Dumbo-NG: Fast Asynchronous BFT Consensus with Throughput-Oblivious Latency

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ABSTRACT

Despite recent progresses of practical asynchronous Byzantine-fault tolerant (BFT) consensus, the state-of-the-art designs still suffer from suboptimal performance. Particularly, to obtain maximum throughput, most existing protocols with guaranteed linear amortized communication complexity require each participating node to broadcast a huge batch of transactions, which dramatically sacrifices latency. Worse still, the $f$ slowest nodes’ broadcasts might never be agreed to output and thus can be censored (where $f$ is the number of faults). Implementable mitigation to the threat either uses computationally costly threshold encryption or incurs communication blow-up by letting the honest nodes to broadcast redundant transactions, thus causing further efficiency issues.

We present Dumbo-NG, a novel asynchronous BFT consensus (atomic broadcast) to solve the remaining practical issues. Its technical core is a non-trivial direct reduction from asynchronous atomic broadcast to multi-valued validated Byzantine agreement (MVBA) with quality property (which ensures the MVBA output is from honest nodes with 1/2 probability). Most interestingly, the new protocol structure empowers completely concurrent execution of transaction dissemination and asynchronous agreement. This brings about two benefits: (i) the throughput-latency tension is resolved to approach peak throughput with minimal increase in latency; (ii) the transactions broadcasted by any honest node can be agreed to output, thus conquering the censorship threat with no extra cost.

We implement Dumbo-NG with using the current fastest GLL+22 MVBA with quality (NDSS’22) and compare it to the state-of-the-art asynchronous BFT consensus with guaranteed censorship resilience including Dumbo (CCS’20) and Speeding-Dumbo (NDSS’22). Along the way, we apply the techniques from Speeding-Dumbo to DispersedLedger (NSDI’22) and obtain an improved variant of DispersedLedger called sDumbo-DL for comprehensive comparison. Extensive experiments (over up to 64 AWS EC2 nodes across 16 AWS regions) reveal: Dumbo-NG realizes a peak throughput 4-8x over Dumbo, 2-4x over Speeding-Dumbo, and 2-3x over sDumbo-DL (for varying scales); More importantly, Dumbo-NG’s latency, which is lowest among all tested protocols, can almost remain stable when throughput grows.

CCS CONCEPTS

• Security and privacy → Systems security; Distributed systems security; • Computer systems organization → Reliability.

KEYWORDS

Asynchronous consensus, Byzantine-fault tolerance, blockchain

1 INTRODUCTION

The huge success of Bitcoin [63] and blockchain [19, 24] leads to an increasing tendency to lay down the infrastructure of distributed ledger for mission-critical applications. Such decentralized business is envisioned as critical global infrastructure maintained by a set of mutually distrusting and geographically distributed nodes [11], and thus calls for consensus protocols that are both secure and efficient for deployment over the Internet.

Asynchronous BFT for indispensable robustness. The consensus of decentralized infrastructure has to thrive in a highly adversarial environment. In particular, when the applications atop it are critical financial and banking services, some nodes can be well motivated to collude and launch malicious attacks. Even worse, the unstable Internet might become part of the attack surface due to network fluctuations, misconfigurations and even network attacks. To cope with the adversarial deployment environment, asynchronous Byzantine-fault tolerant (BFT) consensuses [4, 20, 35, 47, 58, 60] are arguably the most suitable candidates. They can realize high security-assurance to ensure liveness (as well as safety) despite an asynchronous adversary that can arbitrarily delay messages. In contrast, many (partial) synchronous consensus protocols [5, 6, 8, 15, 17, 24, 45, 64, 73] such as PBFT [26] and HotStuff [75] might sustain the inherent loss of liveness (i.e., generate unbounded communications without making any progress) [36, 66] when unluckyly encountering an asynchronous network adversary.

1.1 Practical obstacles of adopting asynchronous BFT consensus

Unfortunately, it is fundamentally challenging to realize practical asynchronous BFT consensus, and none of such protocols was widely adopted due to serious efficiency concerns. The seminal FLP “impossibility” [36] proves that no deterministic consensus exists in the asynchronous network. Since the 1980s, many attempts [1, 12, 13, 21, 25, 65, 67] aimed at to circumventing the “impossibility” by randomized protocols, but most of them focused on theoretical feasibility, and unsurprisingly, several attempts of implementations [22, 61] had inferior performance.

Until recently, the work of HoneyBadger BFT (HBBFT) demonstrated the first asynchronous BFT consensuses that is performant in the wide-area network [60]. As shown in Figure 1, HBBFT was
instantiated by adapting the classic asynchronous common subset (ACS) protocol of Ben-Or et al. [14]. It firstly starts \( n \) parallel reliable broadcasts (RBCs) with distinct senders. Here \( n \) is the total number of nodes, and RBC [18] emulates a broadcast channel via point-to-point links to allow a designated sender to disseminate a batch of input transactions. However, we cannot ensure that every honest node completes a certain RBC after a certain time due to asynchrony. So an agreement phase is invoked to select \( n - f \) completed and common RBCs (where \( f \) is the number of allowed faulty nodes). In HBBFT, the agreement phase consists of \( n \) concurrent asynchronous binary Byzantine agreement (ABBA). Each ABBA corresponds to a RBC, and would output 1 (resp. 0) to solicit (resp. omit) the corresponding RBC in the final ACS output.

As such, Throughput that is severely hurting latency (e.g. HBBFT) can significantly increase throughput via batching (\( \text{TPKE.Enc} \)). A serious practicality hurdle of many existing asynchronous protocols (e.g. HBBFT and Dumbo) is that their maximum throughput is only achievable when their latency is sacrificed. As early as 2016, HBBFT [60] even explicitly argued that latency is dispensable for throughput and robustness, if aiming at the decentralized version of payment networks like VISA/SWIFT. The argument might be correct at the time of 2016, but after all these years, diverse decentralized applications have been proposed from quick inter-continental transactions [28] to instant retail payments [11]. Hence it becomes unprecedentedly urgent to implement robust BFT consensus realizing high throughput while preserving low latency.

To see the reason behind the throughput-latency tension in the existing performant asynchronous BFT protocols (with linear amortized communication complexity) such as HBBFT/Dumbo, recall that these protocols consist of two main phases—the bandwidth-intensive transaction dissemination phase and the bandwidth-oblivious agreement phase. Different from the dissemination phase that contributes into throughput, the agreement phase just hinders throughput, as it “wastes” available bandwidth in the sense of incurring large latency to block successive epochs’ broadcasts. Thus, to sustain high throughput, each node has to broadcast a huge batch of transactions to “contend” with the agreement phase to seize most available bandwidth resources.

However, larger batches unavoidably cause inferior latency, although they can saturate the network capacity to obtain the maximum throughput. For example, Figure 2 clarifies: (i) when each node broadcasts a small batch of 1k tx in Dumbo (\( n=16 \)), the latency is not that bad (2.39 sec), but the throughput is only 4,594 tx/sec, as the transaction dissemination only takes 16.5% of all running time; (ii) when the batch size increases to 30k tx, the broadcast of transactions possesses more than 50% of the running time, and the throughput becomes 37,620 tx/sec for better utilized bandwidth, but the latency dramatically grows to nearly 9 sec.

### Figure 1: Execution flow of an epoch in HBBFT, Dumbo and their variants. The protocols proceed by consecutive epochs.

The above ACS design separates the protocol into bandwidth-intensive broadcast phase and bandwidth-oblivious agreement phase. Here the broadcast is bandwidth-intensive (i.e., latency heavily relies on available bandwidth), because of disseminating a large volume of transactions; and the agreement is bandwidth-oblivious (i.e., latency depends on network propagation delay more than bandwidth), as it only exchanges a few rounds of short messages. HBBFT then focused on optimizing the bandwidth-intensive part—transaction broadcasts. It adapted the techniques of using erasure code and Merkle tree from verifiable information dispersal [23] to reduce the communication cost of Bracha’s RBC [18], and realized amortized \( O(n) \) communication complexity for sufficiently large input batch. As such, HBBFT can significantly increase throughput via batching more transactions, but its \( n \) concurrent ABBAs incurred suboptimal expected \( O(\log n) \) rounds. A recent work Dumbo [47] concentrated on the latency-critical part consisting of \( n \) ABBA, and used a single asynchronous multi-valued validated Byzantine agreement (MVBA) to replace the slow \( n \) ABBA. Here MVBA is another variant of asynchronous BA whose output satisfies a certain global predicate, and can be constructed from 2-3 ABBA (e.g., CKPS01 [20]) or from more compact structures (e.g., AMS19 [4] and GLL+22 [46]). Thanks to more efficient agreement phase based on MVBA, Dumbo reduced the execution rounds from expected \( O(\log n) \) to \( O(1) \), and achieved an order-of-magnitude of improvement on practical performance.

Actually, since HBBFT [60], a lot of renewed interests in addition to Dumbo are quickly gathered to seriously explore whether asynchronous protocols can ever be practical [4, 35, 38, 50, 74].

Notwithstanding, few existing “performant” asynchronous BFT consensuses can realize high security assurance, low latency, and high throughput, simultaneously. Here down below we briefly reason two main practical obstacles in the cutting-edge designs.

### Throughput that is severely hurting latency.

A serious practicality hurdle of many existing asynchronous protocols (e.g. HBBFT and Dumbo) is that their maximum throughput is only achievable when their latency is sacrificed. As early as 2016, HBBFT [60] even explicitly argued that latency is dispensable for throughput and robustness, if aiming at the decentralized version of payment networks like VISA/SWIFT. The argument might be correct at the time of 2016, but after all these years, diverse decentralized applications have been proposed from quick inter-continental transactions [28] to instant retail payments [11]. Hence it becomes unprecedentedly urgent to implement robust BFT consensus realizing high throughput while preserving low latency.

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### Figure 2: Latency breakdown of Dumbo (on 16 Amazon EC2 c5.large instances across different regions). [8] is batch size, i.e., the number of tx to broadcast by each node (where each tx is 250-byte to approximate the size of Bitcoin’s basic tx). TPKE is a technique from HBBFT for preventing censorship.

**Liveness** relies on heavy cryptography or degraded efficiency. Besides the unpleasant throughput-latency tension, the asynchronous protocols might also face serious censorship threat. This is because during the transaction dissemination phase, the

\[ \text{Remark that liveness in the asynchronous setting cannot be guaranteed by merely ensuring protocols to progress without stuck. It needs to consider the liveness notion (e.g. validity from [20]) to ensure that any tx input by sufficient number of honest nodes must eventually output, which was widely adopted in [35, 38, 44, 47, 50, 60, 74].} \]
adversarial network can delay the broadcasts containing its disliked transactions and prevent the certain transactions from being output.

To mitigate the censorship threat and ensure liveness, existing designs rely on asymptotically larger communications, costly cryptographic operations, or probably unbounded memory. Specifically,

- One somewhat trivial "solution" to censorship-resilience is to diffuse transactions across all nodes and let every node work redundantly. Therefore, even if the adversary can slow down up to \( f \) honest nodes’ broadcasts, it cannot censor a certain transaction \( tx \), because other \( n - 2f \) honest nodes still process \( tx \). This is the exact idea in Cachin et al.’s asynchronous atomic broadcast protocol [20], but clearly incurs another \( O(n) \) factor in the communication complexity. Recently, Tusk [32] leveraged de-duplication technique to let a small number of \( k \) nodes process each transaction according to transaction hash [72] or due to the choice of clients. Here \( k \) is expected a small security parameter to luckily draw a fast and honest node. Nevertheless, an asynchronous adversary (even without actual faults) can prevent up to \( f \) honest nodes from eventually output in Tusk, and therefore the transactions duplicated to \( k \) nodes can still be censored unless \( k \geq f + 1 \), i.e., \( O(n) \) redundant communication still occurs in the worst case. That means, though de-duplication techniques are enticing, we still need underlying consensus stronger (e.g., any honest node’s input must eventually output) to reduce redundant communication by these techniques without hurting liveness.

- As an alternative, HBBFT introduces threshold public key encryption (TPKE) to encrypt the broadcast input.\(^2\) Now, transactions are confidential against the adversary before they are solicited into the final output, so that the adversary cannot learn which broadcasts are necessary to delay for censoring a certain transaction. But TPKE decryption could be costly. Figure 2 shows that in some very small scales \( n = 16 \), TPKE decryption already takes about 20% of the overall latency in Dumbo (using the TPKE instantiation [9] same to HBBFT). For larger scales, the situation can be worse, because each node computes overall \( O(n^2) \) operations for TPKE decryptions.

