Multilateral Micro-Monitoring for Internet Streaming

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ABSTRACT

Video streaming is dominating the Internet. To compete with the performance of traditional cable and satellite options, content providers outsource the content delivery to third-party content distribution networks and brokers. However, no existing auditing mechanism offers a multilateral view of a streaming service’s performance. In other words, no auditing mechanism reflects the mutual agreement of content providers, content distributors and end-users alike about how well, or not, a service performs.

In this paper, we present UgoVor, a system for monitoring multilateral streaming contracts, that is enforceable descriptions of mutual agreements among content providers, content distributors and end-users. Our key insight is that real-time multilateral micro-auditing—capable of accounting for every re-buffering event and the resolution of every video chunk in a stream—is not only feasible, but an Internet-scalable task. To demonstrate this claim we evaluate UgoVor in the context of a 10-month long experiment, corresponding to over 25 years of streaming data, including over 430,000 streaming sessions with clients from over 1,300 unique ASes. Our measurements confirm that UgoVor can provide an accurate distributed performance consensus for Internet streaming, and can help radically advance existing performance-agnostic pricing models towards novel and transparent pay-what-you-experience ones.

1 INTRODUCTION

Video streaming is thriving on the Internet. Globally, video traffic will be 82% of the entire Internet traffic by 2022, up from 75% in 2017 [2]. A large user demand along with advancements in content access devices, such as tablets, smart TVs, and smartphones, have all contributed to a dramatic growth of the video streaming applications in the last decade. Consequently, significant advances were made, both by industry and academia, to develop and deploy ever-improving streaming technologies [11, 15, 19, 21, 25, 28, 30, 34].

“Cord-cutting”—a multi-year trend of viewers shifting their “eyeballs and dollars” from traditional cable and satellite options to streaming TV— is becoming a reality [1]. Yet for streaming TV to cope with the legacy cable and satellite competition, it is paramount to retain the same level of service. Specifically, users are shown to be highly impatient with low-quality streaming sessions such as those that involve rebuffering events, which are known as “silent engagement killers” [3].

To achieve the high quality video streaming performance required by end-users, content providers outsource the content delivery to the “industry,” namely third-party Content Delivery Network (CDN) providers, e.g., [4, 6, 7, 9], and brokers [8, 17]. CDNs typically deploy a large network infrastructure, thus bringing streaming servers closer to end-users. To mask ISP performance “glitches,” CDNs on the fly, mid-stream, redirect a user to a different CDN replica, or brokers redirect a client to a different CDN [27].

Content providers, CDNs and other entities regularly collect information to audit the performance of streaming services. For instance, CDN brokers [17], largely have access to end-user streaming health metrics [3]. Similarly, third-party entities can collect and aggregate client measurements from many vantage points [10]. Likewise, CDNs deploy client-side plugins to obtain video performance insights directly from clients [5]. Content providers do the same via the video players they distribute to end-users. However, client-only measurements cannot be used for settling payments between content providers, CDNs and end-users. Without transparent, consistent, independent and auditable information from both end-users and the CDNs, no multilateral consensus about the streaming performance is possible. In sum, current auditing mechanisms are largely unilateral and do not use information that is mutually agreed by all participants in a streaming sessions: the content provider, the CDN and the end-user.

The starting point of this paper is that the obstacle for multilateral stream-auditing is the status quo of coarse-grained agreements between content providers, CDNs and end-users. Specifically, streaming quality service agreements are in terms of target aggregate metrics over (long) periods of time, which are difficult to reconcile when measured from different vantage points.

In response, this paper introduces micro-auditable streaming contracts. These contracts aim to account for fine-grained aspects of a video stream’s performance such as every rebuffering event or the resolution of every single video chunk in a stream. Their micro-auditable nature renders them multilateral and enforceable at real-time by design. Indeed, we construct UgoVor, a real-time monitoring system for micro-auditable streaming contracts, and demonstrate that multilateral stream-auditing is a feasible Internet-scale task.

