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Characterizing IOTA Tangle with Empirical Data

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***Abstract*—IOTA organizes transactions in the ledger as a Directed Acyclic Graph (DAG) called Tangle, instead of a hash chain of transaction blocks used by most of traditional blockchains. IOTA is considered a promising platform to support Internet-of-Things (IoT) applications with its key features such as micro-payment support and absence of transaction fees. While prior art shows extensive analysis based on synthetic data generated through simulations, an analysis based on empirical data from a deployed IOTA network is still missing. In this paper, we provide the first comprehensive analysis by using real transaction data officially published by IOTA Foundation. Our key finding is that neither the tangle's topological features nor the actual observed performance is consistent with the main conclusions from the literature. In particular, most of transactions take roughly 10 minutes to be officially confirmed, which is not exactly instant as commonly assumed; yet, what is arguably worse is that there is a certain amount (5%) of transactions experiencing exceptionally long confirmation time. This shows that IOTA still has gaps to meet the stringent requirements of IoT applications that are delay sensitive.**

***Index Terms*—IoT, Blockchain, IOTA Tangle, Performance Evaluation**

I. INTRODUCTION

Blockchain technology enables distributed consensus and is regarded as the ultimate tool to establish a trustworthy relationship in a large-scale anonymous environment. Recently, blockchain technology is being adopted by many industry sectors from finance, logistics, decentralized web services and so on [1].

In 2016, IOTA Foundation (IF)[1] proposed a blockchain network, namely IOTA, using Directed Acyclic Graph (DAG) (called *tangle*) as the ledger data structure to organize transaction data on every IOTA node [2]. In a tangle, a vertex, namely *site*, represents a single transaction object. A direct edge from one site pointing to another site indicates that the source site approves the destination site. Regarding its consensus mechanism, IOTA removes the proof-of-work (PoW) mining phase used in traditional blockchain. Instead, IOTA allows every node to update its local ledger immediately where a new site (i.e., a new transaction) is attached into the tangle by approving two existing sites (called *tips*) in the ledger. Technically, which two tips are selected is not arbitrary but determined by a *Tip Selection Algorithm* (TSA), wherein the TSA executes two weighted random walks in the tangle until two tips are identified. In IOTA, every IOTA node receives transactions from clients, adds them into its tangle and keeps propagating the processed transactions to its neighbors. As a result, every transaction is propagated across the entire IOTA network, where the distributed tangle ledgers converge to a synchronized status. The mechanism of IOTA will be revisited with more details in the next section.

The key feature of IOTA is its lightweight transaction processing manner without a heavy PoW mining phase. For this reason, IOTA and its variants seem suitable for IoT applications, wherein tiny, massive and "instant" transactions are typical. For example, IOTA is used as a marketplace where electricity trading is directly done by IoT devices as sellers and buyers in [3]. Another example is IOTA usage in vehicular communication [4].

Previous studies extensively analyzed IOTA using synthetic data [5]–[11]. These works build their own applications and evaluate system performance using the transaction data generated in a simulated environment. However, an analysis based on empirical data generated in the IOTA *mainnet*, i.e., the official IOTA network on the Internet, is still not available in the research community. Consequently, many questions remain open, such as the real tangle topology, the actual transaction confirmation rate in the deployed system, and, in case of diverging findings, the reasons behind the present observations. In this paper, we try to answer all these questions. More concretely, our main contributions are:

- Since the published transaction datasets do not explicitly contain topology information, we first fully reconstruct all the ledger tangles through identifying all sites and directed edges by looking for every approval relationship among all transactions. In total, 96 tangles were reconstructed from a 322GB original dataset.
- With the reconstructed tangle ledgers, then we compute interested properties based on graph theory and IOTA specification. Specifically, we analyze the diameters, in-degree distribution, cumulative weight of the ledger tangles and measure the actual performance regarding transaction confirmation delay;
- Based on the derived properties and metrics, we found that the real IOTA tangles present different topological features (e.g. site in-degree distributions). More importantly, we observed that the actual transaction confirmation time shows higher latency, which is not as usual beliefs that IOTA can provide much faster transaction rate than traditional blockchain.