- Recently, DAG-Rider [50] presented a (potentially unimplementable) defense against censorship: the honest nodes do not kill the instances of the slowest \( f \) broadcasts but forever listen to their delivery. So if the slow broadcasts indeed have honest senders, the honest nodes can eventually receive them and then attempt to put them into the final consensus output. This intuitively can ensure all delayed broadcasts to finally output, but also incurs probably unbounded memory because of listening an unbounded number of broadcast instances that might never output due to corrupted senders (as pointed out by [32]).\(^3\)

\(^2\)Remark that one also can use asynchronous verifiable secret sharing (AVSS) to replace TPKE, since both can implement a stronger consensus variant called casual broadcast [20], i.e., it first outputs transactions in a confidential manner, and then reveals. We do not realize any practical censorship-resilience implementation based on AVSS.

\(^3\)In DAG-Rider [50], every node has to keep on listening unfinished broadcasts. So if there are some nodes get crashed or delayed for a long time, the honest nodes need to listen more and more unfinished broadcasts with the protocol execution. The trivial idea of killing unfinished broadcasts after some timeout would re-introduce censorship threat, because this might kill some unfinished broadcasts of slow but honest nodes.

Given the state-of-the-art of existing "performant" asynchronous BFT consensuses, the following fundamental challenge remains:

*Can we push asynchronous BFT consensus further to realize minimum latency, maximum throughput, and guaranteed censorship-resilience, simultaneously?*

### 1.2 Our contribution

In short, we answer the above question affirmatively by presenting Dumbo-NG—a direct, concise and efficient reduction from asynchronous BFT atomic broadcast to multi-valued validated Byzantine agreement (MVBA). In greater detail, the core contributions of Dumbo-NG can be summarized as follows:

- *Resolve the latency-throughput tension,* Dumbo-NG resolves the severe tension between throughput and latency in HBBFT/Dumbo. Recall the issue stems from: for higher throughput, the broadcasts in HBBFT/Dumbo have to sacrifice latency to disseminate a huge batch of transactions, and this is needed to "contend" with the agreement modules to seize more bandwidth resources. Dumbo-NG solves the issue and can approach the maximum throughput without trading latency, i.e., realize throughput-oblivious latency. This is because it supports to run the bandwidth-intensive transaction broadcasts completely concurrently to the bandwidth-oblivious agreement modules. Remark that the concurrent execution of broadcasts and agreement is non-trivial in the asynchronous setting, as we need carefully propose and implement a few properties of broadcast and agreement to bound communication complexity and ensure censorship resilience, cf. Section 2 for detailed discussions about the challenges and why existing techniques to parallelize agreement and broadcast (e.g., [32]) cannot help us simultaneously realize guaranteed censorship resilience in the hostile asynchronous setting.

### Table 1: Validity (liveness) of asynchronous atomic broadcast if stressing on nearly linear amortized communication

| Protocol         | Strong validity (Definition 4.1) | Memory-bounded implementation |
|------------------|----------------------------------|-------------------------------|
| DAG-Rider [50], DispersedLedger [74], and Aleph [38] | ✓ * | ✓ O † |
| Tusk [32] | × suboptimal comm.; or after GST ‡ | ✓ |
| HBBFT [60], Dumbo [47] and variants [35, 46] | ✓ diffuse TX + TPKE for de-duplication | ✓ |
| Dumbo-NG (this paper) | ✓ * | ✓ |

\* Here we assume de-duplicated input buffers in DAG-Rider, DispersedLedger and Dumbo-NG, which can be realized (i) in a permissioned setting where a client only has permission to contact several nodes or (ii) by de-duplication techniques [31, 32, 72], cf. Footnote 4.

† The memory-bounded implementation of [38, 50, 74] is unclear, cf. Footnote 3.

‡ Though Tusk employs transaction de-duplication techniques to send transactions to only \( k \) nodes, it doesn’t realize strong validity, so still needs \( k = f + 1 \) to ensure all transactions to output in the worst case asynchronous network, cf. Footnote 4; and a recent improvement of Tusk—Bullshark [43] presents an implementation that explicitly stresses on strong validity only after global stabilization time (GST).

- *Prevent censorship with minimal cost.* As shown in Table 1, similar to DAG-Rider [50] and DispersedLedger [74], Dumbo-NG ensures that any transaction input by an honest node can eventually output (a.k.a. strong validity in [20]), and thus when building a state-machine replication (SMR) service [70] from such atomic broadcasts, one can expect to overcome potential...
censorship with minimized extra cost (e.g., by directly using de-duplication techniques [32, 72]). So we call strong validity and censorship resilience interchangeably, and can safely assume the honest parties have de-duplicated input buffers containing mostly different transactions throughout the paper. Such resilience of censorship is born with our new protocol structure, because no matter how slow a broadcast can be, the concurrently running agreement modules can eventually pick it into the final output through a quorum certificate pointing to it. As such, Dumbo-NG does not rely on additional heavy cryptographic operations (e.g., [35, 46, 47]) or sub-optimal redundant communication (e.g., the worst case of Tusk [32]) to realize guaranteed resilience against an asynchronous censorship adversary. This further demonstrates the strength of our result w.r.t its security aspect in addition to its practicality.

- By-product of adapting DispersedLedger to the state-of-the-art: Along the way, we note that the recent work DispersedLedger was explained by adapting the suboptimal ACS design from HBBFT, and it used an unnecessarily strong asynchronous verifiable information dispersal (AVIS) notion [23] to facilitate transaction dissemination. As a by-product and also since quorum non for fair comparison, we adapt DispersedLedger to Speeding-Dumbo (sDumbo) [46] to enjoy the fast termination of the state-of-the-art ACS design. A weaker thus cheaper information dispersal notion—provocative dispersal from Dumbo-MVBA [58] is also adopted to replace AVIS. The resulting protocol (called sDumbo-DL) realizes asymptotic improvement in message and round complexities, and significantly outperforms sDumbo/Dumbo in terms of hurting latency less while realizing maximum throughput.

### Table 2: In comparison with existing performant asynchronous consensus in the WAN setting at n=4, 16, 64 nodes.

| Protocol         | Peak throughput (tps) | Latency at peak-tps (sec) |
|------------------|-----------------------|---------------------------|
| Dumbo [47]       | 22.038                | 40.943                    |
| Speeding Dumbo [46] | 38.545                | 74.601                    |
| DispersedLedger [74] | 54.868                | 92.402                    |
| Dumbo-NG         | 166,907               | 165,081                   |

1. Throughput of the protocols is evaluated in WAN settings consisting of Amazon EC2 c5 large instances evenly distributed among up to 16 regions, and each transaction is of 250 bytes.
2. We actually evaluate an improved DispersedLedger (called sDumbo-DL by us) using cutting-edge techniques from Speeding-Dumbo [46] and Dumbo-MVBA [58], cf. Section 5 for details.

- **Implementation and extensive experiments over the Internet:** We implement Dumbo-NG and extensively test it among n = 4, 16 or 64 nodes over the global Internet, with making detailed comparison to the state-of-the-art asynchronous protocols including Dumbo and two very recent results—DispersedLedger [74] and Speeding-Dumbo (sDumbo) [46]. At all system scales, the peak throughput of Dumbo-NG is multiple times better than any of the other tested asynchronous BFT ABC protocols, e.g., 4-8x over Dumbo, 2-4x over sDumbo, and 2-3x over the sDumbo-DL version of DispersedLedger.

More importantly, the latency of Dumbo-NG is significantly less than others (e.g., 4-7x faster than Dumbo when both protocols realize the maximum throughput). Actually, the latency of Dumbo-NG is nearly independent to its throughput, indicating how effective it is to resolve the throughput-latency tension lying in the prior designs. As shown in Figure 3, we can quantitatively estimate throughput-obliviousness by the increment ratio of latency from minimum to (nearly) maximum throughputs. In particular, a protocol is said more throughput-oblivious than another protocol, if such the ratio is much closer to zero, so throughput obliviousness is an easily measurable metric that can also be used in many other studies. For n=64, when the throughput increases from minimum to maximum (around 100k tx/sec), the latency increment ratio of Dumbo-NG is only 11% (increased by 0.72 sec); in contrast, Dumbo, sDumbo and sDumbo-DL suffer from 347% (28 sec), 141% (12 sec), 94% (3.4 sec) increment ratio (or increment) in latency, respectively, when pumping up throughput from minimum to maximum.

![Figure 3: Latency increment of async. BFT when throughput increases from minimum to maximum in the WAN setting for n=64 nodes (cf. Section 7 for detailed experiment setup).](image-url)

### 2 PATH TO OUR SOLUTION

Here we take a brief tour to our solution, with explaining the main technical challenges and how we overcome the barriers.

**An initial attempt.** A recent work DispersedLedger (DL) [74] also dissects HBBFT and recognizes the efficiency hurdles lying in the bandwidth wasted during running the agreement phase. Although DispersedLedger originally aimed at throughput (more precisely, throughput in a variable network condition), it actually presents a promising idea of separating the bandwidth-intensive transaction dissemination and the bandwidth-oblivious agreement.

As Figure 4 illustrates, DispersedLedger splits ACS into two concurrent paths: one path first disperses transactions (instead of direct broadcast) and then agrees on which dispersed transactions to appear into the final output; and the other path can concurrently retrieve the transactions supposed to output. Here dispersal and retrieval can be implemented by asynchronous verifiable information dispersal [23]. Remarkably, the communication cost of dispersal can be asymptotically cheaper than that of broadcast in HBBFT/Dumbo: the per node commutation cost in the dispersal phase is $O(|B|)$ bits, and per node commutation cost in the retrieval phase is $O(n|B|)$.
bits, if each node takes a sufficiently large $|B|$-sized input to ACS. Clearly, the retrieval phase becomes the most bandwidth-starving component, and fortunately, it can be executed concurrently to the dispersal and agreement phases of succeeding ACS. This becomes the crux to help DispersedLedger (DL) to outperform HBBFT. To go one step further (and test the limit of DL framework), we use the orthogonal techniques from the Dumbo protocols [46, 47, 58], particularly the very recent Speeding-Dumbo [46], and get a protocol called sDumbo-DL that further reduces DL’s complexities and improves its practical metrics significantly.

![Figure 4: Execution flow of DispersedLedger. Transaction retrieval is executed concurrently to dispersal and agreement. Modules in the light-orange region represents one ACS.](image)

However, the DL framework implements the idea of separating bandwidth-intensive and bandwidth-oblivious modules in a sub-optimal way, in particular: (i) dispersal is still blocked by the agreement phase of preceding ACS; so considerable batch sizes are still needed to fully utilize the bandwidth; (ii) when large batch sizes are adopted for higher throughput, the dispersal phase is no longer bandwidth-oblivious, and it also incurs a lot of network workload, which significantly enlarges the latency.

Even if the improvements of sDumbo-DL greatly alleviates the above issues because of a much faster agreement phase, these issues still take considerable effects to lag the confirmation. For example, in our WAN experiment setting, to fully utilize the bandwidth while GLL+22-MVBA is running, the needed batch size remains larger than 6MB (which even becomes about 20MB after applying erasure-code for fault-tolerant retrieval).

In short, though DispersedLedger can realize considerable improvement in throughput, it cannot preserve a stable latency while approaching the maximum throughput (even after adapting it to the cutting-edge ACS framework [46]), cf. Section 5 for more detailed discussions on DispersedLedger’s merits and bottlenecks.

**Path to our final solution: barriers and techniques.** Taking the merits and issues of DispersedLedger constructively, we aim to make broadcast and agreement to execute completely concurrently.

As Figure 5 illustrates, we let each node act as a sender in an ever-running multi-shot broadcast to disseminate its input transactions, and concurrently, the agreement phase to pack the broadcasted transactions into the final consensus output. Now, the bandwidth-intensive transaction dissemination is continuously running to closely track the network capacity over all running time, and no longer needs to use large batch sizes to contend with the bandwidth-oblivious agreement modules for seizing network resources (as prior art does). As such, it becomes promising to obtain the peak throughput without hurting latency.

However, the seemingly simple idea of running broadcasts concurrent to Byzantine agreement (BA) is facing fundamental challenges in the asynchronous setting. Here we briefly overview the barriers and shed a light on our solution to tackle them.

![Figure 5: High-level of Dumbo-NG. Each node leads an ever-running multi-shot broadcast to disseminate its input transactions. Aside from broadcasts, a sequence of asynchronous multi-valued validated Byzantine agreements (MVBA) are executed to totally order all broadcasted transactions.](image)

### Challenge I: allow BA to pack broadcasts, concurrently & validly.

In an asynchronous network, the adversary can arbitrarily delay broadcasts, and thus some multi-shot broadcast might progress very fast while some might move forward much slower. So the concurrent Byzantine agreement modules have to agree on the “valid” progress of each multi-shot broadcast instance, where “valid” progress means the broadcast has indeed progressed up to here. The above task, intuitively, is much more challenging than the agreement problem in HBBFT/Dumbo/DispersedLedger (which only decides 1/0 for each single-shot broadcast to mark whether the broadcast is completed or not). At first glance, we seemingly need asynchronous BA with strong validity, because the agreed broadcast progress needs to be from some honest node to ensure it was indeed completed (otherwise, the adversary can manipulate the agreement result to let honest nodes agree on some broadcast progresses that were not completed). But, unfortunately, strong validity is unimplementable for multi-valued agreement in the asynchronous setting, as it needs huge communication cost exponential in input length [37].

