# On Congestion Control for Distributed Ledgers in Adversarial IoT Networks

A. Cullen, P. Ferraro, W. Sanders, L. Vigneri and R. Shorten

Abstract-Distributed Ledger Technologies (DLTs) (the agnostic term for blockchain) are a potential solution for many pressing issues arising in the Internet of Things (IoT) domain. These issues include facilitating secure transactions between IoT devices and immutably recording data. Most DLT architectures were not designed with IoT in mind and consequentially do not satisfy the requirements of many IoT applications. However, the relatively new class of Directed Acyclic Graph (DAG) based DLTs show great promise for IoT networks. These DLTs require the rate at which transactions are issued and disseminated to be explicitly managed in order to ensure fairness among users. We present a congestion control algorithm for these DLTs, which optimises dissemination rate and guarantees that all nodes receive the same information and have fair access even in a dishonest environment, subject to the computing limitations of nodes. Our algorithm takes inspiration from well-known areas of networking research, such as QoS, and TCP. However, an important distinction between the DLT setting and traditional networks is the unique nature of traffic in DLT networks and the fact that nodes cannot trust familiar feedback measurements, such as packet acknowledgements or congestion notifications. Our solution realises a decentralised congestion control algorithm for DLTs without the need for trust among

#### I. INTRODUCTION

The Internet of Things (IoT) is becoming increasingly prevalent in both industrial and academic communities. IoT devices are now ubiquitous, including smart home and personal devices, a vast array of urban and industrial sensors, and increasingly intelligent vehicles. Many of these IoT devices must conduct secure financial transactions, such as machine (M2M) payments, and immutably record data. Blockchain and, more generally, Distributed Ledger Technology (DLT) has been proposed to facilitate such interactions. DLTs represent an attractive alternative to centralised services amid mounting concerns about privacy and data integrity from the public, following recent data controversies1. A further concern is around the emergence of monopolies in certain domains. However, despite their great promise, many DLT architectures are incapable of providing a service comparable to centralised alternatives, due to either security concerns or their ability to scale to the large number of nodes and high transaction rate that would be required in the IoT setting.

A DLT architecture is a *trustless* peer-to-peer (P2P) network where nodes store a local copy of a database called a ledger.

A fundamental property of DLTs is that nodes must reach consensus on the state of the ledger without the aid of a central entity. Here, trustless means that nodes do not need to trust any other individual node, but must only trust that the system as a whole is functioning correctly. The first generation of DLTs were blockchains, such as Bitcoin [1], but these DLTs are unsuitable for IoT environments for several reasons [2]. In particular, the ledger in a blockchain is stored in blocks, each one cryptographically linked to the previous one. The longest chain contains the correct blocks, and new blocks should be added to this chain. However, due to network delays, if several blocks are created at the same time, multiple chains could have the same length, and only one can become part of the ledger. Therefore, blocks should only be created one at a time, and the time between blocks should be reasonably large, at least greater than the network delay. This process is too slow and inefficient for IoT devices. Moreover, only so many nodes can regularly create blocks, and so small IoT devices would have to rely on larger, more centralised nodes to add information to the ledger.

Recently, interesting new DLT architectures have emerged which generalise the blockchain structure. Specifically, we refer to Directed Acyclic Graph (DAG) based DLTs, in which transactions are added to the ledger individually rather than in blocks. Each new transaction is cryptographically linked to two or more existing transactions. As a result, nodes can write transactions simultaneously, and therefore, there is no implicit throughput limit, as with blockchain counterparts. However, a DAG based DLT requires congestion control since the nodes have constrained resources. Specifically, network resources must be allocated to nodes based on their possession of a cryptographically verifiable resource. In blockchains like Bitcoin, this resource is computing power, which is typically limited in IoT devices. Alternatively, the proportion of resources allocated to a node can be proportional to an uninflatable number which we will call reputation.