The first challenge for multilateral real-time micro-auditing is scalability: how can UgoVor account for every rebuffering
event and monitor the resolution of every video chunk without adding significant communication overhead between endpoints? In other words, to achieve scalability, UgoVor needs to deal with the fundamental information asymmetry between the clients and servers in streaming systems. Clients have detailed information about streaming performance metrics; servers, on the other hand, are “dummy boxes” that simply respond to requests. To address the asymmetry, UgoVor introduces a virtual buffer on its server side monitor, which conservatively approximates the client buffer state. Specifically, the virtual buffer of the server monitor does not ideally replicate the client’s buffer state, yet it includes sufficient information for the confirmation of video chunk resolution and buffer health metrics that the client observes. That is, in UgoVor, the client monitor, which has the perfect knowledge, exclusively raises contract violation challenges. The server monitor, on the other side, is capable of deterministically confirming all actual contract violations raised by the client. As a result both clients and servers independently but in tandem monitor streaming contracts with minimal overhead.

However, contract monitoring cannot be blindly trusted. Indeed, clients may try to fabricate contract violations while servers may try to deny real contract violations. To address this second challenge, UgoVor relies on a simple tit-for-tat mechanism. In particular, UgoVor forces client and server monitors to reach a consensus on the underlying performance measures over short time scales. Since the virtual buffer of the server monitor soundly approximates the state of the client’s buffer, consensus is always reached unless if one of the endpoints is misbehaving. To disincentivize misbehaving endpoints, when consensus is not reached, UgoVor interrupts the streaming session. As a result, both servers and clients have limited benefits from being untruthful but a lot to lose. After all, the CDN does not want to lose a client, and the client does not want to stop receiving the stream. In sum, UgoVor’s simple tit-for-tat incentive mechanism enables truthful reporting without strong identities.

Adoption incentives and ease of deployment are essential for the success of any Internet-scale system, and strong incentives are indeed present for streaming contracts. Content providers and advertisers are vitally interested in auditing how their money is spent, and how are clients actually being served. CDNs and other streaming providers are incentivized to support streaming contracts in order to sustain the growing competition on the streaming delivery market. Finally, end-users likely benefit the most because their experience is transparently accounted for. As for ease of deployment, UgoVor’s client monitors can be seamlessly installed via updates of the content provider’s client players. In general, UgoVor is compatible with existing auditing mechanisms that are already in wide use. All content providers and CDNs need to do is update their software to implement UgoVor’s tit-for-tat approach to monitoring streaming contracts.

To evaluate UgoVor, we utilize a 10-month long experiment, which corresponds to over 25 years of streaming data, and includes over 430,000 streaming sessions with clients from over 1,300 unique ASes. The collected data demonstrates that streaming quality reduction, manifested in lower streaming resolution and rebuffering events, is a common case on the Internet. In particular, we find that nominally High Definition (HD) streams contain approximately 13% of non-HD, lower resolution chunks. We also find that 12.5% of flows experience at least one rebuffering event, and that rebuffering events are quite severe, i.e., 95% of them are longer than a second.

Using the experimental data, we show that UgoVor accurately verifies streaming resolution and rebuffering events from the experimental data. Most importantly, we demonstrate that UgoVor scales. In particular, there exists no difference in the service quality experienced by users when UgoVor is deployed vs. when it is not. The most significant increase in CPU utilization between video servers with and without UgoVor is 4.05%, while the network bandwidth increase with UgoVor is 0.51% in the worst case scenario. We achieve this via a careful design and implementation at endpoints – by decoupling traffic sniffing and contract monitoring. Moreover, a single server contract monitoring machine can serve a number of CDN replicas which speaks for the practical server-side deployment of UgoVor.

