Transaction Characteristics of Bitcoin

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***Abstract*—Blockchain has been considered as an important technique to enable secure management of networks and network-based services. To understand such capabilities of a blockchain, e.g. transaction confirmation time, demands a thorough study on the transaction characteristics of the blockchain. This paper presents a comprehensive study on the transaction characteristics of Bitcoin – the first blockchain application, focusing on the underlying fundamental processes. A set of results and finding are obtained, which provide new insight into understanding the transaction and traffic characteristics of Bitcoin. As a highlight, the validity of several hypotheses / assumptions used in the literature is examined with measurement for the first time.**

***Index Terms*—Blockchain, Bitcoin, Transaction Characteristics**

I. Introduction

Blockchain has been considered as an important technique to enable secure management of networks and network-based services, such as virtual network functions (VNF) [1] and network slices in 5G and beyond networks [23]. To this aim, understanding the capabilities of the blockchain, e.g. in terms of delay or transaction-confirmation time, is necessary. This naturally demands a thorough study of the transaction characteristics of the blockchain [25], with which, analytical methods (e.g. queueing theory) may be employed to estimate the performance of the blockchain [11] [17].

Surprisingly, even for the first blockchain application, Bitcoin [22], such studies are still limited. Most of the literature studies focus on analyzing the Bitcoin transaction's identity and security impact, such as [2], [12], [14], [15], [16], [19] [21], [24], and [27], while only a few have investigated the transaction and block characteristics. For instance, to motivate an exponentially distributed block inter-generation time, two hypotheses on block generation at each miner have been made, namely Bernoulli trial in [13] and uniform distribution in [26]. However, no existing work has investigated whether exponentially block inter-generation times can be justified by measurements. In addition, among the existing results, e.g. various Bitcoin statistics [9], block propagation delay [7], block arrival process [5], transaction rate and transaction confirmation time [11] [17], most are directly generated or derived from the information carried on the Bitcoin blockchain. However, to obtain a deeper understanding of the transaction characteristics of Bitcoin, such information is not sufficient. For instance, in the literature, Poisson transaction arrival process has been widely assumed, e.g., [11] [17], but due to lack of information on the blockchain about the arrival time of a transaction to a node, the validity of this assumption has never been verified.

The objective of this paper is to report results and findings from an extensive study of the transaction characteristics of Bitcoin, which not just provide answers to the above mentioned open questions, but also sheds new light on understanding and studying the capabilities of the Bitcoin blockchain. Specifically, the focus is on the most fundamental processes behind Bitcoin, which include the transaction arrival process, the block generation and arrival processes, and the mining pool process. To this aim, a measurement-based study has been conducted, where a dataset has been gathered which contains both information that is globally available from the Bitcoin blockchain, i.e. the ledger, and information that is not available from the ledger but is measured from the local memory pool (mempool). It is worth highlighting that, among these focused processes, the ledger only has timing information for the block generation process, and for the other processes, local measurements are necessary. Based on the collected data, an exploratory study on the transaction characteristics of Bitcoin has been conducted.

The results and findings, which constitute the main and novel contributions of this paper, are organized and presented from three angles. Firstly, transaction characteristics at the block level, such as block generation, block arrival and block size characteristics, are considered. As a highlight, it is found that, even though the block generation time (at the Bitcoin system level) fits well with an exponential distribution, *the two hypotheses on block generation at each miner are both not justified*. Instead, we find another explanation, which is, *block generation at major miners has exponentially distributed inter-block generation time*. Secondly, transaction level characteristics are focused, which include transaction generation, transaction arrival, transaction size and fee characteristics. Here, *the Poisson transaction arrival assumption is examined*. Thirdly, the dynamics of the mining pool, which underlays the block generation process and relates it to the transaction arrival process, are investigated. In particular, the effect of fee, a fundamental element of Bitcoin as a digital currency, is included. As a highlight, it is found that *the fee-based priority queueing model* assumed in the literature [11] [17] *does not match with the observation*. These results and findings, to the best of our knowledge, has not been previously reported, which provide new insights into understanding the transaction characteristics of Bitcoin.

The rest of this paper is organized as follows. Section II introduces the measurement setup and the collected dataset. After that, Section III introduces results and findings on block level transaction characteristics. Section IV presents results and findings on transaction level characteristics. Following that, in Section V, the dynamics of mempool are focused. Finally, Section VI summarizes the paper.