# A. Problem Statement

We propose a reputation based congestion control algorithm for DLTs which require throughput of transactions to be explicitly managed, such as the aforementioned DAG based DLT. Each node must validate each transaction, add it to the ledger, and then run some consensus algorithm. We call this bottleneck *writing*. The specifics of writing will vary across DLT implementations and may even vary from node to node. For example, in certain DLTs some nodes may do the most computationally heavy tasks, while other limited nodes, like IoT devices, perform lighter tasks while writing. Without congestion control, unwritten transactions could accumulate in

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<sup>&</sup>lt;sup>1</sup>https://www.wsj.com/articles/google-s-secret-project-nightingale-gathers-personal-health-data-on-millions-of-americans-11573496790

queues causing delays and discrepancies between nodes' local ledgers. Moreover, overwhelmed nodes may drop transactions, potentially causing inconsistencies in the ledger.

Our congestion control algorithm seeks to maximise throughput subject to the writing bottleneck, while minimising delays and satisfying the following requirements:

- Consistency: If a transaction is written by one correct node, it should be written by all correct nodes, within some delay bound.
- Fairness: All nodes should get a fair share of throughput, achieving max-min fairness in the number of transactions issued by each node during congestion, weighted by an node's reputation [3].
- Security: Malicious nodes should be unable to interfere with either of the above requirements.

## B. Specific Contributions

Following a brief summary of related work, in Section II, we contribute the following.

- In Section III, we provide a node model capturing the main bottleneck of writing transactions.
- In Section IV, we propose a congestion control algorithm for DAG-based distributed ledgers, which is also applicable to any distributed database replication architecture with the requirements listed above. The algorithm has two core components: a scheduling algorithm which ensures fair access for all nodes according to their reputation; a TCP-inspired algorithm for decentralised rate setting to utilise the bottleneck while preventing delays.
- In Section V we describe a simulator which we built to test our algorithm, and provide simulation results which demonstrate that the algorithm satisfies our requirements.
- In Section VI, we summarise our results and propose directions for future work.

## II. RELATED WORK

Placing this work in the context of the existing literature is challenging, as congestion control for DLTs lies at the intersection of DLTs, and many topics within the networking community, such as Quality of Service (QoS), TCP, network security, gossip protocols, and many more. Specifically, our solution employs a scheduler, and a decentralised rate setting algorithm, so we discuss some instances of these in the networking literature. A similar algorithm, in spirit, to the one proposed in this paper, but unsuitable for our requirements, can be found in [4], in which the authors analyse a number of epidemic algorithms and present a 'flow control' algorithm for a replicated database. Their algorithm addresses how nodes should adaptively control their update rate to avoid backlogs. However, the algorithm in [4] is unsuitable for the trustless DLT setting for the following reasons: firstly, congestion is detected by overflows of updates in the buffer, which could result in inconsistency across nodes; additionally, fairness is achieved in [4] through communication and agreement with neighbouring nodes, which is not a reasonable assumption in our trustless setting. Our problem is also closely linked to resource management in a number of network architectures, but our DLT setting presents new challenges, as well as opportunities. Namely, our DLT setting does not permit the assumption of trusted communication between nodes, rendering traditional means of detecting congestion, such as acknowledgements, vulnerable to attack.

From the perspective of achieving QoS in IP networks, the well-known differentiated services (DiffServ) [5] and integrated services (IntServ) [6] architectures offer opposing approaches: DiffServ offering approximate, but scalable and interoperable differentiated treatment of traffic; IntServ permitting more precise, though less scalable, control through explicit reservation of network resources. These solutions rely heavily on a backbone of trusted routers, and are therefore unsuitable for our problem. A common thread for these, and many modern QoS solutions is the use of packet scheduling at routers. By employing a fair queuing algorithm at the scheduler, honest network users are protected from the congestion caused by malicious flows. Typically, increased precision of a fair queuing algorithm comes at the cost of increased complexity. Solutions range from the fine-grained and complex Weighted Fair Queueing (WFQ) [7] to the course-grained and efficient Deficit Round Robin (DRR) [8]. FQ-CoDel [9] provides a combined packet scheduler and active queue management system to prevent the problem of bufferbloat [10]. Some variant of TCP is typically used by nodes to adaptively set their packet rate in these networks. In TCP, nodes additively increase their packet rate until congestion is detected, at which point they multiplicatively decrease their packet rate. However, TCP requires some form of feedback from congested routers, either through acknowledgements [11], or explicit congestion notifications (ECNs) [12], which make them unsuitable for our trustless setting.