Finally, beyond detecting subpar service, multilateral micro-auditing for Internet streaming can improve currently heavily coarse-grained streaming redirection practices [27], and help advance the existing performance-agnostic pricing models towards novel and transparent pay-what-you-experience models. Hence, we discuss how UgoVor can play an important role in these two directions. First, UgoVor allows CDNs and CDN brokers, currently reliant on aggregate quality indicators, to leverage UgoVor for fine-grained streaming management. Second, UgoVor enables performance-centric valuation and pricing models that can close the gap between the streaming quality that clients are paying for on one hand, and actually experiencing on the other. 

To summarize, our main contributions are the following:

- We introduce multilateral streaming contracts which offer transparent and consistent auditing of streaming sessions by all parties involved.

1Such novel pricing models do not need to add uncertainty on how much a user will be charged – the user still pays a flat fee upfront, yet gets reimbursed, partially or fully, when the quality of the service is subpar.
• We identify that information asymmetry between clients and servers is the key roadblock to the correct and scalable monitoring of streaming contracts, and we remove it by introducing a virtual buffer on the server side.

• We implement and release UgoVor, a monitoring system for streaming contracts. UgoVor relies on a generic client-server streaming model, and as such is compatible with any existing underlying streaming algorithm that we are aware of.

• We deploy UgoVor in a testbed and, by emulating a Internet-scale real-world streaming trace, we demonstrate that it scales and is capable of accounting for each and every chunk resolution and rebuffering event.

• We discuss how UgoVor opens the doors to novel, fine-grained performance-based streaming management and pricing policies.

2 THE DESIGN OF UGOVOR

As discussed in the introduction, there are two significant technical issues that the design of UgoVor needs to deal with head on. First, UgoVor targets a setting with asymmetric participants; the streaming client, e.g., the video player of a browser, and the server, e.g., a CDN that the content provider employs, have different views of a streaming session. Specifically, the server knows when and what video chunks it sends to the client but, due to network effects, cannot reliably determine when the client receives and actually plays these chunks. Besides the client and the server, the content provider should also be able to observe and agree on at least some of the parameters of the service’s quality. In many cases it may be in control of the client’s player and thus have access to the client’s view of the session but it has no independent access to the server’s view.

In response to this challenge, UgoVor’s contract language focuses on quality of service parameters that any point in the network can soundly estimate as long as it has access to the confirmed video chunks the server sends to the client. By default the client and the server are such points but UgoVor also supports further observers of the service. Their role is to exchange information with the server and the client and make it available to third-party auditors or even the content provider when it can’t obtain the information directly from the client. Thus all interested parties can share a common view of the quality parameters that are expressible in UgoVor’s contract language, by design, agree if the quality of the service is acceptable or not.

The second challenge is that UgoVor cannot assume that clients and servers are honest. After all they both have very good financial reasons to “lie”. UgoVor deals with this issue by discouraging dishonesty through a careful management of the incentives of all involved parties. As we discuss in the introduction, UgoVor relies on that fact if the parties disagree on their view of the service, one of the parties must be dishonest. Hence, UgoVor plays termination of the service against dishonesty and monitors the service at micro-intervals, dubbed contract windows, to quickly minimize any short-term benefits for a dishonest party. However, this does not mean that if, for example, the user’s ISP or home network has a poor connection and cannot achieve a target video quality, that UgoVor will disallow the user to watch any videos. UgoVor terminates a session only when one of the parties is provably dishonest.

2.1 UgoVor Contracts

The language of UgoVor contracts is limited but tailored to streaming quality. Figure 1 demonstrates a typical UgoVor contract. In general, UgoVor contracts are JSON objects with three key/value pairs: (i) The value of the “window” key corresponds to the duration in seconds of the portion of the streaming session that the contract applies to. Once the window expires, UgoVor starts checking the contract afresh with a new window. (ii) The value of “resolution” is an ordered list of lists of pairs. Each pair maps a video resolution to the maximum percentage of the contract’s window that the streaming video can have that resolution. Each list of pairs indicates a contract level. When UgoVor discovers that the service does not live up to the contract at a given level, for the remainder of the window it starts monitoring the subsequent level. Outside UgoVor, the contract parties can agree on a pricing schema for the different contract levels (obviously, a lower QoS level incurs a lower price), including the price of service that fails at all levels. Back to figure 1, the list

```
{ "window" : 120,
  "resolution" : [[{"720p", 0.5}, {"1080p", 1}, {"4K", 1}],
    [{"720p", 0.7}, {"1080p", 1}, {"4K", 1}],
    [{"720p", 0.9}, {"1080p", 1}, {"4K", 1}]],
  "rebuffering" : [1, 5, 10] }
```