II. Measurement Setup and Dataset Summary

For the measurement study, a testbed as shown in Fig. 1, has been implemented to record information about Bitcoin transactions. The testbed includes a server installation of a full Bitcoin node.

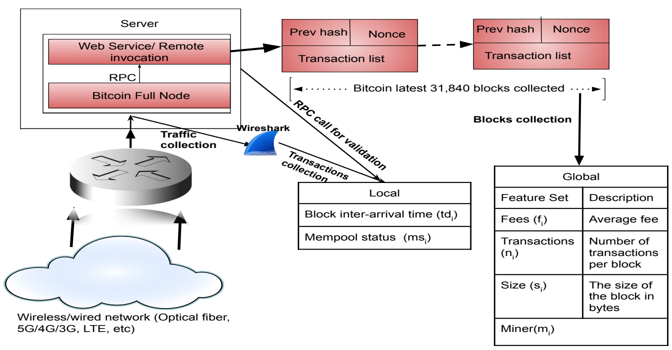


Figure 1. Testbed deployment and dataset attributes

Through the testbed, a dataset, consisting of two parts, has been collected. One part of the dataset records information from the ledger that is globally available, called the *global information part*. Another part records locally available information about each transaction and block as well as the backlog status of the mempool. This part is called the *local information part*. The measurement period of the dataset is from 7th March 2019 till 3rd October 2019, and the dataset consists of over 79 million transactions contained in 31 thousand blocks on the ledger and recorded at the installed full node.

The ledger dataset was collected through a REST API that enables RPC calls to the installed node to collect information about blocks and transactions. The mempool dataset was collected through Wireshark that collects traffic information from the network interface of the node, while RPC calls to the installed node were done to validate that the extracted transaction is available at the mempool. To do so, we used a C++ code to act as a middleman between the installed node and traffic collection from the interface, as demonstrated in Fig. 1.

The recorded information in the global information part of the dataset includes, for each block b on the blockchain, the number of transactions (n_b) in the block, the block generation time (g_b), its miner (m_b), the size of the block (s_b), and the fee (f_b). The locally recorded information from the installed full node includes for each transaction i, the arrival time timestamps (a_i), the transaction fee (f_i), and the size (s_i), and additionally for each block b, its arrival time (a_b). A brief summary of these focused features is also shown in Fig. 1.

In the literature, several platforms provide similar datasets. However, the data extracted from such a source lacks some information that is available in ours. For instance, the set of mempool features, timestamp (a_i), transaction fee (f_i), and size (s_i), which are related to transaction arrivals, are unique in our dataset which generally is not available form the literature platforms. With such information, we can extract the number of bytes that arrive at the mempool in an interval. Additionally, some more detailed information related to each block, which is gathered from the installed full node in our testbed, is not available in the other sources. In particular, in each block, there are many transactions, and each transaction has a number of attributes such as size, fee, and timestamp. Such detailed information cannot be found from outside sources: What is available there is only some piece of general information. Table I provides a comparison of what transaction and block attributes are included in the several well-known platforms and ours, where *IIK testbed* represents our testbed.

Table I
Data source comparison

Dataset	Locally recorded attributes				Block attributes			
	a_i	f_i	s_i	a_b	g_b	f_b	n_b	s_b
Blockstream [4]	×	✓	✓	×	✓	×	✓	✓
Bitaps [3]	×	×	×	×	×	✓	✓	✓
Btc [9]	×	×	×	×	✓	×	✓	✓
Explorers [8]	×	×	✓	×	×	✓	✓	✓
IIK testbed	✓	✓	✓	✓	✓	✓	✓	✓

III. Block-Level Characteristics

In this section, a number of transaction characteristics at the block level are investigated, which are related to block generation and arrival time processes, the number of transactions in a block, and block size.

A. Inter-Block Generation Time

The Bitcoin system uses the UTC +1 zone to synchronize full nodes. Using the same timezone among nodes helps to reduce wrong interpretation or modification of information to a different order. At the generation of a block b, its generation time g_b is added to the block. In this way, the Bitcoin blockchain keeps track of block generations in the system.