To circumvent the challenge, we carefully add quorum certificates to the multi-shot broadcasts by threshold signature, such that the adversary cannot forge a certificate for some uncompleted broadcast progress. In particular, our multi-shot broadcast can be thought of a compact variant of running a sequence of verifiable consistent broadcasts [68], in which a quorum certificate can prove that the honest nodes either have delivered (or can retrieve) the same sequence of all broadcasted transactions [20, 32]. This allows us to design the needed agreement module by (implementable) asynchronous MVBA with fine-tuned external validity. We let MVBA’s input/output to be a vector of $n$ broadcasts’ certificates, and the external validity checks: (i) all $n$ certificates are valid, (ii) at least $n - f$ certificates attest that their corresponding $n - f$ broadcasts have progressed. As such, we can run a sequence of MVBAs completely
concurrent to the \( n \) ever-running broadcasts, and each MVBA can pack \( n - f \) progressed broadcasts to form a final consensus output. **Challenge II**: output all completed broadcasts to prevent censorship. Nevertheless, external validity of MVBA is not enough to ensure liveness, as it cannot guarantee that all progressed broadcasts can be solicited by some MVBA to output, and the censorship threat is still a valid concern. The reason behind the problem is: the conventional MVBA notion [20] allows the adversary to fully decide the agreed result (as long as satisfying the external validity condition), so in our context, the adversary can exclude up to \( f \) honest nodes’ broadcasts from the final consensus output.

To overcome this subtle issue, we realize that some recent MVBA protocols [4, 46, 58] actually have an additional quality property (at no extra cost). Here quality means that with at least 1/2 probability (or other constant probability), the MVBA’s output is proposed by some honest node. Hence, if we carefully choose a MVBA protocol with quality, liveness (aka censorship-resilience) can be guaranteed because: once a broadcast’s quorum certificate is received by all honest nodes, it will be decided to output after expected 2 MVBAs.

**Our techniques v.s. Tusk’s transaction diffuse.** Recently, Tusk [32] adapted Prism’s [10] core idea to separate transaction diffuse and agreement into the asynchronous setting, and presented how to diffuse transactions concurrently to a compact DAG-based asynchronous consensus: each node multicasts transaction batches to the whole network and waits \( n - f \) naive receipt acknowledgements, such that the digests of transaction batches (instead of the actual transactions) can be agreed inside Tusk’s DAG. Nevertheless, the above transaction diffuse does not generate quorum certificates for transaction retrievability by itself, but relies on consistent broadcasts inside Tusk’s DAG to generate such certificates.

That means, diffused transactions of \( f \) honest nodes might have no quorum certificates generated for retrievability in Tusk because their corresponding consistent broadcasts are never completed (and they will finally be garbage collected). In contrast, we require every node (even the slowest) can generate certificates for retrievability of its own input transactions through a multi-shot broadcast instance. This is critical for preventing censorship, because any honest node, no matter how slow it is, can generate these certificates and use them to convince the whole network to solicit its disseminated input into the final consensus output. This corresponds to the reason why Tusk’s transaction diffuse cannot directly replace our transaction dissemination path without hurting censorship resilience.

## 3 OTHER RELATED WORK

Besides closely related studies [32, 46, 47, 50, 60, 74] discussed in Introduction, there also exist a few works [53, 68] including some very recent ones [41, 57] that consider adding an optimistic “fast-lane” to the slow asynchronous atomic broadcast. The fastlane could simply be a fast leader-based deterministic protocol. This line of work is certainly interesting, however in the adversarial settings, the “fastlane” never succeeds, and the overall performance would be even worse than running the asynchronous atomic broadcast itself. This paper, on the contrary, aims to directly improve asynchronous BFT atomic broadcast, and can be used together with the optimistic technique to provide a better underlying pessimistic path. In addition, BEAT [35] cherry-picked constructions for each component in HBBFT (e.g., coin flipping and TPKE without pairing) to demonstrate better performance in various settings, and many of its findings can benefit us to choose concrete instantiations for the future production-level implementation. There are also interesting works on asynchronous distributed key generation [2, 33, 39, 52], which could be helpful to remove the private setup phase in all recent asynchronous BFT protocols.

In addition to fully asynchronous protocols, a seemingly feasible solution to robust BFT consensus is choosing a conservative upper bound of network delay in (partially) synchronous protocols. But this might bring serious performance degradation in latency, e.g., the exaggeratedly slow Bitcoin. Following the issue, a large number of “robust” (partially) synchronous protocols such as Prime [5], Spinning [73], RBFT [8] and many others [29, 30] are also subject to this robustness-latency trade-off. Let alone, none of them can have guaranteed liveness in a pure asynchronous network, inherently [36]. In addition, a few recent results [3, 64, 71] make synchronous protocols to attain fast (responsible) confirmation in certain good cases, but still suffer from slow confirmation in more general cases.

## 4 PROBLEM DEFINITION & PRELIMINARIES

### 4.1 System/threat models and design goals

**System and adversary models.** We adopt a widely-adopted asynchronous message-passing model [4, 7, 20, 21, 35, 47, 58, 60] with setup assumptions. In greater detail, we consider:

- **Known identities & setup for threshold signature.** There are \( n \) designated nodes in the system, each of which has a unique identity. W.o.l.g, their identities are denoted from \( \mathcal{P}_P \) to \( \mathcal{P}_n \). In addition, non-interactive threshold signature (TSIG) is properly set up, so all nodes can get and only get their own secret keys in addition to the public keys. The setup can be done through distributed key generation [2, 33, 34, 39, 42, 49, 52, 66] or a trusted dealer.

- **\( n/3 \) Byzantine corruptions.** We consider that up to \( f = \lfloor (n - 1)/3 \rfloor \) nodes might be fully controlled by the adversary. Remark that our implementation might choose statically secure threshold signature as a building block for efficiency as same as other practical asynchronous protocols [35, 47, 60], noticing that a recent adaptively secure attempt [56] has dramatically degraded throughput less than half of its static counterpart for moderate scales \( \approx 50 \) nodes. Nevertheless, same to [4, 20, 58], our protocol can be adaptively secure to defend against an adversary that might corrupt nodes during the course of protocol execution, if given adaptively secure threshold signature [54, 55] and MVBA [4, 58]. Besides adaptively secure building blocks, the other cost of adaptive security is just an \( O(n) \)-factor communication blow-up in some extreme cases.

- **Asynchronous fully-meshed point-to-point network.** We consider an asynchronous message-passing network made of fully meshed authenticated point-to-point (p2p) channels [7]. The adversary can arbitrarily delay and reorder messages, but any message sent between honest nodes will eventually be delivered to the destination without tampering, i.e., the adversary cannot drop or modify the messages sent between the honest nodes. As [60] explained, the eventual delivery of messages can be realized by letting the sender repeat transmission until
receiving an acknowledge from the receiver. However, when some receiver is faulty, this might cause an increasing buffer of outgoing messages, so we can let the sender only repeat transmissions of a limited number of outgoing messages. To preserve liveness in the handicapped network where each link only eventually delivers some messages (not all messages), we let each message carry a quorum certificate allowing its receiver sync up the latest progress, cf. Appendix B for details.

**Security goal.** We aim at a secure asynchronous BFT consensus satisfying the following atomic broadcast (ABC) abstraction:

**Definition 4.1.** In an atomic broadcast protocol among $n$ nodes against $f$ Byzantine corruptions, each node has an implicit input transaction buffer, continuously selects some transactions from buffer as actual input, and outputs a sequence of totally ordered transactions. In particular, it satisfies the following properties with all but negligible probability:

- **Agreement.** If one honest node outputs a transaction $tx$, then every honest node outputs $tx$;
- **Total-order.** If any two honest nodes output sequences of transactions $(tx_0, tx_1, \ldots, tx_j)$ and $(tx'_0, tx'_1, \ldots, tx'_{j'})$, respectively, then $tx_i = tx'_i$ for $i \leq \min(j, j')$;
- **Liveness (strong validity [20] or censorship resilience).** If a transaction $tx$ is input by any honest node, it will eventually output.

In [20], Cachin et al. called the above liveness “strong validity”, which recently was realized in DAG-rider [50] and DispersedLedger [74]. As we explained in Footnote 4, strong validity is particularly useful for implementing state-machine replication API because it prevents censorship even if applying de-duplication techniques. Nevertheless, there are some weaker validity notions [20] ensuring a transaction to output only if all honest nodes (or $f+1$ honest nodes) input it, cf. Appendix A for more detailed separations between strong validity and weaker notions.

Note that there are also other complementary liveness notions orthogonal to validity, for example, [20] proposed “fairness” that means the relative confirmation latency of any two transactions is bounded (at least $f + 1$ honest nodes input them), and Kelkar et al. [51] and Zhang et al. [76] recently introduced “order-fairness”. Nevertheless, following most studies about practical asynchronous BFT consensus, we only consider liveness in form of strong validity without fairness throughout the paper.

**Performance metrics.** We are particularly interested in constructing practical asynchronous BFT protocols. So it becomes meaningful to consider the following key efficiency metrics:

- **Message complexity** [20]: the expected number of messages generated by honest nodes to decide an output;
- **(Amortized) communication complexity** [20]: the expected number of bits sent among honest nodes per output transaction;
- **Round complexity** [25]: the expected asynchronous rounds needed to output a transaction $tx$ (after an honest node invokes the protocol to totally order $tx$). Here asynchronous round is the “time” measurement in an asynchronous network, and can be viewed as a “time” unit defined by the longest delay of messages sent among honest nodes [25, 50].

### 4.2 Preliminaries

**Multi-valued validated Byzantine agreement (MVBA).** MVBA [4, 20, 58] is a variant of Byzantine agreement with external validity, such that the participating nodes can agree on a value satisfying a publicly known predicate $Q$. Here we recall its formal definition:

**Definition 4.2.** Syntax-wise, each node in the MVBA protocol takes (a probably different) value validated by a global predicate $Q$ (whose description is known by the public) as input, and decides a value satisfying $Q$ as the output. The protocol shall satisfy the next properties except with negligible probability:

- **Termination.** If all honest nodes input some values satisfying $Q$, then each honest node would output;
- **Agreement.** If two honest nodes output $v$ and $v'$, respectively, then $v = v'$.
- **External-Validity.** If an honest node outputs a value $v$, then $v$ is valid w.r.t. $Q$, i.e., $Q(v) = 1$;
- **Quality.** If an honest node outputs $v$, the probability that $v$ was input by the adversary is at most 1/2.

Note that not all MVBA protocols have the last quality property. For example, a very recent design mentioned in [41] might leave the adversary a chance to always propose the output if without further careful adaption. Through the paper, we choose GLL+22-MVBA [46] as MVBA instantiation, as it is the state-of-the-art quality-featured MVBA protocol.

**Cryptographic abstractions and notations.** We consider a $(2f + 1, n)$ threshold signature scheme TSIG consisting of a tuple of algorithms (Share-Sign, Share-Verify, Combine, Sig-Verify) that is unforgeable under chosen message attacks. $H$ denotes a collision-resistant hash function. The cryptographic security parameter is denoted by $\lambda$ and captures the size of (threshold) signature and the length of hash value. We let $|B|$ to denote the batch size parameter, i.e., each node always chooses $|B|$ transactions from its buffer to disseminate. $|n|$ is short for $\{1, 2, \ldots, n\}$.

### 5 INITIAL ATTEMPT: DispersedLedger MARRIED TO Dumbo

Here we take a brief tour to the enticing DispersedLedger (DL) protocol, then alleviate its performance bottlenecks by adapting it into the cutting-edge ACS framework-Speeding-Dumbo, the resulting sDumbo-DL already outperforms all existing asynchronous consensus with linear worst-case amortized communication complexity. Finally, we also explain why sDumbo-DL still cannot achieve throughput-oblivious latency and effective censorship-resilience.

**Overview of DL.** At a very high-level, DL proceeds as follows. Splitting broadcast into dispersal and retrieval. First, DL separates the bandwidth-intensive transaction dissemination phase into two parts: dispersal and retrieval. The dispersal phase alone is much cheaper than the whole transaction dissemination, because it only disperses encoded fragments of transactions instead of broadcasting transactions themselves. The retrieval phase remains bandwidth-bound, but it can execute concurrently to the bandwidth-oblivious dispersal phase.