Figure 1: An Example Streaming Contract

specifies that the strictest level of the contract requires that the video has resolution 720p for at most half of each 120 second window of the contract and for the rest of the window it can have either resolution 1080p or 4K. (iii) The value of “rebuffering” constraints is the ordered list of the maximum allowed number of rebuffering events per contract level during the contract’s window.

For simplicity, in the remainder of this section, we focus on contracts for video resolution and number of rebuffering
events. However, in section 4, we extend contracts to include rebuffering events’ duration.

### 2.2 The architecture of UgoVor

Figure 2 depicts UgoVor’s three components (in black) and how they cooperate to monitor contracts.

The **client monitor** is part of the client’s machine. Its role is to (i) intercept messages between the client and server; (ii) monitor the video player of the client’s browser to assess the status of the player’s buffer and the resolution of the video chunks the client receives. Thus it gathers all the necessary information to check locally if a contract holds. When it detects a change in the quality of the service session, it notifies the rest of UgoVor to validate the status of the service session with respect to the contract. In other words, the client monitor is the piece of UgoVor that discovers and signals contract violations.

The **server monitor** confirms or challenges any violations the client monitor signals. However, to do so, due to the inherent asymmetry between the client and the server, the server monitor needs to simulate information that the client monitor directly obtains from the player. In other words, the server monitor maintains a virtual video player buffer. For that, the video player’s configuration comes with a map from the byte range of the video file chunks that the server hosts to their resolution and duration. For scalability, the main piece of the server monitor that performs the core contract-related tasks — i.e. maintaining the virtual buffer and keeping track of video resolution statistics — resides on a machine other than the server. This piece of the monitor is also responsible for communicating with the rest of UgoVor to confirm or challenge the information the client monitor collects. The server monitor has a secondary piece that lives on the server machine and carries out the lightweight task of sniffing the HTTP(S) messages that the server sends to the client. After each message, the sniffer forwards byte range metadata from the payload of the message to the main piece of the server monitor to update of the monitor’s state.

The **auditor** is the component of UgoVor that the client and the server monitor communicate with to confirm their views of the quality of the service. If it detects a disagreement between the server and the client monitor, it notifies the two monitors to end the service. However, the role of the auditor goes beyond making sure that all parties are in sync and enforcing contracts. It is an independent mechanism that allows the content provider to audit the quality of the streaming service.

### 2.3 UgoVor in Action

To describe the workings of UgoVor, herein, we focus on a simple, yet comprehensive, model of video streaming. In particular, we assume that UgoVor monitors a single live streaming session over a single connection between a client and a server. We discuss scenarios that go beyond this model in section 4. Furthermore we assume that both the client and the server have deployed UgoVor and that their monitors “know” the contract and the address of the auditor. We explain how we bootstrap UgoVor in Appendix A. Note that the exposition in this section is intentionally agnostic of how the server decides which data to send when to the client to reflect that UgoVor is compatible with any streaming algorithm we are aware of.

The active role of UgoVor starts as soon as the server pushes data to the client (step 1 in Figure 2). The server monitor intercepts the server’s message and updates its virtual buffer to reflect a conservative approximation of the client’s buffer and the resolution related statistics of the video.