In general, to the best of our knowledge, we are the first trying to present such an in-depth study where we publish all our source code for this empirical data analysis online[2].

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[1] The official IOTA development and operation consortium

[2] https://github.com/goldrooster/IOTA-Empirical-Data-Analysis

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The structure of this paper is outlined as follows. In Section II, we provide a concise introduction about key mechanisms of IOTA; in Section III, we provide a literature review; Section IV introduces our analysis methodology; full results are presented in Section. V and Section.VI concludes the paper.

II. IOTA PRELIMINARY

IOTA is a distributed network consisting of voluntary *nodes* that maintain a distributed consensus on their local tangles keeping transaction records. Every node has two main tasks: 1) validating and attaching transactions into its local tangle and 2) propagating added transactions to other nodes. In the following discussions, we use *site* and *transaction* as well as *tangle* and *ledger* interchangeably.

A. Transaction Attachment

A new transaction (cf. the blank square in Fig. 1) is composed at a client and submitted to a node. An initial validation is done by checking some attributes that can be locally verified such as signature, balances and so on. A validated transaction is attached to two *tips* selected from the tangle, where a tip is a site that is not yet referenced (i.e., approved) by any other site (e.g. Tip$_a$ and Tip$_b$ in Fig. 1).

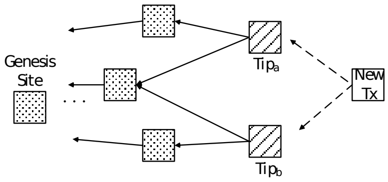

Fig. 1: Transaction Attached to A Tangle

IOTA Tip Selection Algorithm (TSA) is executed by a node locally to select two tips. Every site in the tangle has an initial own weight 1 and a *cumulative weight* (CW), which is the total sum of the weight of all sites that directly or indirectly point to the considered site. CW is defined as the oldness/importance of the site in a tangle in IOTA. With CW values, TSA applies random walks starting from a pre-defined site in the tangle and jumps to the next site by Markov Chain Monte Carlo (MCMC) method, whose transition probability is proportional to the CW values of inspected candidate sites. The stop position of the random walk determines the first Tip$_a$ and a second time random walk runs to find the second Tip$_b$. The new transaction is attached by simply including into its transaction header the hash values of the two identified tips. The newly attached site becomes a new tip in the tangle, while the original two are not tips anymore. During this attachment process, the two tips are approved by the newly added site (i.e., the new tip), and the new tip is waiting for being selected in the next round TSA to be approved by a further new incoming transaction.

B. Transaction Propagation

In parallel, a node receives forwarded transactions from neighboring nodes (as shown in Fig. 2). A forwarded transaction could already exist in the local ledger. In this case, the node ignores it locally, but forwards it to all neighbors, except to the expedient. If the transaction does not exist in its local ledger (e.g., node B does not have the transaction received from node A), a node (here: node B) saves the transaction and checks, whether the two referenced sites (denoted as two small eclipses on the transaction) can be found in its tangle. If so, the node simply adds the transaction to its tangle; otherwise, the transaction is suspended, until the missing sites are provided from neighbors.

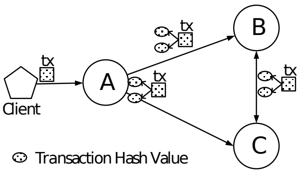

Fig. 2: Transaction Propagated to Other Nodes

The node will send requests to neighbors for finding a missing site. For example, if node B does not have the two sites, it will broadcast requests to both nodes A and C. If any node knows any of the requested transactions, it (e.g., node A) it replies to the requester (i.e., node B). Note that this could recursively trigger further missing site requests. Hence, missing sites in a local tangle are progressively completed with the helps of other nodes, until tangles are synchronized.

C. Transaction Confirmation

A synchronized tangle does not mean that all contained transactions can be trusted or said *confirmed*. In the IOTA mainnet, IF introduces a *Coordinator* (COO) to protect the tangle against attacks such as parasite chain, where nodes try to use overwhelming computing resources to manipulate the tangle updates in order to achieve malicious goals such as double-spending. COO participates and periodically issues a special type of transactions called *milestones*. Milestones are processed as usual transactions from users. The most important thing is that a milestone verifies and confirms transactions that exist in its connected sub-tangle. Clearly, COO plays a partially centralized role in the real IOTA, which also influences the transaction confirmation delay. IF is working on a fundamental upgrade to remove COO under a project named *Coordicide*.