Fig. 2 shows that the inter-block generation time of Bitcoin can be excellently matched with a negative exponential distribution, as also reported in the literature [13][26], event though there is some deviation at the tail likely attributed to the very low number of observations in the tail. Additionally, the inter-block generation times are tested for dependencies and none are found

To further find explanation for the exponentially distributed inter-block generation time, we investigate this distribution of each miner. To this aim, the contributions of main miners to block generation is first examined and the results are shown in Fig. 3(a). The figure shows that the majority (80%) are contributed by the few top private miners including Antipool, BTC, BTC.Top, BitFury, F2pool, and viaBtc. In addition, some public mining pools such as Poolin exist, used by

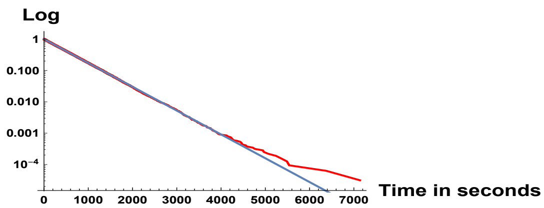
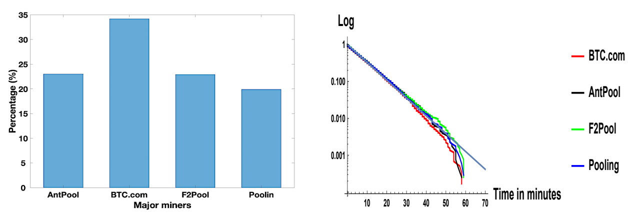


Figure 2. The inter-block generation time and the inter-block arrival time, fit to an exponential distribution

nodes to participate in the mining pool. We also observed that BTC.com, AntPool, F2Pool, and Poolin mining pools contributes the majority of the blocks to the ledger. The number of blocks generated by these pools are not evenly distributed, while the few major miners take most of the valid block.

Fig. 3(a) shows the contribution of the chosen major mining pools and Fig. 3(b) reports their inter-block generation time distribution, normalized to the same mean. In Fig. 3(b) the fit to an exponential distribution, the straight line, is observed, and hence, the inter-block generation time from each mining pool may be well approximated by an exponential distribution. This is different from the two hypotheses found in [13] and [26].



(a) Mining pool contribution in terms of generating blocks (b) Inter-block arrival time distribution at a miner

Figure 3. Block contribution by miners and per-miner inter-block generation

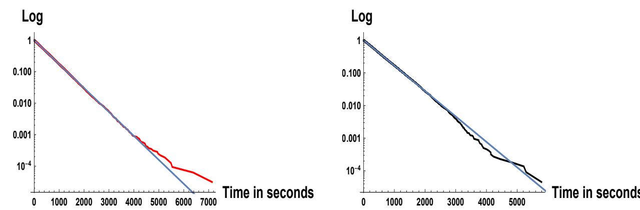
Note that, It is well-known from Palm-Khintchine theorem states that if we combine events from significant, continuous, independent renewal processes, the result will have Poisson properties under certain conditions [18], or in other words, the aggregate point process of independent point processes, each of which has exponentially distributed inter-arrival time, also has exponentially distributed inter-arrival time. It is then worth highlight that the finding in Fig. 3(b) provides a previously unreported explanation for the exponentially distributed inter-block generation time in the Bitcoin system, i.e., it is resulted from similar distributions at the miners.

Finding 1: **The exponentially distributed inter-block generation time on the blockchain is likely attributed to the exponentially distributed inter-block generation time at major miners.**

B. Inter-Block Arrival Time

It is worth highlighting that the block arrival process to a node is different from the block generation process of the Bitcoin system. This is due to that after the generation of a new block, the updated ledger containing the new block needs to be propagated through the Bitcoin network to each node. This causes propagation delay from the generation of each block at its miner to the arrival of the block to a node, $a_b - g_b$.

In the literature, e.g. [7], it has been discussed and conjectured that the block propagation delay is exponentially distributed, but the conjecture is not examined with measurement. We have also performed analysis on the propagation delay with our collected measurement dataset. Based on the arrival time a_b recorded at our node and its generation time g_b, we have found an average of 53 seconds for the block propagation delay. Its distribution is shown in Fig. 4(b). It can be observed from the figure that the block propagation delay well fits an exponential distribution, validating the conjecture in [7].