To add quality in MVBA mentioned in Appendix C of Ditto [41], it is needed to enforce each node to propose its height-2 $f$-block chained to its own height-1 $f$-block in the first view (iteration). Without the adaption, the honest nodes would propose its height-2 $f$-block chained to any earliest height-1 $f$-block that it receives, and unfortunately the adversary can always propose the fastest height-1 $f$-block to manipulate the output.
agreement modules, thus better utilizing the previously wasted bandwidth while running agreement.

To implement dispersal and retrieval, the authors of DL adopted the classic notion of asynchronous verifiable information dispersal (AVID) [23, 48] that can be defined as follows:

**Definition 5.1.** AVID with a designated sender $P_a$ consists of two sub-protocols (Disperse, Retrieve). In Disperse, the sender $P_a$ takes a value $v$ as input, and every node outputs a fragment of $v$ (probably together with some auxiliary metadata); in Retrieve, a node can interact with the participating nodes of Disperse sub-protocol to recover a value. The AVID protocol shall satisfy the following properties with all but negligible probability:

- **Totality.** A.k.a. agreement, if any honest node outputs in Disperse, all honest nodes would output in Disperse;
- **Recoverability.** If $f + 1$ honest nodes output in Disperse, any node can invoke Retrieve to recover some value $v’$;
- **Commitment.** If some honest nodes outputs in Disperse, there exists a fixed value $v’$, such that if any node recovers a value $v’$ in Retrieve, then $v’ = v$;
- **Correctness.** If the sender is honest and has input $v$, then all honest nodes can eventually output in Disperse, and the value $v’$ (fixed due to commitment) equals to $v$.

DL also gave an AVID construction AVID-M, which slightly weakens Cachin et al.’s AVID construction [23]: AVID-M might have $f$ honest nodes do not receive the correct fragments of input value, though they did output in Disperse. Thanks to such weakening, the Disperse sub-protocol of AVID-M costs only $O(|B| + \lambda n^2)$ bits in total, where $|B|$ represents the size of input (i.e., batch size) and $\lambda$ is security parameter. For Retrieve, each node can spend $O(|B| + \lambda n \log n)$ bits to recover each dispersed $|B|$-sized input.

So given AVID at hand, DL can tweak HBBFT’s ACS execution flow as follows to avoid sequentially running all consecutive ACS: each node uses a Disperse protocol to disperse the encoded fragments of its input (instead of directly reliably broadcasting the whole input), thus realizing a dispersal phase that costs only $O(|B|n + \lambda n^2 \log n)$ bits and saves an $O(n)$ order in relative to transmission dissemination for sufficiently large batch size. Then, similar to HBBFT, DL invokes an agreement phase made of $n$ ABBAs to agree on which senders’ Disperse protocols have indeed completed. Once the agreement phase is finished, DL starts two concurrent tasks that can execute independently: (i) it starts a new ACS to run new Disperse protocols followed by new ABBA protocols; (ii) it concurrently run Retrieve protocols to recover the dispersed transactions.

The most bandwidth-consuming path in DL is retrieval. It costs $O(|B|n^2 + \lambda n^2 \log n)$ bits in total to enable all $n$ nodes to recover all necessary transactions, and now it can simultaneously execute aside the succeeding ACSes’ dispersal and agreement phases. *Listen forever for slow dispersals.* To prevent censorship without using threshold cryptosystems, DispersedLedger is conceptually similar to DAG-rider [50], that is: forever listening unfinished Disperse protocols, and once a delayed Disperse belonging to previous ACS delivers, try to decide it as part of the output of the current ACS.

**sDumbo-DL: apply DL to sDumbo.** Nevertheless, the protocol structure of DL heavily bases on HBBFT, which uses a sub-optimal design of $n$ ABBAs. This can incur $O(n^3)$ messages and $O(n \log n)$ rounds per ACS. Moreover, AVID-M is unnecessarily strong, and $O(n^2)$ messages are expected to implement every Disperse due to totality. Hence, we present an improved version of DL using techniques from Dumbo protocols [46, 47, 58] to alleviate its efficiency bottlenecks. We nickname the improved DL by sDumbo-DL, as it can be thought of applying DL’s idea to Speeding Dumbo. The improvement involves the next two main aspects:

- We replace the agreement phase of $n$ concurrent AVID instances by one single MVBA (instantiated by the state-of-the-art GLL+22-MVBA [46]). This reduces the expected rounds of protocol to asymptotically optimal $O(1)$, and also reduces the expected message complexity to $O(n^2)$.
- Thanks to the external validity of MVBA, the totality property of AVID-M becomes unnecessary, and thus we replace AVID-M by a weakened information dispersal primitive without totality (provable dispersal, PD) [58]. PD has a provability property to compensate the removal of totality, as it allows the sender to generate a proof to attest: at least $f + 1$ honest nodes have received consistent encoded fragments, and thus a unique value can be recovered later (with using a valid proof). Dumbo-MVBA [58] constructed PD with using only $O(n)$ messages, $O(|B| + \lambda n \log n)$ bits and two rounds for dispersal.

Due to lack of space, we defer the formal description and security analysis of sDumbo-DL to Appendix C.

We compare the complexities of the original DL and sDumbo-DL in Table 3. sDumbo-DL strictly outperforms DL: they have same communication complexity, while sDumbo-DL is asymptotically better than DL w.r.t. round complexity and message complexity. Also, in experimental evaluations, sDumbo-DL outperforms sDumbo in concrete performance. See details in Section 7, e.g., Figure 9.

**Table 3: Complexities per ACS in DL and sDumbo-DL; $|B|$ is the size of each node’ input, and $\lambda$ is security parameter.**

| Protocol          | Round Complexity | Communication Complexity | Message Complexity |
|-------------------|------------------|--------------------------|--------------------|
| DispersedLedger   | $O(\log n)$      | $O(|B|n^2 + \lambda n^2 \log n)$ | $O(n^2)$           |
| sDumbo-DL         | $O(1)$           | $O(|B|n^2 + \lambda n^2 \log n)$ | $O(n^2)$           |

† For ACS where each node takes a $|B|$-sized input, the lower bound of communication is $O(|B|n^2)$, so $O(|B|n^2 + \lambda n^2 \log n)$ is optimal for sufficiently large $|B|$; $\geq \frac{\lambda n \log n}{\log |B|}$.

‡ To exchange quadratic messages in sDumbo-DL, each node can multicast only one retrieval message by concatenating the fragments (and metadata) associated to different PD instances.

**Why DL cannot realize a throughput-oblivious latency?** After improving DL with PD and GLL+22-MVBA as described above, we obtain sDumbo-DL, which seemingly can make full use of bandwidth resources, if the input batch size is sufficiently large, such that the bandwidth-intensive dispersal phase is running all the time.

Unfortunately, while increasing the batch size $|B|$ to saturate the network capacity, two undesired factors might take effect in sDumbo-DL: (i) the communication cost of provable dispersal PD quickly grows up, because each node sends $O(|B| + \lambda n^2)$ bits to disperse its input, causing the overall latency to increase; (ii) the cost of retrieval might soar even more dynamically, because each node needs to send/receive $O(|B|n + \lambda n^2 \log n)$ bits.

We quantitatively measure the unpleasant tendency in a WAN experiment setting among $n=16$ nodes from distinct AWS regions.
(cf. Section 7 for detailed experiment setup). We gradually increase the input batch size, and plot in Figure 6 to illustrate the latency of dispersal and retrieval phases (at some random node) under varying batch sizes. The latency of dispersal experiences a continuing growth that finally triples, and the latency of retrieval even becomes 5X slower, when the batch size increases from 100 tx to 25,000 tx, where 25,000 tx (6.25MB) is the batch size saturating bandwidth.

Figure 6: Latency of dispersal/retrieval as batch size grows.

In short, even if we use more efficient components to improve DispersedLedger, its latency remains to be dramatically sacrificed while approaching larger throughput. Let alone its censorship prevention technique might be “unimplementable” due to the same unbounded memory issue lying in DAG-rider (as earlier mentioned in Footnote 3) in adversarial situations, e.g., some nodes crashed (or simply got delayed) for a long time.

6 Dumbo-NG: REALIZING THROUGHPUT-OBLIVIOUS LATENCY

Given our multiple improvements, DispersedLedger still does not completely achieve our ambitious goal of asynchronous BFT consensus with high-throughput, low-latency, and guaranteed censorship-resilience. The major issue of it and also HBBFT/Dumbo is: the agreement modules block the succeeding transaction dissemination, so huge batches are necessary there to utilize most bandwidth for maximum throughput, which unavoidably hurts the latency.

To get rid of the issue, we aim to support concurrent processes for bandwidth-intensive transaction dissemination and bandwidth-oblivious BA modules, so we can use much smaller batches to seize most bandwidth for realizing peak throughput. Here we elaborate our solution Dumbo-NG that implements the promising idea.

Overview of Dumbo-NG. At a very high level, Dumbo-NG consists of (i) n ever-running broadcasts and (ii) a sequence of BAs.

Each node uses an ever-running multi-shot broadcast to continuously disseminate its input transactions to the whole network. As Figure 7 illustrates, the broadcast is never blocked to wait for any agreement modules or other nodes’ broadcasts, and just proceeds by consecutive slots at its own speed. In each slot, the broadcast delivers a batch of transactions along with a quorum certificate (containing a threshold signature or concatenating enough digital signatures from distinct nodes). A valid certificate delivered in some slot can prove: at least $f + 1$ honest nodes have received the same transactions in all previous slots of the broadcast. The multi-shot broadcast is implementable, since each node only maintains several local variables (related to the current slot and immediate previous slot), and all earlier delivered transactions can be thrown into persistent storage to wait for the final output.

Because we carefully add certificates to the ever-running broadcasts, it becomes possible to concurrently execute MVBA with fine-tuned external validity condition to totally order the disseminated transactions. In particular, a node invokes an MVBA protocol, if $n - f$ distinct broadcasts deliver new transactions to it (so also deliver $n - f$ new certificates), and the node can take the $n - f$ certificates as MVBA input. The MVBA’s external validity is specified to first check all certificates’ validity and then check that these $n - f$ indeed correspond to some newly delivered transactions that were not agreed to output before. Once MVBA returns, all honest nodes receive a list of $n - f$ valid certificates, and pack the transactions certified by these certificates as a block of consensus output.

One might wonder that MVBA’s external validity alone cannot ensure all broadcasted transactions are eventually output, because the adversary can let MVBA always return its input of $n - f$ certificates, which can always exclude the certificates of $f$ honest nodes’ broadcasts. As such, the adversary censors these $f$ honest nodes. Nevertheless, the quality property of some recent MVBA protocols [4, 46, 58] can fortunately resolve the issue without incurring extra cost. Recall that quality ensures that with at least $1/2$ probability, the output of MVBA is from some honest node. So the probability of censorship decreases exponentially with the protocol execution.

Figure 7: Ever-growing multi-shot broadcast.

Figure 8: Illustration on how to totally order the received broadcasts through executing a sequence of MVBAs.

Details of the Dumbo-NG protocol. Here we elaborate how we construct Dumbo-NG in the spirit of aforementioned high-level ideas (cf. Figure 14 for formal pseudo-code description). As Figure 8 illustrates, Dumbo-NG is composed of two concurrent components, $n$ ever-running multi-shot broadcasts and a sequence of MVBAs, which separately proceed as follows in a concurrent manner:
**Broadcasts:** There are $n$ concurrent broadcasts with distinct senders. The sender part and receiver part of each broadcast proceed by slot $s$ as follows, respectively:

- **Sender Part.** At the sender $P_j$'s side, once it enters a slot $s$, it selects a $|B|$-sized batch $TX_{j,s}$ of transactions from buffer, then multicasts it with the current slot index $s$ (and probably a threshold signature $\Sigma_{s-1}$ if $s > 1$) via PROPOSAL message, where $\Sigma_{s-1}$ can be thought as a quorum certificate for the transaction batch $TX_{j,s-1}$ that was broadcasted in the preceding slot $s - 1$. After that, the node $P_j$ waits for $2f + 1$ valid Vote messages from distinct nodes. Since each Vote message carries a threshold signature share for $TX_{j,s}$, $P_j$ can compute a threshold signature $\Sigma_s$ for $TX_{j,s}$. Then, move into slot $s + 1$ and repeat.