#### III. NODE AND NETWORK MODEL

We denote the set of all nodes participating in the network as  $\mathcal{M}$ . Each node,  $m \in \mathcal{M}$ , has a set of neighbours,  $\mathcal{N}_m \subset \mathcal{M}$ , with which it communicates directly over a secure bidirectional channel. The data shared by nodes are referred to as transactions and can include, for example, signed updates of account balances, or IoT sensor data. A transaction is referred to as disseminated when it is present in all ledgers. Conversely, undisseminated transactions are those which have been created, but are not yet disseminated. The rate at which node i's transactions are disseminated is denoted  $D_i$ , and the dissemination rate of all transactions is denoted D. Dissemination rate can be thought of as a measure of network throughput in DLTs. D is bounded, in the long run, by the writing bottleneck at nodes and will be the primary metric we use to evaluate the performance of our congestion control algorithm. Figure 1 illustrates the model of a node, m, and its neighbours. Some of the key notation for the following section is outlined in Table I. Each node has an identity and an associated reputation. Examples of reputation systems which fit our model include reputation directly linked to a node's wealth, delegated forms of reputation, such as the mana system employed in the IOTA network [13], or permissioned

DLTs with an elected consortium of reputable nodes [14]. Node m's reputation is denoted  $rep_m$ . The reputation distribution is assumed to be known by all nodes. Additionally, in this work, reputation is assumed not to vary with time.

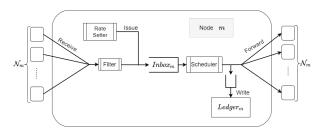


Fig. 1. Model for a node m.

The relevant operations performed on transactions, by nodes, are: *issuing*; *receiving*; *forwarding*; *writing*.

#### A. Issuing Transactions

Transactions are issued and cryptographically signed by nodes, linking that transaction to the issuer. This means that a receiving node can identify the node from which any transaction originates. The rate at which node m issues new transactions is denoted  $\lambda_m$ . As we shall describe below, we impose a global limit,  $\nu$ , on transaction writing in order to ensure consistency, and each node is entitled to a minimum fraction of this, proportional to their reputation. In other words, node m has an assured rate,  $\tilde{\lambda}_m$ , defined as:

$$\tilde{\lambda}_m = \frac{\nu \cdot rep_m}{\sum_{i \in \mathcal{M}} rep_i}.$$
(1)

Note that if all nodes always had transactions to issue, or could exchange trusted communications, the problem of congestion control would be trivial: specifically, each node could either set their issue rate to  $\lambda_m = \tilde{\lambda}_m$ , or coordinate a fair issue rate with their peers, as in [4]. In reality, many nodes are likely to be offline at various times, while other nodes have additional transactions to issue, resulting in under-utilisation of network resources if a fixed rate were to be used. Thus, in the presence of varying traffic conditions and a trustless, decentralised environment, managing transaction issue rate becomes considerably more difficult. To capture these varying traffic conditions, we define four modes of operation for nodes issuing transactions: leftmargin=1em

- *Inactive:* Not issuing any transactions i.e.  $\lambda_m = 0$ .
- Content: Issuing transactions at a fixed rate  $\lambda_m \leq \tilde{\lambda}_m$ . This is modelled as Poisson process with rate parameter  $\lambda_m$ , which is a standard model for arrival processes.
- Best-effort: Issuing transactions at the highest rate possible under the current traffic conditions, without causing excessive congestion. This requires a node to use the rate setting algorithm, outlined in Section IV, to utilise unused network resources and adaptively set  $\lambda_m > \tilde{\lambda}_m$ . We assume that a leaky bucket regulator with rate  $\lambda_m$  is employed to achieve the set issue rate i.e. the rate is deterministic, rather than Poisson.