(a) The block inter-arrival time fitting to a n.e.d (b) Block propagation delay distribution fitting to a n.e.d

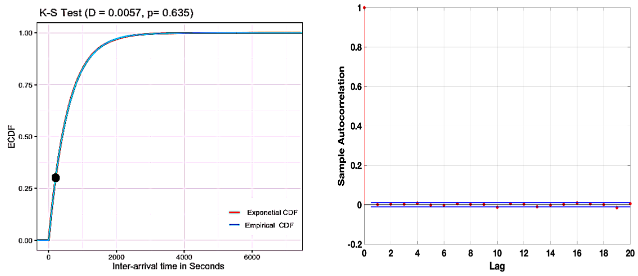
Figure 4. Block arrival time and block propagation delay

For the inter-block arrival time between two adjacent blocks b_i and b_{i+1}, it can be calculated from their arrival times recorded in the local information, i.e. $a_{b_{i+1}} - a_{b_i}$. Its distribution is shown in Fig. 4(a). As can be observed from Fig. 4(a), the distribution can be well approximated by an exponential distribution. This appealing finding can indeed be expected from the distribution of inter-block generation time and the distribution of propagation delay due to the following relationship between them:

$$(a_{b_{i+1}} - a_{b_i}) = (g_{b_{i+1}} - g_{b_i}) + [(a_{b_{i+1}} - g_{b_{i+1}}) - (a_{b_i} - g_{b_i})]$$

where, on the right side, the inter-block generation time $g_{b_{i+1}} - g_{b_i}$ is approximately exponentially distributed as discussed in the previous subsection, and the second term is the propagation delay difference. Since propagation delay is also approximately exponentially distributed, the difference shown as the second term can be approximated to have a Laplace distribution, from the well-known result of difference of two exponentially distributed random variables. Furthermore, from the sum of exponential and Laplace distributions [6], an exponential decay in the inter-block arrival time is expected.

In addition to a K-S test [20] confirming the excellent match, which is shown in Fig. 5(a), we have also examined if blocks arrive independently. This is done by checking the autocorrelation of the block arrival time series, under different time lags. A summary of the autocorrelation values is presented in Fig. 5(b). As can be seen from the table, the autocorrelation is close to zero under all these lags with the largest difference only around 1%, which is an indication that block arrivals are not correlated.



(a) K-S test for block inter-arrival time distribution where D represents the maximum distance between the exponential and empirical CDF

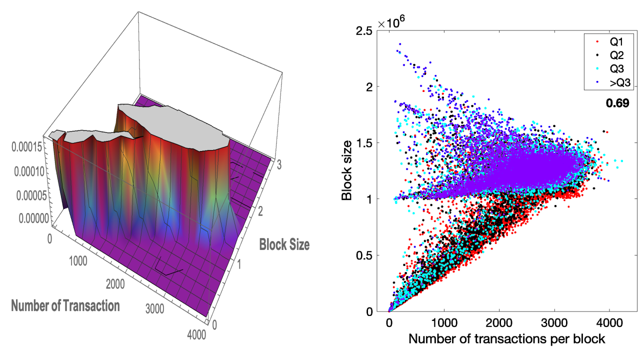
(b) The autocorrelation of block inter-arrival time in seconds

Figure 5. K-S test and autocorrelation

Finding 2: **The block arrival process to a node approximately has an exponentially distributed inter-block arrival time with independent block arrivals, i.e. a homogeneous Poisson process.**

C. Number of Transactions in a Block and Block Size

In contrast to very few results about inter-block generation and arrival time distributions, the literature has a lot of results about n_b, the number of transactions in a block, and s_b, the size of a block, such as those reported for the various platforms [3] [4] [8] [9]. In this and the subsequent subsections, we report results that are either with more detailed information or from new different perspectives.



(a) The joint PDF of n_b and s_b

(b) scatterplot of n_b and s_b

Figure 6. Relation between n_b and s_b

1) Correlation between n_b and s_b: Fig. 6(a) illustrates the joint PDF of n_b and s_b. As we can see from the figure, the dependence between the two variables varies. In general, a larger block has a higher number of transactions included. While this is as expected, Fig. 6(a) details this relationship. In addition, Fig. 6(b) illustrates the scatter diagram of the size of a block, s_b vs. the number of transactions in the block, n_b. It also demonstrates the relationship of s_b and n_b for Q1 (25%), Q2 (50%), Q3 (75%), and greater than Q3 (>Q3) for f_b. These intervals are (0,Q1), (Q1,Q2), (Q2,Q3), and (Q3,∞). As can be observed from Fig. 6(b), there is strong correlation between s_b and n_b. There is a clear pattern shown by the correlation scatter points.