In summary, the key idea behind IOTA is that new transactions approve existing transactions, which progressively gain on weight as more sites approve them. Through transaction propagation, tangles on different nodes mix, grow and finally converge to one. Invalid transactions are blocked locally. The reason for this is that attaching invalid transactions is futile, even for malicious nodes, as during propagation, these will not pass the validation phase on any (benign) node. Recent theoretical analysis has proved the convergence and equilibrium of the tangle synchronization in IOTA [10].

III. RELATED WORK

In [5], this pioneering work was the first to simulate the development of the site CW values in time. However, this work is the first work to mimic an IOTA network with limited sizes as well as insufficient parameters. In [6], it further analyzed impacts of two different TSAs to site CWs and the number of tips in the tangle in a continuous-time model. However, the random walk depth is too low compared to the TSA random walk depth of 5000 used in real IOTA. The same team in [7] studied the relationship between the so-called *Probability of Being Left Behind*, the coefficients of walking randomness and the transaction arrival rate. A similar deficiency is also the limited size of the simulated tangles, comparing with the million-site scale in the real IOTA.

In [8], an IOTA network is simulated as a multi-agent system by Netlogo, a simulation environment [12]. Based on the simulation, the work concludes that IOTA overcomes the shortcomings of traditional blockchains and shows both faster confirmation speed and lower computation requirement. However, the experiment is largely simplified with small sizes of the synthetic tangles and some idealistic assumptions. Besides, in [9], an offline IOTA network was deployed to evaluate the performance by simulating some more realistic assumptions. The derived conclusion is that IOTA presents good scalability in terms of transaction confirmation rate, increasing accordingly. However, the provided results rather suggest a steady transaction rate, even if more resources are dedicated to IOTA.

In [11], TSA performance in blockchains based on DAGs was evaluated. This work is also based on simplified settings such as shallow TSA random walk depth. A self-defined approval time was used to measure the confirmation rate. However, this definition is aligned neither with the real IOTA case nor with the theoretical definition from the IOTA whitepaper [2]. This may yield a wrong interpretation of the actual performance in deployed IOTA networks.

In summary, the fundamental difference of this work to the state of the art is that it uses neither simulation to mimic the behaviors of IOTA for statistical analysis, nor any offline deployment for performance evaluations. We emphasize that the main objective of this work is to understand the nature of the real-world IOTA by statistically analyzing the original ledger data kindly made publicly available by the IOTA Foundation.

IV. OUR METHODOLOGY

A. Motivation

The key factors that make the IOTA mainnet different from a simulated IOTA system are:

- *Transaction Arrival Rate*: It is usually modeled as a Poisson distribution controlled by a parameter λ. However, from other online real-world blockchains do not only follow a Poisson distribution [13]. A different transaction arrival pattern influences the order of transaction attachment, which could further influence the topological features in the resulting tangle topology.
- *TSA Options*: Simulation-based studies rely on a simplified and unified random walk-based TSA assumption. In contrast, in the IOTA mainnet, TSA is not limited to one common option. Instead, various strategies are used in practical situations. For example, Uniform Random Tip Selection (URTS), MCMC with customized parameters or directly referring to the COO-issued milestone are acceptable choices.
- *COO Intervention*: This could be the most critical factor. As introduced in Section II-C, a COO keeps issuing milestones, which dominates several parameters of the transaction confirmation performance. Moreover, milestones act as a special type of sites in the tangle and could affect the tangle topology properties in IOTA mainnet.

Given these differences, the question arises, whether IOTA mainnet performs anywhere near the observations in the prior art, and, in particular, to which extent COO - not considered in the prior art - affects the transaction confirmation delay. This question is the main motivation for this study, which seeks to characterize the IOTA performance using the available empirical data.