• *Malicious:* Issuing transactions at a rate  $\lambda_m \gg \tilde{\lambda}_m$ , without concern for the congestion caused. There are many strategies a malicious node could adopt, depending on their goal, some of which we shall discuss in Section V.

**Note:** The issue rate of a node can be capped to prevent certain malicious behaviour, such as spamming. The interested reader can refer to [15] for more details.

## B. Receiving and Forwarding Transactions

Nodes receive transactions from their neighbours, and also forward transactions to their neighbours, as illustrated in Figure 1. Each node maintains an inbox buffer, denoted  $Inbox_m$ , which contains transactions received from neighbours and issued by itself. Transactions are filtered before being to added the inbox, to prevent spam [15]. We denote by  $Inbox_m(i)$ , the set of transactions issued by node i in m's inbox buffer. The size of each buffer is finite, and each node, m, should ensure that  $Inbox_i(m)$  at other nodes  $i \in \mathcal{M}$  does not become too large, as this could lead to excessive queuing delays. We assume that *flooding* is employed here for forwarding of transactions, meaning that all new information is forwarded to all neighbours (except the source node) without regard for whether or not neighbours already possess it. Hence, the stream of transactions from m to i consists of transactions issued by all nodes (except those received from i itself). We refer to a sequence of transactions, issued by node i, as i's flow. Gossip protocols can be employed in some DLT networks, to reduce forwarding overhead, but we defer the discussion of such optimisations to future work.

#### C. Writing Transactions

When a node is informed of a new transaction, a series of actions must be taken to add the transaction to the node's local copy of the ledger. We refer to these steps as writing, and the details of what is required to write a transaction will depend on the underlying ledger structure, and details which are specific to the DLT implementation. We note that, fundamentally, if a transaction is to become part of the distributed ledger, it must be written by every node<sup>2</sup>. For this reason, we impose a global transaction writing rate,  $\nu$ , to ensure consistency. Transactions from  $Inbox_m$  are scheduled for writing at a deterministic rate,  $\nu$ , by a scheduling algorithm which is described in Section IV. Transactions are added to a writing buffer after they are scheduled, so although the time required to write transactions will vary slightly, nodes must only ensure that a writing rate of  $\nu$  can be achieved in the long run to ensure this buffer does not overflow.

# IV. CONGESTION CONTROL ALGORITHM

Our congestion control algorithm seeks to maximise resource utilisation, while ensuring that the requirements laid out in Section I-A, namely consistency, fairness and security, are

<sup>&</sup>lt;sup>2</sup>DLTs with sharding are an exception to this rule as each node must only keep track of relevant shards. Although sharding is beyond the scope of this work, our solution applies to a single shard.

TABLE I. NOTATION FOR NODE AND NETWORK MODEL.

$\mathcal{M}$	set of all nodes in the network
$\mathcal{N}_m$	set of all nodes that are neighbours of node $m$
D	total dissemination rate
$D_i$	dissemination rate of i's transactions
$\nu$	global transaction writing rate
$rep_m$	reputation of node $m$
$\lambda_m$	issue rate of node $m$
$\tilde{\lambda}_m$	assured issue rate of node $m$

met. The two core components of our solution are a scheduling algorithm and a rate setting algorithm:

Scheduling: The goal of this component is to schedule transactions, issued by each node  $i \in \mathcal{M}$ , at a rate proportional to  $rep_i$ . In other words, we wish to achieve weighted maxmin fairness [3] in the writing rate across issuing nodes. This ensures that, for a node m, that issues transactions at an appropriate rate relative to its reputation, the aforementioned requirements will be met: namely, m's transactions will not become backlogged at any node, so consistency will be ensured; m's fair share of the network resources are allocated to it, guaranteeing fairness; malicious nodes sending above their allowed rate will not interrupt m's dissemination rate, fulfilling the security requirement.