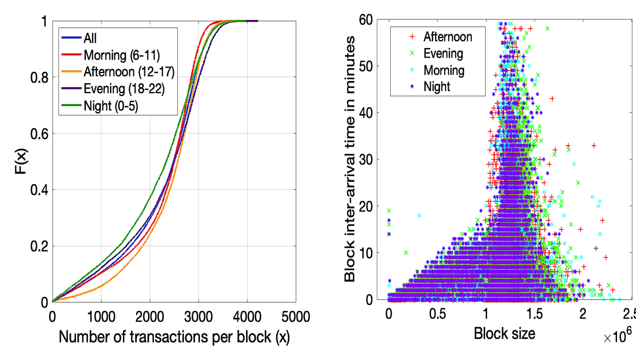
Specifically, it is visible that having a large n_b often implies a higher chance of being in a bigger s_b, as illustrated by blue and bold black dotted blocks when the n_b higher than 2000, even though some high size blocks have a small number of transactions in the block. Sometimes, the number of transactions waiting for confirmations is smaller than the block size capacity; in such cases, we will see blocks filled with fewer numbers than the expected. In Fig. 6(b), we can see the black and red dotted straight line around 0 - 1 MB, indicating generating a block not filled with a maximum capacity as the consequence of the mempool containing a small number of transactions waiting. On the other hand, we can also observe a horizontal line around the s_b 1 - 1.5 MB and where n_b is more significant than 2000, which indicates more transactions waiting while the block filled to the maximum limit. Additionally, we can also see pink and light-green colored blocks with a small number of transactions in a block while the size is pushed to the maximum limit.

Furthermore, we can also observe that the average gain of miners playing a crucial role. The blocks with a higher average fee per block (>Q3) contain a higher gain; on the other hand, most less-filled black and red colored blocks contain less average gain.

Finding 3: **There is positive, strong, and nonlinear relation between the size of a block and its number of transactions.**

D. Characteristics in Different Time Periods

We are interested in finding if and how n_b and s_b may differ in different time periods. As the CDF of n_b reported in Fig. 7(a), in the morning and evening, a block holds on average 2500 transactions, and in the night and afternoon, a block contains no more than 3300 transactions in 90% of cases. Still, in all the cases, it can grow larger than 3500 in 1% of the cases.

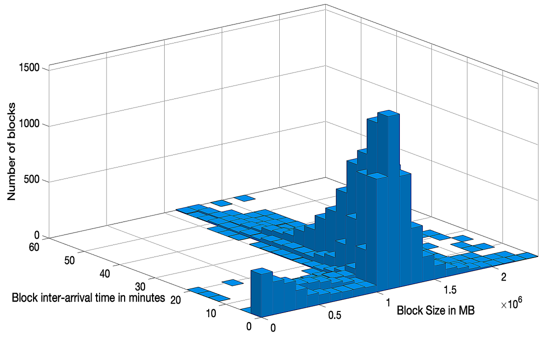


(a) Observed CDF of transactions per block, n_b

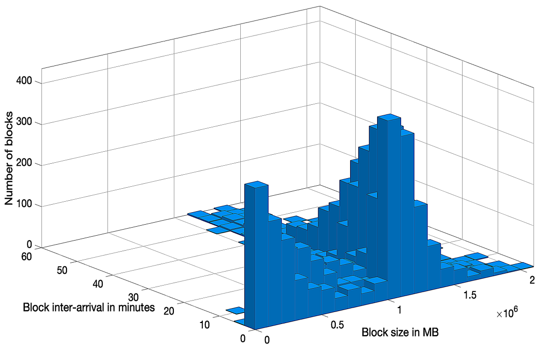
(b) Sctterplot of interarrival times vs. block size, s_b

Figure 7. n_b and s_b characteristics in different time periods

Fig. 7(b) reports that s_b's having values that varies with different time periods . In the afternoon and evening, the s_b's ranges are higher than in the morning and night. The s_b in the evening is relatively larger than in other periods. This may be due to a higher n_b in the evening. In the morning and evening, the number of blocks are generated less frequently, i.e. with



(a) Working days



(b) Weekend

Figure 8. Block generation in working and weekend days

higher inter-block generation time shown in the figure, than the rest of the day.