B. Tangle Reconstruction

Transaction data are being regularly collected from the IOTA mainnet by IF and published online[3]. The ledger data are archived periodically (every two or three months). The archiving activity is called *generating a mainnet snapshot* (MS), wherein transactions are frozen and account balances are settled. Then, a new archive period starts. A MS mainly contains transaction records including issued milestones from COO and an approvee list that contains key-value pairs, whose key is a hash value of a transaction, and value fields contain the hash values of its direct approver transactions.

The first obstacle is that the published ledger data are represented in trytes but compressed in bytes. Therefore, decompression and data format conversion have to be done at the first place. After the data conversion, snapshot datasets are converted into human-readable format and saved as JSON files.

The next challenge is that tangle topology information is not explicitly kept in the datasets when generating every MS. This means that tangle topology has to be reconstructed manually. Given a MS, we have to iterate all transaction records to identify their edges and connected sites according to the hash values of the two referenced transactions (sites). A more challenging case is that multiple tangles could exist in one MS. This further requires us to manually identify the first and the last sites in order to determine one sub-tangle instance.

We provide an overview of the published MS datasets in Table. I. Note that IF did not officially publish MS anymore after April 2019.

C. Property Extraction

Given the reconstructed tangles, we then characterize their properties. First of all, we study typical graph-theoretical properties (e.g., diameter, vertex in-degree, etc.) of the tangles. Furthermore, we also calculate specific IOTA properties, e.g., site CW related to TSA. To determine the actual confirmation time, we identify the earliest milestone that approves a considered transaction from the tangle.

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[3] http://dertangle.iota.cafe/

MS Index	Date (month)	Tangle#	Site# (million)	Average Site# (million)
1	2016.11	1	0.043	0.043
2	2017.01		0.115	0.115
3	02		0.09	0.09
4	06		2.5	2.5
5	08		3.5	3.5
6	09		2.1	2.1
7	10		1.2	1.2
8	2018.01	8	4.3	0.55
9	04	4	9.6	2.4
10	07	9	15.4	1.7
11	09	26	19.6	0.7
12	12	20	49.1	2.4
13	2019.04	22	43.5	2.0
Total	**28**	**96**	**151.280210**	**1.575835**

TABLE I: IOTA Mainnet Snapshot (MS) Overview

The challenge here is that most properties are not directly available but rather have to be calculated from the tangle. Among them, the most difficult one is to compute site CW values. The reasons are as follows. A site CW is computed on the fly during TSA random walk procedure in the transaction attachment stage, as described above. Ergo, every attachment of a new site into the tangle may change the CW values of preceding sites. This means that the site CW value is not a static value, thus it is not provided with the published data. Calculating site CW is a graph traversal problem according to the definition of CW. Given a n-vertex graph and the graph traversal complexity $O(n)$, thereby $O(n^2)$, there is a significant computational effort given that tangle size n equals to 1.57 millions on average as per TABLE I.

In addition, the actual transaction confirmation time is also not readily available. The main effort is on identifying the earliest milestone that approves a site. To do this, we first have to visit every milestone site in a tangle and identify all its preceding sites; after that, we calculate the time interval between the site issuing timestamp and the milestone timestamp, which tells the actual confirmation time of the corresponding transaction in the real-world IOTA. Provided that every tangle contains millions of sites, this also takes quite a long processing time.

D. *IOTA Network Simulator*

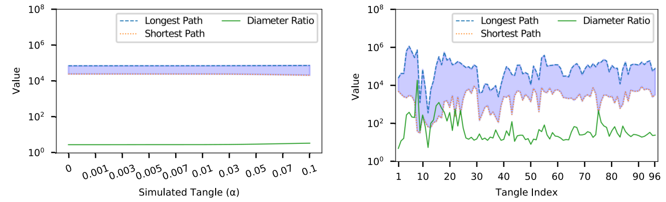
To facilitate our comparisons, we also use a network simulator, *TangleSimulator* [4], to generate simulated tangles, whenever necessary. There are two main parameters for tuning the simulation process. The first one is transaction arrival rate denoted as λ, and the second one is a coefficient α influencing the TSA random walk procedure. To align with the previous work [6], [7], we choose $\lambda = 10$ but vary the value of α, and generate 10 simulated or *synthetic* tangles, each of which contains 1 million sites without particular notes.