Rate setting: The rate setting component seeks to allow best-effort nodes (see Section III) to issue at a rate above their assured rate,  $\tilde{\lambda}_m$ , without causing excessive congestion elsewhere, which could cause a violation of the consistency requirements. We also wish to maintain weighted max-min fairness among best-effort nodes, so that each node can claim a portion of the available dissemination rate proportional to their reputation.

## A. Scheduling Algorithm

Nodes in our setting are capable of more complex and customised behaviour than a typical router in a packet-switched network, but our scheduler must still be lightweight and scalable due to the potentially large number of nodes requiring differentiated treatment. It is estimated that over 10,000 nodes operate on the bitcoin network<sup>3</sup>, and we expect that an even greater number of nodes are likely to be present in the IoT setting. For this reason, we adopt a scheduler based on DRR [8]. The Linux implementation of the FQ-CoDel packet scheduler, which is based on DRR, supports anywhere up to 65535 separate queues [9].

The scheduling algorithm is described in Algorithm 1, and algorithm parameters are given in Table II. Transactions are scheduled at a maximum rate  $\nu$ .  $Q_i$  is proportional to  $rep_i$ , to give a weighted share of the scheduler output to nodes, based on their reputation.

TABLE II. SCHEDULING ALGORITHM PARAMETERS.

$DC_j(i)$	deficit counter for transactions in $Inbox_j(i)$
$Q_i$	quantum added to $DC_j(i)$ , $\forall j$ in each round $(\propto rep_i)$

<sup>&</sup>lt;sup>3</sup>https://bitnodes.io/

## Algorithm 1 DRR Scheduler

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Repeat for i \in \mathcal{M} in a round robin cycle:

1: if |Inbox_m(i)| > 0 then

2: DC_m(i) \leftarrow DC_m(i) + Q_i

3: if DC_m(i) \geq 1 and then

4: Schedule a transaction from Inbox_m(i)

5: DC_m(i) \leftarrow DC_m(i) - 1

6: Wait \frac{1}{\nu} seconds

7: end if

8: end if
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## B. Rate Setting Algorithm

If all nodes always had transactions to issue, the problem of rate setting would be very straightforward: nodes could simply operate in *content* mode i.e. at a fixed, assured rate,  $\tilde{\lambda}_m$ . The scheduling algorithm ensures that this rate is enforceable, and that increasing delays or dropped transactions are only experienced by misbehaving node. However, it is highly unlikely that all nodes will always have transactions to issue, and we would like *best-effort* nodes to better utilise network resources, without causing excessive congestion and violating requirements.

Our rate setting algorithm, for best-effort nodes is inspired by TCP — each node employs additive increase, multiplicative decrease (AIMD) rules to update their issue rate in response to congestion events [16]. However, in the trustless DLT setting, the traditional means of responding to congestion is compromised. For example, malicious nodes could attempt to deflate the issue rate of their neighbours by not sending acknowledgements, or sending illegitimate congestion notifications. We recall, however, that in the case of distributed ledgers, all transaction traffic passes through all nodes, contrary to the case of traffic typically found in packet switched networks and other traditional network architectures. Under these conditions, local congestion at a node is all that is required to indicate congestion elsewhere in the network. This observation is crucial, as it presents an opportunity for a congestion control algorithm based entirely on local traffic.

Recall that when a node m issues a transaction, it is added to its inbox buffer to be scheduled. Node m's own transactions in its inbox,  $Inbox_m(m)$ , are then scheduled at a rate which depends on the other traffic present in the buffer. We observe that the length of  $Inbox_m(m)$  gives an estimate of congestion in node m's traffic, not only at its own inbox buffer, but at  $Inbox_i(m)$  for all properly behaving nodes  $i \in \mathcal{M}$ , within some network network delay.