Fig. 8(a) and Fig. 8(b) further show how s_n's distribution dependent on the interarrival time varies over working and weekend days. In the working days, the s_n is more concentrated over the range of 1 to 1.5 MB, and there are 9229 blocks arrival with an inter-generation time of less than 5 minutes. However, in the weekend days, s_n stands between 0.2 to 1.8 MB, and about 3700 blocks are found with an inter-generation time of less than 5 minutes.

Finding 4: **The characteristics of block size and number of transactions can differ significantly in different time periods.**

IV. Transaction-Level Characteristics

In Bitcoin's design, a transaction confirmation time of 10 minutes is inherent [22]. Based on the arrival time a_b recorded at our node and its generation time g_b, we have found that on average a transaction needs 600 seconds (T_w) from it is received by the Bitcoin system till the corresponding block is generated, i.e. the transaction is confirmed then. This confirms the design principle of Bitcoin.

In the remainder of this section, we focus on the transaction arrival process itself, which is characterized by transactions' inter-arrival times, and the size and fee of each transaction. Fig. 9 provides a trace of this process, where 5000 unique transaction arrivals are ordered based on their arrival times a_i recorded at our full node.

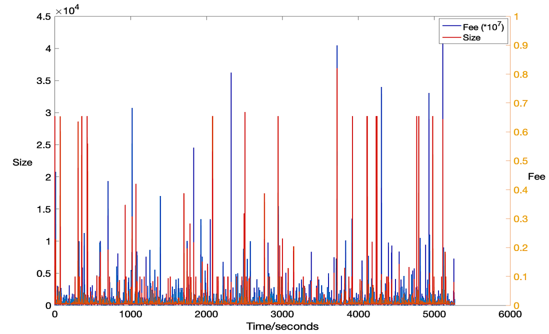


Figure 9. An overview of the transaction arrival process

A. Transactions' Inter-Arrival Time

In the literature, it is often assumed that the transaction arrival process is a Poisson process. However, the validity of this assumption was not examined previously. To bridge this gap, a random period in the dataset was picked, which consists of 1861 transactions, and the inter-arrival time distribution of these transactions is illustrated in Fig. 10.

As we can see from Fig. 10, the transactions' inter-arrival times can be approximately fitted with an exponential distribution, which partially supports the Poisson arrival assumption. However, the figure also shows noticeable deviation. While the deviation for the CCDF value below 1% may be attributed to the number of samples in this fitting test, the derivation is also visible for CCDF above 1%, which can hardly be found in the inter-block generation time and inter-block arrival time curves in Fig. 2 and Fig. 4(a).

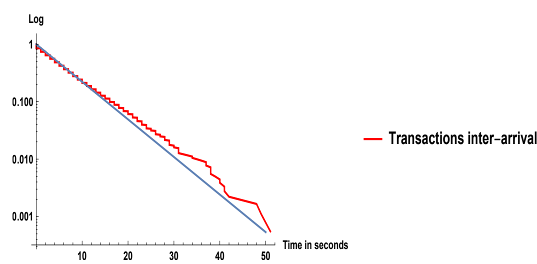


Figure 10. Distribution of transaction inter-arrival times, fitted with n.e.d

Finding 5: **The transaction inter-arrival time may be approximated by an exponential distribution, but with noticeable deviation.**

B. Transaction Size and Fee

According to the design of Bitcoin [22], how a miner selects transactions to form a block depends on the sizes s_i and fees f_i of transactions in the mempool. In Fig. 9, an overview of them with regard to each transaction has been shown. To have a better understanding of them, we investigate their distributions and the correlation between them.

Fig. 9 shows that transaction size and fee do not seem to exhibit a clearly visible, strong positive correlation. While some of the low fee transactions have high sizes s_i, we can also see transactions with higher fees having smaller transaction sizes. To gain a more complete view, the joint distribution of s_i and f_i is investigated. For the same transactions shown in Fig. 9, the joint distribution result is shown in Fig. 11.

Fig. 11 indicates that 90% of the transactions have a size of not more than 500 bytes. But, in 1% of the cases, the transaction size can be more than 30 kilobytes. Similarly, the fee associated with each transaction is below 0.0006 BTC 90% of the time, but it can grow higher than 0.001 BTC in 1% of the cases. The distribution shows that while there are a lot of small transactions, there is a significant fraction of tens and hundreds of transactions with a higher fee. Fig. 11 also confirms that the correlation between transaction size and fee is weak.