- **Receiver Part.** At the receivers' side of a sender $P_j$'s broadcast, if a receiving node $P_i$ stays in slot $s$, it waits for a valid PROPOSAL message that carries $(s, TX_{i,s}, \Sigma_{j,s-1})$ from the designated sender $P_j$. Then, $P_i$ records $TX_{j,s}$, and also marks the transaction batch $TX_{j,s-1}$ received in the preceding slot $s - 1$ as the “fixed” (denoted by fixed-$TX_{j,s-1}$) and can be thrown into persistent storage. This is because $\Sigma_{s-1}$ attests that $TX_{j,s-1}$ was received and signed by enough honest nodes, so it can be fixed (as no other honest node can fix a different $TX_{j,s-1}$). Meanwhile, $P_i$ updates its local current-cert vector, by replacing the $j$-th element by $(s - 1, \text{digest}_{j,s-1}, \Sigma_{j,s-1})$, because $P_i$ realizes the growth of $P_j$’s broadcast. Next, $P_i$ computes a partial signature $\sigma_i$ on received proposal $TX_{j,s}$, and sends a Vote message carrying $\sigma_i$ to $P_j$. Then $P_j$ moves into the next slot $s + 1$ and repeats the above. In case $P_j$ (staying at slot $s$) receives a PROPOSAL message $(s', TX_{j,s'}, \Sigma_{j,s'-1})$ with some $s' > s$, it shall first retrieve missing transaction batches till slot $s' - 1$ and then proceed in slot $s'$ as above to vote on the latest received transaction $TX_{j,s'}$ and then move to slot $s' + 1$. The details about how to pull transactions from other nodes will be soon explained in a later subsection.

**Agreements:** Aside the transaction broadcasts, a separate asynchronous agreement module is concurrently executing and totally order the broadcasted transaction batches. The agreement module is a sequence of MVBAs and proceeds as follows by epoch $e$.

Each node initializes a vector (denoted by ordered-indices) as $[0, \ldots, 0]$ when $e = 1$. The $j$-th element in ordered-indices is denoted by $\text{ordered}_j$ and represents how many transaction batches from the sender $P_j$ have been totally ordered as output. Also, every node locally maintains a $n$-size vector denoted by current-cert to track the current progresses of all broadcasts. In particular, the $j$-th element (current$_j$, digest$_j$, $\Sigma_j$) in current-cert tracks the progress of $P_j$’s broadcast, and current$_j$, digest$_j$ and $\Sigma_j$ presents the slot index, the hash digest, and the threshold signature associated to the last transaction batch received from the sender $P_j$, respectively.

Then, a node waits for that at least $n - f$ broadcasts deliver new transactions (along with new certificates), i.e., current$_j > \text{ordered}_j$, for at least $n - f$ distinct $j$. Then, it invokes an MVBA for each transaction $\sigma$ instance associated to the current epoch $e$ with taking current-cert as input. The global predicate $Q_e$ of MVBA[$e$] is fine-tuned to return a vector current-cert' = $\left(\text{current}'_1, \text{digest}'_1, \Sigma'_1, \ldots, \text{current}'_m, \text{digest}'_m, \Sigma'_m\right)$, such that: (i) all $\Sigma_j'$ are a valid threshold signature for the current'_j'-th slot of $P_j$’s broadcast, and (ii) current'_j' > ordered_j for at least $n - f$ different $j \in [n]$. Finally, all nodes decide this epoch’s output due to current-cert’. Specifically, they firstly check if $TX_{j,\text{current}'_j}$ was received and fixed-$TX_{j,\text{current}'_j}$ was not recorded, if that is the case and digest$_j' = H(TX_{j,\text{current}'_j})$, they mark $TX_{j,\text{current}'_j}$ as fixed and record it as fixed-$TX_{j,\text{current}'_j}$. Then, the honest nodes pack the output of the epoch: for each $j \in [n]$, find the fixed transaction batches fixed-$TX_{j,\text{current}'_j}$, fixed-$TX_{j,\text{current}_j}$, fixed-$TX_{j,\text{current}_j}$, and put these batches into the epoch’s output. After output in the epoch $e$, each node updates ordered-indices by the latest indices in current-cert', and enters the epoch $e + 1$.

**Handling missing transaction batches:** Note that it is possible that some node might not store fixed-$TX_{j,k}$ when $i$ has to put fixed-$TX_{j,k}$ into its output after some MVBA returns in epoch $e$ or (ii) has to sync up to the $k$-th slot in the sender $P_j$’s broadcast instance because of receiving a PROPOSAL message containing a slot number higher than its local slot. In both cases, each node can notify a CallHelp process (cf. Figure 15 in Appendix D for formal description) to ask the missing transaction batches from other nodes, because at least $f + 1$ honest nodes must record or receive it because of the simple property of quorum certificate (otherwise they would not vote to form such certificates). We can adopt the techniques of erasure-code and Merkle tree used in verifiable information dispersal [23, 60] to prevent communication blow-up while pulling transactions. In particular, the CallHelp function is invoked to broadcast a CAHHHELP message to announce that fixed-$TX_{j,k}$ is needed. Once a node receives the CallHelp message, a daemon process Help (also cf. Figure 15) would be activated to proceed as: if the asked transaction batch fixed-$TX_{j,k}$ was stored, then encode fixed-$TX_{j,k}$ using an erasure code scheme, compute a Merkle tree committing the code fragments and $i$-th Merkle branch from the root to each $i$-th fragment. Along the way, the Help daemon sends the Merkle root, the $i$-th fragment, and the $i$-th Merkle branch to who is requesting fixed-$TX_{j,k}$. Every honest node requesting fixed-$TX_{j,k}$ can receive $f + 1$ valid responses from honest nodes with the same Merkle root, so it can recover the correct fixed-$TX_{j,k}$. As such, each Help daemon only has to return a code fragment of the missing transactions under request, and the fragment’s size is only $O(1/n)$ of the transactions, thus not blowing up the overall communication complexity.

**Security intuitions.** Dumbo-NG realizes all requirements of ABC (cf. Appendix E for detailed proofs). The security intuitions are:

- **Safety** intuitively stems from the following observations:
- For any sender $P_j$’s broadcast, if a valid quorum certificate $\Sigma_{j,s}$ can be produced, at least $f + 1$ honest nodes have received the same sequence of transaction batches $TX_{j,s}, TX_{j,s-1}, \ldots, TX_{j,1}$. In addition, if two honest nodes locally store fixed-$TX_{j,s}$ and fixed-$TX_{j,s}$ after seeing
\(\Sigma_{j,s}\) and \(\Sigma'_{j,s}\), respectively, then fixed-TX_{j}[s] = fixed-TX'_{j}[s].

The above properties stem from the simple fact that quorum certificates are \(2f + 1\) threshold signatures on the hash digest of received transaction batches, so the violation of this property would either break the security of threshold signatures or the collision-resistance of cryptographic hash function.

**External validity and agreement of MVBA.** The global predicate of every MVBA instance is set to check the validity of all broadcast certificates (i.e., verify threshold signatures). So MVBA must return a vector current-cert’ = \((\text{current}_1’\text{, digest}_1’\text{, }\Sigma_1’), \ldots, (\text{current}_n’\text{, digest}_n’\text{, }\Sigma_n’)\), such that each \((\text{current}_j’\text{, digest}_j’\text{, }\Sigma_j’)\) ∈ current-cert’ is valid broadcast certificate. In addition, any two honest nodes would receive the same current-cert’ from every MVBA instance, so any two honest nodes would output the same transactions in every epoch, because each epoch’s output is simply packing some fixed transaction batches according to current-cert’ returned from MVBA.

**Liveness** (censorship-resilience) is induced as the following facts:

- **Optimistic liveness of broadcasts.** If a broadcast’s sender is honest, it can broadcast all input transactions to the whole network, such that all nodes can receive an ever-growing sequence of the sender’s transactions with corresponding quorum certificates.

- **Quality of MVBA.** Considering that an honest sender broadcasts a transaction batch TX_{j,s} at slot s, all nodes must receive some quorum certificate containing an index equal or higher than s eventually after a constant number of asynchronous rounds. After some moment, all honest nodes would input such certificate to some MVBA instance. Recall the quality of MVBA, which states that with 1/2 probability, some honest node’s input must become MVBA’s output. So after expected 2 epochs, some honest node’s input to MVBA would be returned, indicating that the broadcast’s certificate with index s (or some larger index) would be used to pack TX_{j,s} into the final output.

- **Termination of MVBA.** Moreover, MVBA can terminate in expected constant asynchronous rounds. So every epoch only costs expected constant running time.

**Complexity and performance analysis.** The round and communication complexities of Dumbo-Ng can be analyzed as follows:

- **The round complexity is expected constant.** After a transaction is broadcasted by an honest node, every honest node would receive a valid quorum certificate on this transaction after 3 asynchronous rounds. Then, the transaction would output after expected two MVBA instances (due to the quality of MVBA). In case of facing faults and/or adversarial network, there could be more concrete rounds, for example, some nodes might need two rounds to retrieve missing transaction batches and MVBA could also become slower by a factor of 3/2.

- **The amortized communication complexity is nearly linear, i.e. \(O(n)\),** for sufficiently large batch size parameter, if we consider the input transactions of different nodes are de-duplicated (e.g., \(k\) random nodes are assigned to process each transaction as this is sufficient in the presence of a static adversary). Due to our broadcast construction, it costs \(O(|B|n + \lambda n)\) bits to broadcast a batch of \(|B|\) transactions to all nodes. The expected communication complexity of an MVBA instance is \(O(\lambda n^3)\). Recall that every MVBA causes to output a block containing at least \(O(n|B|)\) probably duplicated transactions, and without loss of generality, we consider that an output block contains \(O(K|B|)\) probably duplicated transactions (where \(K \geq n - f\)), out of which there are probably \(O(K|B|)\) transactions need to bother Help and CALLHelp subroutines, costing at most \(O(K(n|B| + \lambda n^2 \log n))\) bits. So, in sum, each epoch would output \(O(K|B|)\) probably duplicated transactions (which on average contains \(O(K|B|/k)\) distinct transactions) with expected \(O(K(n|B| + \lambda n^2\log n))\) bits despite the adversary, which corresponds to nearly linear amortized communication complexity \(O(kn)\) if \(|B| \geq \lambda n \log n\), where \(k\) is a small security parameter allowing \(k\) random nodes to include at least one honest node.

## 7 IMPLEMENTATION AND EVALUATIONS

We implement Dumbo-Ng and deploy it over 16 different AWS regions across the globe. A series of experiments is conducted in the WAN settings with different system scales and input batch sizes. The experimental results demonstrate the superiority of Dumbo-Ng over the existing performant asynchronous BFT consensus protocols including two very recent results DispersedLedger (DL) [74] and Speeding-Dumbo (sDumbo) [46]. In particular, Dumbo-Ng can preserve low latency (only several seconds) while realizing high throughput (100k tx/sec) at all system scales (from 4 to 64 nodes).

### 7.1 Implementation & WAN experiment setup

**Implementations details.** We implement Dumbo-Ng, sDumbo, Dumbo, and DispersedLedger (more precisely, the improved version sDumbo-DL, cf. Section 5) in Python3.\(^9\) The same cryptographic libraries and security parameters are used throughout all implementations. Both Dumbo-Ng and sDumbo-DL are implemented as two-process Python programs. Specifically, sDumbo-DL uses one process to deal with dispersal and MVBA and uses another process for retrieval; Dumbo-Ng uses one process for broadcasting transactions and uses the other to execute MVBA. We use gevent library for concurrent tasks in one process. Coin flipping is implemented using with Boldyrev’s pairing-based threshold signature [17].

Regarding quorum certificates, we implement them by concatenating ECDSA signatures. Same to HBFT [60], Dumbo [47] and BEAT

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\(^7\)Note that there could be some ways to allowing the honest nodes to verify transaction de-duplication and thus enforce that, for example, the client can encapsulate its \(k\) randomly selected nodes in each of its transactions with digital signature. As such, if some malicious nodes do not follow the de-duplication rules and broadcast repeated transactions to launch downgrade attack, the honest nodes can verify that an undesignated malicious node is broadcasting unexpected transactions and therefore can stop voting in the malicious node’s broadcast instance.

\(^8\)Proof-of-concept implementation is available at https://github.com/fascy/Dumbo_NG. Though our proof-of-concept implementation didn’t implement the processes for pulling missing transactions in Dumbo-Ng, it cautiously counts the number of such retrievals and found that there were less than 1% missing transaction batches to retrieve in all WAN evaluations.
our experiments focus on evaluating the performance of standalone asynchronous consensus, and all results are measured in a fair way without actual clients.

Implementation of asynchronous network. To realize reliable fully meshed asynchronous point-to-point channels, we implement a (persistent) unauthenticated TCP connection between every two nodes. The network layer runs on two separate processes: one handles message receiving, and the other handles message sending. If a TCP connection is dropped (and fails to deliver messages), our implementation would attempt to re-connect.

Setup on Amazon EC2. We run Dumbo-NG, Dumbo, Speeding-Dumbo (sDumbo), and DispersedLedger (the sDumbo-DL variant) among EC2 c5.large instances which are equipped with 2 vCPUs and 4 GB main memory. Their performances are evaluated with varying scales at n = 4, 16, and 64 nodes. Each transaction is 250-byte approximating the size of a typical Bitcoin transaction with one input and two outputs. For n = 16 and 64, all instances are evenly distributed in 16 regions across five continents: Virginia, Ohio, California, Oregon, Canada, Mumbai, Seoul, Singapore, Sydney, Tokyo, Frankfurt, London, Ireland, Paris, Stockholm and São Paulo; for n = 4, we use the regions in Virginia, Sydney, Tokyo and Ireland.