In parallel, the client monitor collects information about the service on its own by tapping directly into the video player’s buffer. In detail, the client monitor uses the information it collects to detect events of interest: (i) a rebuffering event; (ii) a change in the resolution event; and (iii) a contract violation event due to lack of change in the resolution of the video. When it detects one of these events, it notifies the auditor about the kind of the event and sends along any relevant information (step 2 in Figure 2). For rebuffering events, it sends along the time point in the video when rebuffering occurred, dubbed the presentation timestamp of the event. For a change in resolution event, it sends the new resolution together with the presentation timestamp of the change. For a contract violation event, it sends the resolution changes in the current window together with their presentation timestamps.

The auditor reacts to the receipt of notifications from the client monitor by asking from the server monitor to send its side of the story (step 3). If the notification from the client monitor is for a rebuffering or change of resolution event at some presentation timestamp then the auditor asks the server monitor to confirm whether an event of the same kind...
occurred at that presentation timestamp. If the notification is for a contract violation event, the auditor asks the server monitor to confirm the resolution changes in the current window of the contract and their presentation timestamps.

In turn, the server monitor uses its virtual buffer to procure its reply to the auditor. Specifically, the server monitor updates its buffer as soon as the server sends a video file to the client. Thus, the virtual buffer records what file is served at what point in time from the perspective of the server. Hence, for video resolution, the server monitor can simply use its buffer and its configuration to figure out the video quality at particular presentation times.

For rebuffering information, in addition to the virtual buffer and the configuration, the server monitor needs to take into account the HTTP(S) responses (which we call acknowledgments) from the client. In particular, from the viewpoint of the server monitor, the only way the server monitor can dispute a rebuffering event is only when the server receives an acknowledgment for the delivery of the “missing” chunk before the end of the preceding video chunk in the buffer. Put differently, the server monitor should always confirm to the auditor that there is rebuffering after the end of chunk A, if \( t_A + \text{length}(A) \leq t_B^{ACK} \) where \( t_A \) is the server timestamp for the outgoing message that carries A and \( t_B^{ACK} \) the server timestamp for the receipt of the acknowledgment for the “missing” chunk B, while \( \text{length}(A) \) is the length of the video playtime of chunk A. Note that this condition is compatible with a worst case scenario; the virtual buffer of the server assumes that the client’s player starts playing chunk A as soon as the server starts sending it and requires that the next chunk B is downloaded and confirmed by the client monitor before the duration of A eclipses.

Figure 3 depicts how the server monitor populates its buffer side by side with the view of video player buffer from the perspective of the client monitor. For chunk A the server monitor knows that it is delivered in time as its acknowledgment arrives before the estimated end of the preceding chunk (the red line in the figure). However for chunk B it cannot claim the same as its acknowledgment arrives after the expected end of chunk A even though no actual rebuffering took place. We return to how incentives minimize the risk that a client can take advantage of such situations in section 2.4. The important point here is that the virtual buffer of the server monitor guarantees that the server detects all real rebufferings such as the one between chunks B and C.

After the server monitor’s reply to the auditor (step 3 in Figure 2), the auditor decides further actions. If the two parties agree about a change in an event of interest, the auditor notifies the monitors (steps 4 and 5) that they are in sync and the session should proceed (with a new contract window or a downgraded contract level if necessary). If the auditor doesn’t confirm that the client and server monitor are in agreement, they interrupt the service.

If all parties are honest, our discussion so far is exhaustive. For video resolution, the views of the two monitors are based on the metadata of HTTP(S) messages. Thus, they cannot have a different “view” of an event. For rebuffering, each keeps track of its own buffer, but as we describe above, the server’s one is always a conservative approximation of the actual buffer of the client since the two sync up based on the client’s acknowledgments. Furthermore, the client monitor that has access to most precise information about the client’s buffer is the one that detects events of interest; the server’s monitor simply confirms or disputes them. These points guarantee the accurate detection of contract violations. If both parties are honest, as all the intermediate events of interest originate from the client and cannot be disputed, a contract violation detection is always valid.