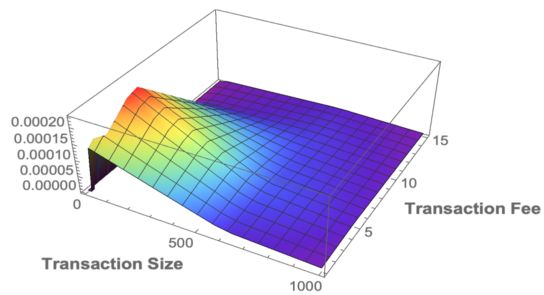


Figure 11. The joint PDF of s_i and f_i

Finding 6: **The correlation between the size of a transaction and its fee is weak.**

V. Mining Pool Dynamics

In this section investigates the dynamics of the memory pool (mempool), which is affected by the transaction arrival process and underlays the block generation process.

A trace of the mempool size in terms of bytes and accumulated fee over ten-block formations is shown in Fig. 12. The x-axis represents arrival times of the blocks, and the y-axis the accumulated entry size and fee, where the fee is scaled for better visibility. Each vertical descent in the size curve represents a new block formation and the height of the descent implies the total size of transactions included in the block, i.e. the size of the block. The corresponding vertical descent in the fee curve represents the fee of the block.

As indicated by Fig. 12, the relationship between block size and block fee is not linear: a bigger block does not guarantee a higher fee and vice versa. When adding transactions into a block, higher priority may be given to the fee than to the number of transactions waiting for confirmation. For instance, we have observed there were often 5000 - 15000 transactions waiting, while the blocks consider fee rather than the mempool size. It is also visible that the mempool state has a fee close to zero at two times, implying that most transactions by then have been confirmed. However, we have also observed that these are low fee transactions that have to wait even longer time to be processed. If a transaction has a bigger size and small fee combination, it may occupy the memory space for a longer time before confirmation.

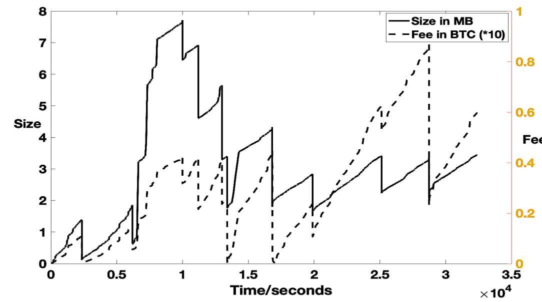


Figure 12. The mempool state change at block generation

For the same reason, in the literature, a fee-based priority queueing model has been simply assumed for the mempool [4] [5]. However, this assumption is too coarse to explain what are shown in Fig. 9 and Fig. 12. For instance, Fig. 12 shows some blocks contain only a few transactions while the block size is filled to the maximum, implying that in these cases, transaction size seems to have been prioritized rather than fee.

Finding 7: **A simple fee-based priority queueing model cannot well capture the dynamics of the mempool.**

VI. Conclusion

Through analyzing the data collected from a measurement setup, which contains transaction and block information both on the blockchain and from the node, we presented a comprehensive study on the transaction characteristics of Bitcoin. A set of new results and findings have been reported, including examining the validity of several hypotheses / assumptions used in the literature.

Specifically, for exponentially distributed inter-block generation / arrival times, we found that the two literature hypotheses cannot be justified by the measurement, and it is likely attributed to exponentially distributed block generation at major miners. In addition, for transaction inter-arrival time, though its distribution may be approximated with an exponential distribution, there is noticeable deviation. Besides, for characterizing the mining pool, no convincing evidence has been found to support the fee-based priority queueing model. Furthermore, while the size of a block and the number of transactions in it exhibit a strong functional relationship dependent on the size and value of the mempool, transaction size and fee seem to be more independent.

As a highlight, the idea of involving the mempool in the measurement, in addition to the commonly used ledger information, has enabled us to study the transaction characteristics of Bitcoin and find the fundamental relationships among the core features. As a future work, we will investigate how to exploit this idea to manage the mempool to improve the throughput and reduce transaction waiting time while keeping the current block size limit.

For more discussion and results, such as Bitcoin workflow and details of various distribution fitting results, they can be found from an extended version of this paper [10].

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