7.2 Evaluation results in the WAN setting

Dumbo-NG v.s. prior art. To demonstrate the superior performance of Dumbo-NG, we first comprehensively compare it to the improved DispersedLedger (sDumbo-DL) as well as other performance-agnostic protocols (sDumbo and Dumbo). Specifically,

- **Peak throughput.** For each asynchronous consensus, we measure its throughput, i.e., the number of transactions output per second. The peaks of the throughputs of Dumbo-NG, sDumbo-DL sDumbo and Dumbo (in varying scales) are presented in Figure 9a. This reflects how well each protocol can handle the application scenarios favoring throughput. Overall, the peak throughput of Dumbo-NG has a several-times improvement than any other protocol. Specifically, the peak throughput of Dumbo-NG is more than 7x of Dumbo when n = 4, about 4x of Dumbo when n = 16, and roughly 3x of Dumbo when n = 64. As for sDumbo, it is around 4x of sDumbo when n = 4, over 2x of sDumbo when n = 16, and almost 3x of sDumbo when n = 64. Even if comparing with sDumbo-DL, Dumbo-NG still achieves over 3x improvement in peak throughput when n = 4, and about 2x when n = 16 or n = 64.

- **Latency-throughput trade-off.** Figure 9b, 9c and 9d illustrate the latency-throughput trade-off of Dumbo-NG, sDumbo-DL, sDumbo and Dumbo when n = 4, 16 and 64, respectively. Here latency is the time elapsed between the moment when a transaction appears in the front of a node’s input buffer and the moment when it outputs, so it means the “consensus latency” excluding the time of queuing in mempool. The trade-off between latency and throughput determines whether a BFT protocol can simultaneously handle throughput-critical and latency-critical applications. To measure Dumbo-NG’s (average) latency, we attach timestamp to every broadcasted transaction batch, so all nodes can track the broadcasting time of all transactions to calculate latency. The experimental results show: although Dumbo-NG uses a Byzantine agreement module same to that in sDumbo and sDumbo-DL (i.e., the GLL+22-MVBA), its trade-off surpasses sDumbo in all cases. The more significant result is that at all system scales, Dumbo-NG preserves a low and relatively stable latency (only a few seconds), while realizing high throughput at the magnitude of 100k tx/sec. In contrast, other protocols suffer from dramatic latency increment while approaching their peak throughput. This demonstrates that Dumbo-NG enjoys a much broader array of application scenarios than the prior art, disregarding throughput-favoring or latency-favoring.
Latency/throughput while varying batch sizes. The tested asynchronous protocols do have a parameter of batch size to specify that each node can broadcast up to how many transactions each time. As aforementioned, the latency-throughput tension in many earlier practical asynchronous BFT consensuses like HBBFT and Dumbo is actually related to the choice of batch size: their batch size parameter has to be tuned up for higher throughput, while this might cause a dramatic increment in latency.

Here, we gradually increase the batch size and record the latency and throughput to see how batch size takes effect in the tested protocols. Figure 10 plots a sample when \( n = 16 \) for Dumbo-NG, sDumbo-DL, sDumbo and Dumbo. It is observed that with the increment of batch size, the throughput of all protocols starts to grow rapidly but soon tends to grow slowly. The latency of Dumbo and sDumbo grows at a steady rate as the batch size increases. The latency of sDumbo-DL tends to increase slowly in the beginning but then increase significantly (once the batch size reaches 20k-30k tx). However, the latency of Dumbo-NG remains constantly small. When the batch size increases from 1k to 5k, Dumbo-NG reaches its peak throughput (about 160k tx/sec), and its latency only increases by less than 0.5 sec; in contrast, sDumbo-DL, sDumbo and Dumbo have to trade a few seconds in their latency for reaching peak throughput. Clearly, Dumbo-NG needs a much smaller batch size (only about 1/10 of others) to realize the highest throughput, which allows it to maintain a pretty low latency under high throughput.

7.3 More tests with controlled delay/bandwidth

The above experiments in the WAN setting raises an interesting question about Dumbo-NG: why it preserves a nearly constant latency despite throughput? We infer the following two conjectures based on the earlier WAN setting results:

1. The MVBA protocols are actually insensitive to the amount of available bandwidth, so no matter how much bandwidth is seized by transaction broadcasts, their latency would not change as only rely on round-trip time of network.
2. The nodes in Dumbo-NG only need to broadcast a small batch of transactions (e.g., a few thousands that is 1/10 of Dumbo and DispersedLedger) to closely track bandwidth.

Clearly, if the above conjectures are true, the latency of Dumbo-NG would just be 1-2x of MVBA’s running time. Hence, we further conduct extensive experiments in a LAN setting (consisting of servers in a single AWS region) with manually controlled network propagation delay and bandwidth to verify the two conjectures, respectively.

Figure 11: Latency of GLL+22-MVBA [46] with \( n=16 \) nodes in varying bandwidth for (a) 50ms and (b) 200ms one-way network delay, respectively.

Evaluate MVBA with controlled network bandwidth/delay.

We measure MVBA, in particular, its latency, in the controlled experiment environment (for \( n=16 \) nodes). Here the input-size of MVBA is set to capture the length of quorum certificates. Figure 11 (a) and (b) show the results in the setting of 50 and 100 ms network propagation delays, respectively, with varying the bandwidth of each peer-to-peer tcp link (5, 10, 20, 50, 75, or 100 Mbps). Clearly, our first conjecture is true, as MVBA is definitely bandwidth-oblivious, as its latency relies on propagation delay other than available bandwidth.

Figure 12: The dependency of throughput on varying batch size in controlled deployment environment with 50 ms one-way delay and (a) 75Mbps and (b) 150Mbps bandwidth.

Test Dumbo-NG with controlled network bandwidth/delay.

Then we verify whether Dumbo-NG can closely track available
bandwidth resources with only small batch sizes. We examine how Dumbo-NG gradually saturates bandwidth resources whiling batch size increases, in a controlled environment (for n=16 nodes). The one-way network delay is set to 50ms, and per-node’s bandwidth is set for (a) 75Mbps (5Mbps per tcp socket) or (b) 150Mbps (10Mbps per tcp socket). The controlled network parameters well reflect an inter-continental communication network. Clearly, the results verify our second conjecture that Dumbo-NG can fully utilize bandwidth while using small batch sizes (less than 1MB).

7.4 Behind the throughput-oblivious latency

Given the extensive experiment results, we now can understand why the latency of Dumbo-NG is almost independent to its throughput: (i) some small batch sizes can already fully utilize network bandwidth, and therefore the latency of broadcasting a batch transactions is much smaller than that of MVBA; (ii) when the broadcast instances seize most bandwidth, the latency of MVBA would not be impacted as its latency is bandwidth-insensitive. So if a broadcast makes a progress when the MVBA of epoch e is running, this progress would be solicited to output by the MVBA of next epoch e + 1 (if no fault), and even if there are n/3 faulty nodes, it is still expected to output by the MVBA of epoch e + 2 (due to MVBA’s quality), which results in throughput-oblivious latency. For sake of completeness, we also interpret the above intuition into analytic formula and perform numerical analysis in Appendix F.

8 DISCUSSIONS

Flooding launched by malicious nodes. In the HBBFT and DAG type of protocols [32, 35, 46, 47, 50, 60], the malicious nodes cannot broadcast transactions too much faster than the honest nodes, because all nodes explicitly block themselves to wait for the completeness of n−f broadcasts to move forward. While one might wonder that in Dumbo-NG, the malicious nodes probably can broadcast a huge amount of transactions in a short term, which might exhaust the resources of the honest nodes and prevent them from processing other transactions.

Nevertheless, this is actually a general flooding attack in many distributed systems, and it is not a particularly serious worry in Dumbo-NG, because a multitude of techniques already exist to deter it. For example, the nodes can allocate an limited amount of resources to handle each sender’s broadcast, so they always have sufficient resources to process the transactions from the other honest senders, or an alternative mitigation can also be charging fees for transactions as in Avalanche [69].

Input tx buffer assumptions related to censorship-resilience.

Censorship-resilience (liveness) in many work [35, 46, 47, 60] explicitly admits an assumption about input buffer (a.k.a. backlog or transaction pool): a transaction is guaranteed to eventually output, only if it has been placed in all honest nodes’ input buffer. Our censorship resilience allows us to adopt a different and weaker assumption about the input buffer (that is same to DispersedLedger [74], Aleph [38] and DAG-rider [50]): if a transaction appears in any honest node’s input buffer (resp. k random nodes’ input buffers), the transaction would output eventually (resp. output with all but negligible probability in k).

Our input buffer assumption is appropriate or even arguably quintessential in practice. First, in many consortium blockchain settings, a user might be allowed to contact only several consensus nodes. For example, a Chase bank user likely cannot submit her transactions to a consensus node of Citi bank. Moreover, even if in a more open setting where a client is allowed to contact all nodes, it still prefers to fully leverage the strength of our censorship resilience property to let only k consensus nodes (instead of all) to process each transaction for saving communication cost.

Challenges and tips to production-level implementation. For production-level implementation of Dumbo-NG with bounded memory, a few attentions (some of which are even subtle) need to be paid. First, the MVBA instantiation shall allow nodes to halt after they decide output (without hurting other nodes’ termination), such that a node can quit old MVBA instances and then completely clean them from memory. Also, similar to Tusk [32], messages shall carry latest quorum certificates to attest that f + 1 honest nodes have stored data in their persistent storage, such that when a slow node receives some ”future” messages, it does not have to buffer the future messages and can directly notify a daemon process to pull the missing outputs accordingly. In addition, Dumbo-NG has a few concurrent tasks (e.g., broadcasts and MVBAs) that rely on shared global variables. This is not an issue when implementing these tasks by multiple threads in one process. Nevertheless, when separating these tasks into multiple processes, inter-process communication (IPC) implementation has to correctly clean IPC buffers to avoid their memory leak due to long network delay. Last but not least, if a node constantly fails to send a message to some slow/crashed node, it might keeps on re-sending, and thus its out-going message buffer might dramatically increase because more and more out-going messages are queued to wait for sending. It can adopt the practical alternative introduced by Tusk, namely, stop (re-)sending too old out-going messages and clean them from memory, because messages in Dumbo-NG can also embed latest quorum certificates (to help slow nodes sync up without waiting for all protocol messages).

For more detailed tips that extend the above discussions and elaborate how to implement Dumbo-NG towards a production-level system with bounded memory, cf. Appendix B.

9 CONCLUSION

We present Dumbo-NG an efficient asynchronous BFT atomic broadcast protocol favoring censorship resilience. It can realize high throughput, low latency and guaranteed censorship resilience at the same time. Nevertheless, despite the recent progress of practical asynchronous BFT consensus, a few interesting problems remain open: practical asynchronous BFT consensus with enhanced fairness guarantees (e.g., order fairness) are largely unexplored; most existing asynchronous BFT protocols cannot smoothly scale up, e.g., to support several hundreds of nodes with preserving a reasonable latency, and a solution to the scalability issue could be very interesting.

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The validity of asynchronous atomic broadcast captures that a certain input transaction would eventually output. It has a few fine-grained flavors [20]:

- **Strong validity** (called censorship resilience through the paper): $tx$ can eventually output, if any honest node takes it as input;

- **Validity** if $f + 1$ honest nodes input $tx$, it can eventually output;

- **Weak validity** if all honest nodes input $tx$, it eventually outputs.

From **strong validity to censorship resilience**: The next examples can demonstrate why strong validity can easily prevent censorship of transactions when building SMR from atomic broadcast, but weaker flavors of validity cannot:

- **In permissioned settings**: Strong validity has practical meaning in real-world consortium blockchain systems, because a client might not be allowed to contact all consensus nodes, and can only rely on several designated nodes to process its transactions [74]. In this setting, strong validity is critical because only it ensures that every client can have the input transactions to eventually output as long as the client has permission to contact an honest consensus node.

- **Enable de-duplication**: In more open settings where a client has the permission to multi-node all nodes to duplicate its transactions, strong validity is still important as it empowers de-duplication techniques [32, 72] to reduce redundant communication. For example, each transaction can be sent to only $k$ nodes (where $k$ is a security parameter), because the $k$ random nodes would contain at least one honest node with a probability exponentially large in $k$ (in case of static corruptions); in contrast, a client has to contact $f + 1$ honest nodes (resp. $2f + 1$ honest nodes) if there is only validity (resp. weak validity).

