market price has driven an increase in mining activities. We expect the market to be stable regarding a few top mining pools if the market price remains at the same level. Mining pools are likely to converge to the same FPPS payout scheme and provide roughly the same reward incentive to miners. Government regulation and policy can have a considerable impact on mining activities. However, Bitcoin mining proved to be quite robust when the Chinese government banned Bitcoin mining. Future work should assess mining activity related to three crucial factors: 1) the compensation of transaction fees due to the block reward diminished, 2) Bitcoin market price, and 3) the environmental cost of Bitcoin mining.

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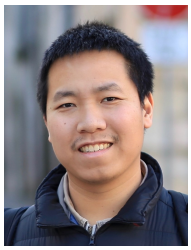

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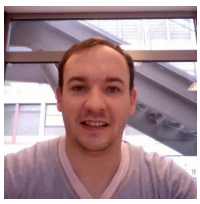

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