V. ANALYSIS RESULTS

Based on the reconstructed 96 tangles, our statistical analysis results are reported here.

A. *Topological Property*

The first part of the analysis is based on graph theory, where a set of graph properties are investigated for both synthetic tangles and MS tangles.

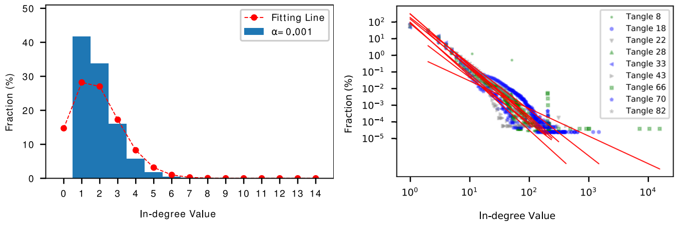


(a) Simulated Tangle (b) MS Tangle

Fig. 3: Ratio of Tangle Longest and Shortest Paths

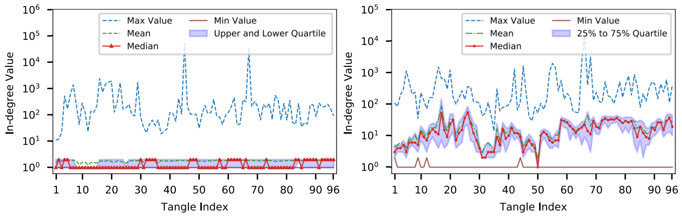
1) Tangle Size: We examined characteristics of the shapes of the tangles. We first calculated the shortest and longest paths of every tangle. After that, we calculated the ratio of the two paths (called diameter ratio). The results are shown in Fig. 3.

The diameter ratio of the simulated tangles (Fig. 3a) is much smaller than the case of MS tangles (Fig. 3b). In other words, the shape of simulated tangles looks closer to a square shape with relatively equal lengths of the longest and shortest paths. However, the shape of MS tangles appear more like a narrow band shape. Another interesting point is that the shape of MS tangles seems irrelevant to the size of MS tangles, because, although the numbers of sites of the MS tangles differ a lot, the lengths of the longest and shortest paths (the blue band height) do not change drastically.



(a) Simulated Tangle (5x10^6 sites) (b) MS Tangle (log x, y-axis)

Fig. 4: Site In-Degree Distribution



(a) Usual Site (b) Milestone

Fig. 5: MS Tangle Usual Site and Milestone In-degree Comparison

2) Site In-degree: We further generally characterize the site in-degree distribution in Fig. 4. We first clustered the 96 MS tangles into 9 groups with k-mean clustering, where $k = 9$ and

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[4] https://github.com/minh-nghia/TangleSimulator

two criteria are the diameter ratio and size of MS tangles. This selects MS tangle samples that are representative enough for diversity.

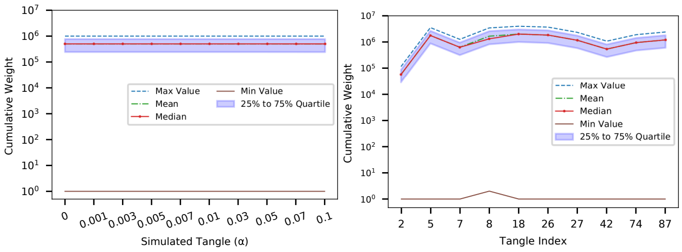
Given the selected MS tangles, we plot the in-degree distribution. A key difference is that the in-degree distribution of nodes in the simulated tangles generally follows a Poisson distribution (Fig. 4a), while the in-degree of MS tangles follows a power law distribution (Fig. 4b), with fitted curves in shown in red respectively.