Algorithm 2 outlines the AIMD rules employed by each node to set their issue rate, and the parameters of the rate setting algorithm are outlined in Table III. Each node sets their own local additive-increase parameter based on the global increase rate A, and their reputation. An appropriate choice of A ensures a conservative global increase rate which does not cause problems even when many nodes increase their rate simultaneously. Nodes wait  $\tau$  seconds after a multiplicative decrease, during which there are no further updates made, to allow the reduced rate to take effect and prevent multiple successive decreases. Waiting after decreases is common in

implementations of AIMD algorithms, such as sliding window flow control in TCP [11]. Rate updates take place each time a transaction is scheduled i.e. at rate  $\nu$  during congestion, when there are always transactions in the inbox. At each update, node m checks how many of its own transactions are in its inbox buffer, and responds with a multiplicative decrease if this number is above a threshold,  $L_m$ , which is proportional to m's reputation. If the number of transactions in  $Inbox_m(m)$  is below the threshold, m's issue rate is incremented by its local increase parameter  $\alpha_m$ .

TABLE III. RATE SETTING ALGORITHM PARAMETERS.

 $\begin{array}{c|c} A & \text{global additive increase parameter} \\ \beta & \text{global multiplicative decrease parameter} \\ \tau & \text{wait time parameter} \\ L_i & \text{inbox length threshold for node } i \ (\propto rep_i) \\ \end{array}$ 

# Algorithm 2 AIMD Rate Setter (Best-effort Mode)

Initialise node  $m \in \mathcal{M}$ :

1:  $\alpha_m \leftarrow A \cdot rep_m / \sum_{i \in \mathcal{M}} rep_i$ Repeat each time a transaction is written (rate  $\nu$ ):

2: **if**  $|Inbox_m(m)| > L_m$  **then**3:  $\lambda_m \leftarrow \lambda_m \cdot \beta$ 4: Wait  $\tau$  seconds for next update

5: **else**6:  $\lambda_m \leftarrow \lambda_m + \alpha_m$ 7: **end if** 

#### V. SIMULATIONS

A simulator was built in Python to test our congestion control algorithm [17]. All node behaviour described in Section III is modelled in the simulator, and the algorithm design considerations that were outlined in Section IV are implemented. Nodes in the simulator share a DAG-based distributed ledger, as described in Section I. We present results from two sets of 100 Monte Carlo simulations: the first set with only non-malicious nodes; and the second set with the addition of malicious behaviour.

Our test network consists of 15 nodes, arranged in a random 4-regular graph i.e. each node has 4 random neighbours. Channel delays are random between 50 ms and 150 ms, and do not vary over time. We first consider a group of five nodes in each of the non-malicious modes of operation. Each group of five nodes has the reputation distribution  $\{3, 2, 1, 1, 1\}$ . We identify nodes by a letter representing their mode of operation and a number representing their reputation. For example, if a node is denoted B2, this is a best-effort node with reputation 2. Simulations begin at time t=0. Content nodes, in these simulations, issue at their full assured rate  $\lambda_i = \tilde{\lambda}_i$ . Best-effort nodes begin the simulation issuing at their assured rate, and start to increase their rate, with the rate setting algorithm, after 10 seconds of the simulation. The parameters used for the congestion control algorithm are given in Table IV.

TABLE IV. CONGESTION CONTROL PARAMETERS.