**Relation/separation to quality**: GKL15 [40] defines quality as: for any sufficiently long substring of consensus output, the ratio of blocks proposed by the adversary is bounded by a non-zero constant. By definition, quality does not prevent the adversary constantly dropping certain honest nodes’ input, and in many asynchronous protocols with quality but without strong validity (e.g., asynchronous common subset [14, 20] and Tusk [32]), the adversary can indeed drop $f$ honest nodes. Thus, quality only implies liveness conditioned on that all honest nodes propose/input all transactions redundantly (as explicitly stated in GKL15 [40]). In other words, if aiming at liveness from quality directly, it needs to duplicate transactions over all honest nodes as redundant input. This “approach”, unfortunately, might incur $O(n)$ communication blow-up in leaderless asynchronous protocols as discussed in Section 1. Alternatively, quality together with threshold encryption can also ensure liveness [60] but might incur heavy computation.

### Appendix A: Asynchronous Liveness Notions

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### B Detailed Tips Towards Production-Level Implementation

In Section 8 we briefly the challenges and tips towards production-level implementation of Dumbo-NG. Here we extend the discussions to give more detailed suggestions for practitioners.

1. **Halt in asynchronous BA without hurting termination.** In many asynchronous BA protocols [4, 21], the honest nodes cannot simultaneously decide their output in the same iteration. So even if a node has decided its output, it might need to continue the execution to help other nodes also output (otherwise, there might exist a few nodes fail to output). Fortunately, a few studies [16, 47, 59, 62] demonstrated how to securely halt in asynchronous BAs without hurting termination. Our MVBA instantiation [46] also has the feature of immediate halt after output, as the honest nodes would always multicast a quorum certificate proving the decided output and then quit.

2. **Share variables across concurrent processes.** Some global variables are shared among the concurrent tasks in Dumbo-NG, for example, the task of MVBAs $n$ shall have access to read the latest broadcast certificates generated in the tasks of $n$ running broadcasts. When practitioners implement these tasks with different processes, inter-process communication (IPC) for sharing these global variables shall be cautiously handled. For example, if IPC socket is used to pass the latest broadcast certificates to the MVBAs’ process, it is important to implement a thread that executes concurrent to MVBAs to continuously take certificates out of the IPC sockets and only track the latest certificates (otherwise, a huge number of certificates could be...
accumulated in the receiving buffer of IPC socket if a single MVBA is delayed).

(3) Use quorum certificates for retrievability to help slow nodes. Up to \( f \) slow honest nodes might receive a burst of “future” messages in an asynchronous network. There are three such cases: (i) a broadcast sender receives \( \text{Vote} \) messages higher than its local slot; (ii) a broadcast receiver gets \( \text{Proposal} \) messages higher than its local slot; or (iii) any nodes receives some MVBA messages with epoch number higher than its local epoch. For case (i), it is trivial that the broadcast sender can just omit such “future” \( \text{Vote} \) messages, because these messages must be sent by corrupted nodes. For case (ii), we have elaborated the solution in Section 6: when a slow node staying at slot \( s \) receives a \( \text{Proposal} \) message with valid quorum certificate but slot \( s' > s \), it needs to first pull the missing transactions till slot \( s' - 1 \) and then increase its local slot number to continue voting in slot \( s' \) and later slots. For case (iii), it can also be trivially solved by letting the \( e \)-th epoch’s MVBA messages carry the unforgeable quorum certificate for MVBA\( [e - 1] \)’s output, such that upon a slow node receives some MVBA message belonging to a “future” epoch \( e' \) larger than its local epoch \( e \), it can pull all missing MVBA outputs till epoch \( e' - 1 \) (similar to pull broadcasted transactions) and then move into epoch \( e' \).

(4) Avoid infinite buffer of out-going messages. To correctly implement asynchronous communication channels, a message sending node might continuously re-send each protocol message until the message receiving node returns an acknowledgment receipt (e.g., through TCP connection). As such, the message sending node might have more and more out-going messages accumulated while stucking in re-sending some very old messages. At first glance, it seemingly requires infinite memory to buffer these out-going messages. However, recall that Tusk [32] can stop re-sending old out-going messages and then securely clean them. The implementation of Dumbo-NG can also adapt the idea to bound the size of out-going buffer by cleaning the “old” out-going messages belong to slot/epoch smaller than the current local slot/epoch, as long as practitioners follow the guidance in (3) to embed previous slot/epoch’s quorum certificate in the current slot/epoch’s out-going messages to help slow nodes to pull missing outputs by a quorum certificate (instead of actually receiving all sent protocol messages).

C. FORMAL DESCRIPTION FOR sDumbo-DL

Here we present the deferred formal description of sDumbo-DL for sake of completeness.

C.1 APDB-W: a week variant of asynchronous provable dispersal broadcast

sDumbo-DL relies on the variant of the Asynchronous Provable Dispersal Broadcast protocol (APDB) [58] for implementing the dispersal phase and the retrieval phase in the DispersedLedger framework. More precisely, sDumbo-DL only needs a subset of APDB’s properties.

Recall that APDB consists of the following two subprotocols:

- **PD subprotocol.** In the PD subprotocol among \( n \) nodes, a designated sender \( P_3 \) inputs a value \( \nu \in \{0, 1\}^f \), and aims to split \( \nu \) into \( n \) encoded fragments and disperses each fragment to the corresponding node. During the PD subprotocol, each node is allowed to invoke an \( \text{abandon} \) function. After PD terminates, each node shall output two strings \( \text{store} \) and \( \text{lock} \), and the sender shall output an additional string proof.

- **RC subprotocol.** In the RC subprotocol, all honest nodes take the output of the PD subprotocol as input, and aim to output the value \( \nu \) that was dispersed in the RC subprotocol. Once RC is completed, the nodes output a common value in \( \{0, 1\}^f \cup \perp \).

A full-fledged APDB protocol (PD, RC) with identifier ID satisfies the following properties except with negligible probability:

- **Termination.** If the sender \( P_3 \) is honest and all honest nodes activate PD[ID] without invoking \( \text{abandon}(\text{ID}) \), then each honest node would output \( \text{store} \) and valid \( \text{lock} \) for ID; additionally, the sender \( P_3 \) outputs valid proof for ID.

- **Recast-ability.** If all honest nodes invoke RC[ID] with inputting the output of PD[ID] and at least one honest node inputs a valid \( \text{lock} \), then: (i) all honest nodes recover a common value; (ii) if the sender dispersed \( \nu \) in PD[ID] and has not been corrupted before at least one node delivers valid \( \text{lock} \), then all honest nodes recover \( \nu \) in RC[ID].

- **Provability.** If the sender of PD[ID] produces valid proof, then at least \( f + 1 \) honest nodes output valid \( \text{lock} \).

- **Abandon-ability.** If every node (and the adversary) cannot produce valid \( \text{lock} \) for ID and \( f + 1 \) honest nodes invoke \( \text{abandon}(\text{ID}) \), no node would deliver valid \( \text{lock} \) for ID.

Nevertheless, in context of implementing the dispersal phase and the retrieval phase in the DispersedLedger, Abandon-ability and Provability are not necessary. Thus, we can set forth to the following weaker variant (that we call it APDB-W).

Formally, APDB-W consists of the following two subprotocols:

- **PD subprotocol.** The syntax is same to that of APDB, except that (i) non-sender node only outputs the \( \text{store} \) string, (ii) sender only outputs \( \text{lock} \) and \( \text{store} \) strings, and (iii) no invocable \( \text{abandon} \) function.

- **RC subprotocol.** The syntax is same to that of APDB.

An APDB-W protocol (PD, RC) with identifier ID satisfies the following properties except with negligible probability:

- **Termination.** If the sender \( P_3 \) is honest and all honest nodes activate PD[ID] without invoking \( \text{store} \) for ID; additionally, the sender \( P_3 \) outputs valid \( \text{lock} \) for ID.

- **Recast-ability.** Same to that of APDB.

For brevity, we consider all PD and RC from APDB-W in the paper since then on. Also, note that the properties of APDB-W is a subset of APDB, so any construction of APDB would naturally implement APDB-W, for example, [58] presented a simple 4-round construction of APDB, and actually [58] also pointed out that APDB without provability (i.e., still an APDB-W) can be realized by only two rounds. We refer the interested readers to [58] for details.
C.2 Formal description for sDumbo-DL

Given APDB-W (and also sMVBA) at hand, we can then construct sDumbo-DL as described in Figure 13, which essentially implements asynchronous common subset (ACS), i.e., an epoch in the DispersedLedger framework. When running a sequence of ACSes together with the inter-node linking technique in DispersedLedger (that we refrain from reintroducing here), asynchronous atomic broadcast can be realized.

C.3 Security for sDumbo-DL

Here we (informally) prove that the sDumbo-DL algorithm presented in Figure 13 securely realizes ACS.

Let us first recall the formal definition of ACS. In the ACS protocol among n nodes (including up to f Byzantine faulty nodes) with identification ID, each node takes as input a value and outputs a set of values. It satisfies the following properties except with negligible probability:

- **Validity.** If an honest node outputs a set of values v, then |v| ≥ n − f and v contains the inputs from at least n − 2f honest nodes.
- **Agreement.** If an honest node outputs a set of values v, then every node outputs the same set v.
- **Termination.** If n − f honest nodes receive an input, then every honest node delivers an output.

**Security intuition.** The Algorithm 13 satisfies all properties of ACS. Its securities can be intuitively understood as follows:

- The termination immediately follows the termination of APDB-W and sMVBA, along with the recast-ability of APDB-W. Due to the number of honest nodes is n − f and the termination of APDB-W, all honest nodes do not get stuck before sMVBA and they can receive n − f Final messages containing valid locks. Hence, all honest nodes have a valid W_e as the input of sMVBA[e]. According to the termination of sMVBA, all honest nodes have an output W and the output of W satisfies a global predicate Q, so following the the recast-ability of APDB-W, all honest nodes can output in this epoch.

- The agreement follows the agreement of sMVBA and the recast-ability of APDB-W because the agreement of sMVBA ensures any two honest nodes to output the same W, and the W satisfies predicate Q, i.e., for any \((h_i, \sigma_i) \in W\), if \(h_i \neq L\) then \((h_i, \sigma_i)\) is a valid lock. Then according to the recast-ability of APDB-W, all honest nodes have the same output in this epoch.

- The validity is trivial because the external validity of sMVBA ensures that it outputs a W containing n − f valid lock from distinct APDB-W instances, and the recast-ability of APDB-W guarantees each node can deliver a value for each valid lock.

D FORMAL DESCRIPTION FOR Dumbo-NG

Here we present the deferred formal description of Dumbo-NG. Figure 14 describes the main protocol of Dumbo-NG including two
let buffer be a FIFO queue of input transactions. Initialize for each buffer
for each slot s ∈ 1, 2, 3, …:
  – TX_{js} ← buffer[i]: B to select a proposal, compute digest_{js} ← H(TX_{js})
  – if s > 1: multicast Proposal(s, TX_{js}, digest_{js}, 𝜎_{js})
  – else: multicast Proposal(s, TX_{js}, ⊥)
  – wait for 2f+1 Vote(s, σ_{js}) messages from 2f+1 distinct nodes \( \{ P_j \} \) s.t. \( \text{Share-Verify}(j)|s| \cdot [ \text{digest}_{js}, \sigma_{js} ] = \text{true} \):
      – compute the threshold signature \( \Sigma_s \) on \( |s| \cdot \text{digest}_{js} \) by combining \( 2f+1 \) received signature shares \( \{ \sigma_{js} \}_{j \in \{ P_j \}} \).

consensus for ordering payloads (one process that initiates current-cert and fixed-TXj

Initial MVBA[e] with global predicate \( Q_e \) (to pick a valid current-cert’ with \( n – f \) currentj increased w.r.t. orderedj).

Consensus for ordering payloads: a concise and highly efficient reduction from asynchronous atomic broadcast to MVBA.