We are further interested in the degree features of different types of sites (e.g., usual sites and milestones). In MS tangles, the in-degree values of usual sites are small (Fig. 5a), where mean and median values are around 1 or 2 overlapping with middle two quartiles, although there are some exceptional cases with higher degrees in the range of $[10, 10^3]$. However, for the case of milestones (Fig. 5b), we notice that the mean and median values of milestones range between $[5, 10^2]$, overlapping with middle two quartiles. This is several magnitudes higher than the cases of usual sites. It seems that milestone sites are selected more frequently in real IOTA.

B. *Specific IOTA Property*

We then present the analysis on IOTA specific properties.

1) Site CW: As we explained in Section IV, site CW is a dynamic value calculated on the fly. Thus, these values are not present in the published MS. We have to repeat the TSA random walks to recalculate them. Similarly, we used k-mean clustering, where $k = 10$ to select 10 MS tangles in different shapes and sizes.

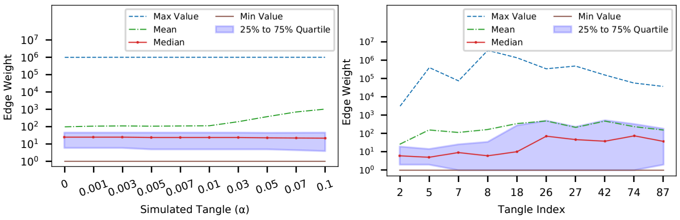


(a) Simulated Tangle (b) Selected MS Tangle

Fig. 6: Site CW Analysis

Site CW values of the selected MS tangles are slightly higher than the case of simulated tangles. It seems that tangle topology does not influence the CW that much. The possible reason could be that site CW is a value added up with all sites in a subtangle, which dissolves and normalizes the impact of topological differences.

2) Edge Weight: Based on site CW, we define a new edge property called *edge weight* (EW) as the absolute difference of its two sites' respective CW values. This value implies the location of a site to attach to. For example, the EW of a newly added edge shall be small, if a new site attaches to a recently attached tip, whose CW is similar to the new site. Oppositely, if a new site attaches to an old site, the EW of the newly added edge is large, because the difference of the two sites' CW values is large. Therefore, EW can be an indicator of 1) a *lazy site*, which does not select a recent tip but an old site or 2) a *parasite chain* phenomenon, where a fork diverts from the main tangle. The two cases are generally called *abnormality*.



(a) Simulated Tangle (b) Selected MS Tangle

Fig. 7: Tangle Abnormality

Both simulated and MS tangles generally show certain amounts of abnormalities according to the results in Fig. 7. It seems that the abnormality of simulated tangles is more stable than the case of MS tangles in terms of the variations of EW values. This might be because the simple TSA strategy is used in simulated cases, while more diversified TSA strategies are adopted in real IOTA. In general, both CW and EW are less influenced by the tangle topology.

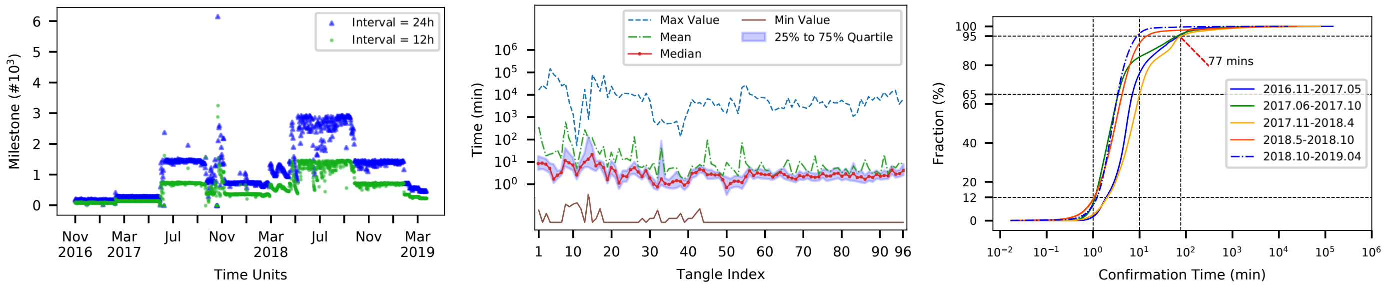
C. *Transaction Confirmation Performance*

Finally, we evaluate the transaction confirmation performance based on the criteria used in IOTA mainnet. Ideally, a transaction is considered as approved, once that transaction is attached by a new coming site in a tangle. However, according to the definition of IF, in reality a transaction is considered as confirmed, only if it is approved by a milestone. In a MS tangle, this means that a milestone site directly or indirectly connects to the considered site. This might delay the confirmation time, because milestones are not always issued timely.