Scheduler		Rate Setter			
$\nu$	$Q_i$	A	$\beta$	$\tau$	$L_i$
10	$rep_i$	0.1	0.5	2	$2 \cdot rep_i$

Figure 2 shows: the dissemination rate of each node; the dissemination rate, scaled by assured issue rate, of each node; and the number of undisseminated transactions for each node. The dissemination rate plots reveal that fairness is achieved, and that the unutilised network resources are fairly distributed among the best-effort nodes. The content nodes' rates converge to their assured issue rate, as expected, and as each group has equal reputation, the best effort nodes converge to twice their assured rate, consuming the unused resources left by the inactive nodes. The plot of undisseminated transactions demonstrates consistency, because the protocol drops no transactions, and the number of undisseminated transactions remains bounded. Figure 3 shows that the overall dissemination rate approaches the maximum writing rate of nodes, and the mean delay remains bounded. Although counter intuitive, the dissemination rate often exceeds the maximum writing rate of nodes  $\nu$  because, although transactions must pass through every node, they have different start and end points. Figure 4 demonstrates that delays are kept low.

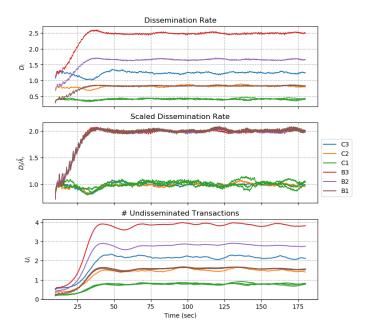


Fig. 2. Simulation set 1: dissemination rate, scaled dissemination rate, and number of undisseminated transactions over time (moving average over a ten second window).

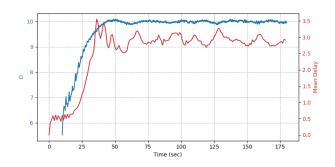


Fig. 3. Simulation set 1: dissemination rate (moving average over a ten second window) and mean transaction delay.

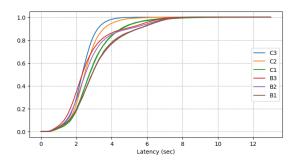


Fig. 4. Simulations set 1: CDF of transaction latency.

The remaining requirement to test is security. In the second set of simulations, one of the B1 nodes is switched from besteffort mode to malicious mode. Specifically, this node issues transactions at 5 times its assured rate. All other simulation parameters remain unchanged. Figure 5 shows that the dissemination rate of the malicious node is very slightly higher than that of the best-effort nodes. However, the number of undisseminated transactions issued by the malicious node is constantly growing, as a result of large backlogs in its transactions in the buffers of non-malicious nodes. Excessively full inbox buffers are therefore a simple means of detecting malicious behaviour, and action can be taken to remove the malicious node from the network. Dealing with detected attackers is implementationspecific and beyond the scope of this work, but will be a subject of future work. Additionally, Figure 6 shows that the malicious node only delays its own transactions. This set of simulations shows that a malicious actor can not violate the requirements of fairness and consistency, as this type of malicious behaviour is easily detectable. In other words, the security requirement is also satisfied.

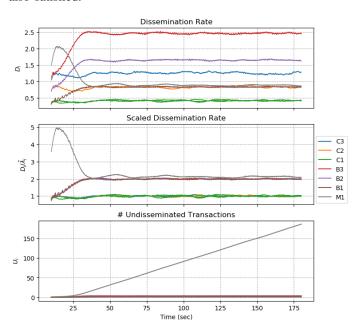


Fig. 5. Simulation set 2: dissemination rate, scaled dissemination rate, and number of undisseminated transactions over time (moving average over a ten second window).

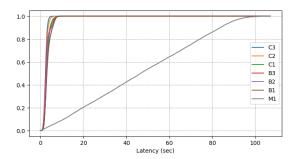


Fig. 6. Simulation set 2: CDF of transaction latency.

Initial results show that our algorithm is robust with respect to different network conditions and algorithm parameters. Future publications will report a detailed sensitivity analysis.

#### VI. CONCLUSIONS

We have presented a congestion control algorithm for DLTs that utilises node resources optimally and minimises delay, satisfying the requirements of fairness, consistency and security. We have evaluated its performance with extensive Monte Carlo analysis using a detailed agent-based Python simulator. Future lines of research will address a broader range of simulation scenarios, as well as deployment of our algorithm on a DLT test network, such as the IOTA Foundation's GoShimmer network [18].

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