Figure 14: The Dumbo-NG protocol: a concise and highly efficient reduction from asynchronous atomic broadcast to MVBA.
CallHelp daemon and Help daemon (for each node $\mathcal{P}_i$)

\noindent\textbf{CallHelp daemon:}
\begin{itemize}
  \item get access to the variables $\{(\text{current}_1, \text{digest}_1, \Sigma_1), \ldots, (\text{current}_n, \text{digest}_n, \Sigma_n)\}$ (which are initialized in Fig. 14)
  \item initialize $\text{max-missing}_j \leftarrow 0$, $\text{max-missing-cert}_j \leftarrow 1$ for each $j \in [n]$
  \item upon receiving $\text{Pull}(j, s', \text{digest}_{j,s'}, \Sigma_{j,s'})$: \hspace{1em} If in case a few Pull messages are received,
    \begin{itemize}
      \item if $s' > \text{max-missing}_j$ and $s' > \text{current}_j$ and $\text{Sig-Verify}(j || s' || \text{digest}_{j,s'}, \Sigma_{j,s'}) = \text{true}$:
        \begin{itemize}
          \item $\text{max-missing}_j \leftarrow \text{max-missing}_j$
          \item $\text{max-missing-cert}_j \leftarrow \Sigma_{j,s'}$
        \end{itemize}
    \end{itemize}
\end{itemize}

\noindent\textbf{Help daemon:}
\begin{itemize}
  \item get access to the variables $\{(\text{current}_1, \text{digest}_1, \Sigma_1), \ldots, (\text{current}_n, \text{digest}_n, \Sigma_n)\}$ (which are initialized in Fig. 14)
  \item upon receiving $\text{CallHelp}(j, k, \Sigma_{j,k})$ from node $\mathcal{P}_k$ for $k$ for the first time:
    \begin{itemize}
      \item record fixed-TX$_{j,k}$ \hspace{1em} \text{if node $\mathcal{P}_k$ does not record it and tries to fetch it via function $\text{CallHelp}(k, s)$}, then $\text{CallHelp}(k, s)$ \text{will return fixed-TX$_{k}$}$
    \end{itemize}
\end{itemize}

\noindent\textbf{Lemma E.1.} If one honest node $\mathcal{P}_i$ records fixed-TX$_{k}$ and another honest node $\mathcal{P}_j$ records fixed-TX$_{k}$, then fixed-TX$_{k}$ = fixed-TX$_{k}$.

\proof When $\mathcal{P}_i$ records fixed-TX$_{k}$, according to the algorithm in Fig. 14, the node $\mathcal{P}_i$ has received a valid $\text{Proposal}(s, \text{TX}_{k,s+1}, \Sigma_{k,s})$ message from $\mathcal{P}_k$ for the first time, where $\text{Sig-Verify}(k || s || \text{hash}(\text{TX}_{k,s}), \Sigma_{k,s}) = \text{true}$ and the $\Sigma_{k,s}$ is a threshold signature with threshold $2f+1$. Due to the fact that each honest node only sends one $\text{Vote}$ message which carries a cryptographic threshold signature share for each slot $s$ of $\mathcal{P}_k$, it is impossible to forge a threshold signature $\Sigma_{k,s}$ satisfying $\text{Sig-Verify}(k || s || \text{hash}(\text{TX}_{k,s}), \Sigma_{k,s}) = \text{true}$ s.t. $\mathcal{H}(\text{TX}_{k,s}) \neq \text{hash}(\text{TX}_{k,s})$. Hence, $\mathcal{H}(\text{TX}_{k,s}) = \mathcal{H}(\text{TX}_{k,s})$, and following the collision-resistance of hash function, so if any two honest $\mathcal{P}_i$ and $\mathcal{P}_j$ records fixed-TX$_{k}$, then fixed-TX$_{k}$ = fixed-TX$_{k}$.

\noindent\textbf{Lemma E.2.} Suppose at least $f+1$ honest nodes record fixed-TX$_{k}$, then CallHelp$(k, s)$ will return fixed-TX$_{k}$.

\proof Since at least $f+1$ honest nodes have recorded fixed-TX$_{k}$, these honest nodes will do erasure coding in fixed-TX$_{k}$ to generate $\{m_j\}_{j \in [n]}$, then compute the Merkle tree root $h$ and the branch. Following the Lemma E.1, any honest node who records fixed-TX$_{k}$ has the same value, so it is impossible for $\mathcal{P}_i$ to receive $f + 1$ distinct valid leaves corresponding to another Merkle tree root $h' \neq h$. Hence, $\mathcal{P}_i$ can receive at least $f + 1$ distinct valid leaves which corresponds to root $h$. So after interpolating the $f + 1$ valid leaves, $\mathcal{P}_i$ can reconstruct fixed-TX$_{k}$.

\noindent\textbf{Lemma E.3.} If MVBA$[e]$ outputs current-cert = $\{\text{current}'_1, \text{digest}'_1, \Sigma'_1, \ldots, \{\text{current}'_n, \text{digest}'_n, \Sigma'_n\}$, then all honest nodes output the same block $e = \bigcup_{j \in [n]} \{\text{fixed-TX}_{j} \text{ordered}_j, \ldots, \text{blocks}_j \text{current}'\}$.

\proof According to the algorithm, all honest nodes initialize ordered-indices := $\{\text{ordered}_1, \ldots, \text{ordered}_n\}$ as $[0, 0, \ldots, 0]$. Then the ordered-indices will be updated by the output of MVBA, so following the agreement of MVBA, all honest nodes have the same ordered-indices vector when they participate in MVBA$[e]$ instance. Again, following the agreement of MVBA, all honest nodes have the same output from MVBA$[e]$, so all of them will try to output block$_e = \bigcup_{j \in [n]} \{\text{fixed-TX}_{j} \text{ordered}_j, \ldots, \text{fixed-TX}_{j} \text{current}'\}$.
For each current', if (current', digest', Σ') is a valid triple, i.e., Sig-Verify(j||current'||digest', Σ') = true, then at least f + 1 honest nodes have received the TX_{j,current'} which satisfied digest' = H(TX_{j,current'}). It also implies that at least f + 1 honest nodes can record fixed-TX_{j[current']}. By the code of algorithm, it is easy to see at least f + 1 honest nodes have \{fixed-TX_{j[ordered] + 1}, ..., fixed-TX_{j[current']}\}. From Lemma E.1, we know these honest nodes have same fixed-TX. From Lemma E.2, we know if some honest nodes who did not record some fixed-TX wants to fetch it via CallHelp function, they also can get the same fixed-TX. Hence, all honest nodes output same block = \{\{\text{fixed-TX}_{j[ordered] + 1}, ..., \text{fixed-TX}_{j[current']}\}\}.

\[ \text{Theorem E.4. The algorithm in Figure 14 satisfies total-order, agreement and liveness properties except with negligible probability.} \]

**Proof:** Here we prove the three properties one by one:

- **For agreement:** Suppose that one honest node \( P_j \) outputs a block = \( \bigcup_{j \in [n]} \{\text{fixed-TX}_{j[ordered] + 1}, ..., \text{fixed-TX}_{j[current']}\} \). then according to the algorithm, the output of MVBA is current-cert' := \{(current', digest', Σ'), ..., (current', digest', Σ')\}. Following Lemma E.3, all honest nodes output the same block = \( \bigcup_{j \in [n]} \{\text{fixed-TX}_{j[ordered] + 1}, ..., \text{fixed-TX}_{j[current']}\} \). So the agreement is hold.

- **For total-order:** According to the algorithm, all honest nodes sequential participate in MVBA epoch by epoch, and in each MVBA, all honest nodes output the same block, so the total-order is trivially hold.

- **For liveness:** One honest node \( P_j \) will start a new broadcast and multicast his proposal message if it can receive 2f + 1 valid vote messages from distinct nodes to generate a certificate. Note that the number of honest nodes is at least n - f so sufficient vote messages can always be collected and \( P_j \) can start new multicast continuously. It also means that \( P_j \) would not get stuck. It also implies at least n - f parallel broadcasts can grow continuously since all honest nodes try to multicast their own proposal messages. Hence, each honest node can have a valid input of MVBA[e] which satisfies the predicate Qe. In this case, we can immediately follow the termination of MVBA[e], then the MVBA[e] returns an output to all honest nodes.

Once an honest node \( P_j \) broadcasts a \( TX_{j,s} \) in slot s, some quorum certificate with the index equal or higher than s can be received by all honest nodes eventually after a constant number of asynchronous rounds. Consequently, all honest nodes will input such a quorum certificate (or the same broadcaster's another valid quorum certificate with higher slot number) into some MVBA instance (because all honest nodes' broadcasts can progress without halt, so all honest nodes can get valid input to MVBA[e] after a constant number of rounds). The probabiliy of not deciding \( TX_{j,s} \) as output by MVBA[e] is 1 - q, where q is the quality of MVBA. In all MVBAs after MVBA[e], the honest nodes would still input the quorum certificate of \( TX_{j,s} \) (or another valid quorum certificate from \( P_j \) with higher slot number), once the first MVBA in those MVBAs returns an output proposed by any honest node, \( TX_{j,s} \) is decided as the consensus result. That said, \( TX_{j,s} \) can be decided with an overwhelming probability of \( 1 - (1 - q)^k \) after executing k MVBA instances, where q is the quality of MVBA. This completes proof of liveness.

We can also calculate round complexity as a by-product of proving liveness. Let the actually needed number of MVBAs to decide \( TX_{j,s} \) as output to be a statistic k. From our liveness proof, k follows a geometric distribution \( \mathbb{P}(k) = q \cdot (1 - q)^{k-1} \), s.t. \( \mathbb{E}[k] = \frac{1}{q} \). In other words, given MVBA with q = 1/2, any quorum certificate received by any honest node will be decided after at most expected three epochs (one current epoch to finish broadcast and expected two other epochs to ensure output). Therefore, any input from an honest node can be output within an expected constant number of rounds.

\[ \Box \]

**F NUMERICAL ANALYSIS TO INTERPRET THROUGHPUT-LATENCY TRADE-OFFS**

In Section 7.4, we have intuitively explained the rationale behind Dumbo-NG to achieve maximum throughput while maintaining a nearly constant and low latency. For sake of completeness, we give numerical analysis to translate the intuition into a quantitative study. Assume that all nodes have the equal bandwidth w and all p2p links have the same round-trip delay \( \tau \), and we might ignore some constant coefficients in formulas.

For Dumbo-NG, its throughput/latency can be roughly written:

\[ \text{tps of Dumbo-NG} = \frac{nB}{nB/w + \tau} \]

\[ \text{latency of Dumbo-NG} = nB/w + \tau + 1.5 \cdot T_{BA} \]

where \( nB/w + \tau \) reflects the duration of each broadcast slot, and \( nB \) represents the number of transactions disseminated by all n nodes in a slot. Recall that our experiments in Section 7 demonstrate that the agreement modules are bandwidth-oblivious and cost little bandwidth, so we ignore the bandwidth used by the agreement modules in Dumbo-NG. Hence, the term \( nB/w + \tau \) reflects the time to disseminate B transactions to all nodes while fully utilizing w bandwidth, and \( \tau \) is for the round-trip delay waiting for \( n - f \) signatures to move in the next slot. The term \( T_{BA} \) represents the latency of MVBA module, and the factor 1.5 captures that a broadcast slot might finish in the middle of an MVBA execution and on average would wait 0.5 MVBA to be solicited by the next MVBA's input.

For Dumbo/HBBFT, the rough throughput/latency formulas are:

\[ \text{tps of HBBFT variants} = \frac{nB}{nB/w + \tau + T_{BA} + T_{TPKE}} < \frac{nB}{nB/w + T_{BA}} \]

\[ \text{latency of HBBFT variants} = nB/w + \tau + T_{BA} + T_{TPKE} > nB/w + T_{BA} \]

where \( nB/w + T_{BA} \) represents the duration of each ACS, and \( nB \) reflects the number of transactions that are output by every ACS (here we ignore some constant communication blow-up factor, so would we do in the following analysis). The term \( nB/w + \tau \) captures the time to disseminate B transactions, \( T_{BA} \) denotes the latency of running the Byzantine agreement phase (e.g., one MVBA in Dumbo or n ABBAs in HBBFT), \( T_{TPKE} \) represents the delay of threshold decryption/encryption for preventing censorship, and \( \tau \) reflects the network propagation delay involved in the phase of
transaction dissemination. To simplify the formulas, we might omit \( \tau \) and \( T_{PKE} \), which still allows us to estimate the upper bound of Dumbo/HBBFT’s throughput and the lower bound of their latency.

Noticeably, both throughput formulas have a limit close to network bandwidth \( w \), but their major difference is whether the \( T_{BA} \) term appears at the denominator of throughput or not (representing whether the Byzantine agreement module blocks transaction dissemination or not). We specify parameters to numerically analyze this impact on throughput-latency trade-off. In particular, for \( n=16 \), we set the per-node bandwidth \( w \) as 150 Mbps, round-trip delay \( \tau \) as 100 ms, the latency of Byzantine agreement \( T_{BA} \) as 1 second, and transaction size as 250 bytes. The throughput-latency trade-offs induced from the above formulas are plotted in Figure 16 (where the throughput varies from 20% of to 90% of network capacity).

![Figure 16: Numerical analysis to show the throughput-latency trade-offs in Dumbo-NG and HBBFT variants.](image)

Clearly, despite their same throughput limitation, the two types of protocols present quite different throughput-latency trade-offs. In particular, when their throughputs increase from the minimum to 90% of network capacity, the latency increment of the Dumbo-NG is only 0.85 sec (only \( \sim 50\% \) increment), while Dumbo suffers from 9.60 second increment (\( \sim 630\% \) increment). This reflects that Dumbo-NG can seize most network bandwidth resources with only small batch sizes, because its transaction dissemination is not blocked by the slow Byzantine agreement modules.