We first summarized in Fig. 8a the issuing rate of milestones in two different scales of time intervals (every 12 and 24 hours). Before May 2018, the issuing rate fluctuated between several hundred and 1800 per day; after that, the issuing rate increased significantly up to 3000. The issuing rate slowed down since September 2018 to 500 per 12 hours and 1500 per day. It further went down to 500 per day since January 2019.

We then studied the distribution of confirmation time of transactions in all MS tangles (Fig. 8b). The median value of confirmation time ranges around 10 minutes. This also applies to 25% to 75% quantile transactions (blue band areas). With some exceptional cases, the confirmation time gets maximum value ranging between $[10^2, 10^4]$ minutes. This also stretches the mean value above the median value curve. Another observation is that before November 2018 (MS Tangle 55), the confirmation performance in real IOTA had larger fluctuation and became more stable after that. It is worth noting that the maximum time range ($[10^2, 10^5]$) is a confirmation time delayed from 1.6 hours to 6.9 days. In the light of the IoT orientation, this would rather seem as a considerably long transaction delay.

We further investigate cumulative proportions of transactions that are confirmed after a certain duration. We divided the whole period, since IOTA mainnet was launched into five periods



(a) Milestone Issuing Time (b) Tx Confirmation Time (c) Tx Confirmation Time CDF in 5 Periods

Fig. 8: MS Tangle Tx Confirmation Performance

with a half-year step. Statistically, we calculated the cumulative density function (CDF) of transaction confirmation times of the five periods in Fig. 8c. In the presented results, we found that the transactions that are confirmed in less than 1 minute are rather very few, at max. 12%, with two of the periods exhibiting values lower than roughly 5%. The confirmation rate increased rapidly in between 1 and 10 minutes, where the proportions of confirmed transactions reached at least 65% in two periods and the other three periods even reached more than 85%. It took 77 minutes for all periods to confirm 95% of transactions. However, almost every period has a small proportion (around 1% to 5%) of transactions that were delayed for an exceptionally long time.

D. *Key Observations*

1) Real IOTA generates tangles with different topological features, compared to the simulated tangles. The shape of the real tangles is narrower. Real IOTA tangles show a power-law degree distribution rather than a Poisson distribution as in simulated cases.
2) Nodes in the real IOTA indeed use various TSAs to attach new sites into their local tangles. Milestones are selected more often than usual sites. Abnormal sites were observed in reality (cf. the result of EW Analysis), which are not simulated in most of the prior art, where nodes perfectly follow the IOTA specification;
3) The transaction confirmation rate is not as high as usual believed, if the confirmation by a milestone is required. This needs the assistants from milestone sites. Because of that, most of transactions ($>$ 50%) are confirmed in around *10* minutes, and there is a small proportion of transactions delayed for several days. The normal confirmation time in IOTA mainnet seems equivalent to the performance in typical traditional blockchains (i.e., having to wait roughly *10* minutes, until the transaction can be considered confirmed). This is far behind the requirement to support lightweight, rapid and instant IoT applications that are delay-sensitive, especially considering those exceptionally delayed transaction cases.

VI. CONCLUSION

In this paper, we provide an in-depth analysis on the real IOTA tangle based on historical empirical data from the IOTA mainnet. We reconstructed the tangles from the empirical ledger data, analyzed the tangle properties and presented a comprehensive statistical analysis. According to the presented results, our key findings are that the features of the real IOTA tangles are topologically different from the simulated tangles; more importantly, the transaction confirmation time largely depends on the milestones issued by COO. In addition, it is inefficient to rely on the mechanism of using site cumulative weight in the random walk of TSA, which aligns with the recent plans of the IOTA Foundation. We hope that the presented results can provide a better understanding of the nature of the real IOTA and motivate to continue further analysis in the IOTA community.

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