### 2.4 Handling Dishonest Parties

The correct operation of UgoVor does not rely on parties behaving honestly. Given that the messages monitors receive from another party are indeed from that other party, which can be guaranteed with standard encryption techniques set in place as part of UgoVor’s bootstrapping, parties need to trust only their own monitor. First, the parties exchange information to verify that they are in agreement about some event, not to make a decision about whether an event has occurred. Hence, they can independently detect a contract violation. Second, since the parties sync up at short time scales, UgoVor minimizes the benefits of dishonesty and, as a result, disincentivizes dishonest parties all together.

In more detail, if the client monitor reports an event of interest falsely, then the server monitor disputes it and the session terminates. Similarly, if the server monitor falsely disputes a real event, the session terminates again. A session
termination never benefits a server as it implies potential loss of income. As for a client, it can only benefit from the termination if it comes after a significant portion of the session and if the pricing schema implies that the client does not have to pay for this portion. However, (i) UgoVor contracts come with windows whose size the server can tune to balance this risk; and (ii) the result of contract checking depends only on intermediate mutually agreed-upon events that are validated as they occur. Finally, the auditor has also no incentive to either report a false disagreement or ignore an event of interest from the client monitor; it represents the content provider whose interests demand that the streaming session continues as long as the client and the server agree its quality is acceptable.

There is one additional way a client monitor can be dishonest: delayed acknowledgments. With delayed acknowledgments, the client may try to trick the server monitor to confirm a false rebuffering event and cause the contract to switch to a lower contract level (with a lower price). However, (i) this is only for the short duration of the current contract window; and (ii) if the client does not also adapt its requests for chunks to a bit rate compatible with the congestion implied by the delay of the acknowledgments, the server monitor can detect it, report it to the auditor and terminate the session.

As a final comment, UgoVor is also resilient against collusion between the auditor and one of the other two parties, the client or the server. Specifically, from the perspective of the non-colluding party the situation is no different that dealing with a dishonest party. Of course if the client and the server collude then the auditor is in the dark about the performance of the streaming session. In practice, though, we anticipate that content providers will deploy their own client monitors alongside those of end-users.

Effects on UgoVor: While it is unknown to what extent Puffer’s results (data center streaming over a wide-area network to clients) generalize to typical paths between a user on an access network and a nearby CDN server [36], it still provides insights from a large-scale streaming experiment. More importantly, it does not prevent us in any way from accurately evaluating UgoVor’s performance, while retaining the invaluable real-world effects existent in the data set.

3.1 Live Streaming Data Analysis

3.1.1 Aggregate-Level Results. We first analyze the share of each streaming quality level in all streaming sessions put together. Independent from the streaming quality resolution, each streaming chunk accounts for 2 seconds of the streamed video. We find that resolution levels 720 (also known as HD Ready) and 1080 (also called Full HD), collectively account for 87.06% of all chunks streamed. We refer to this group as High Definition or HD resolutions. The remaining resolution of chunks, i.e., levels 480, 360, and 240, which we call Standard Definition or SD resolutions, collectively account to 12.94%. It is clear that while HD chunks dominate the streams, there is still a substantial amount of chunks that are below HD quality. Moreover, quality switches among any of the five resolution levels can happen across the duration of a stream.

Effects on UgoVor: In terms of UgoVor, an important parameter is the number of resolution changes over time. Each such event requires a communication between the client and server monitors and auditors. Figure 4(a) depicts the distribution of the number of resolution changes per minute within a session. We can see that the median number of resolution changes per minute is about 5. Necessarily, this includes both resolution upgrades and downgrades. The figure also shows that around 5% of streams experience exactly 30 changes per minute. For these flows, every consecutive chunk, worth 2 seconds of viewing time, has a change in the resolution. Such behavior induces the most load on UgoVor, however, the percent of such streams is rather small.

Next, we focus on the reminder of Figure 4, and analyze the distribution of (i) the duration of the flows in the data set (Figure 4(b)), (ii) the number of rebuffering events per streaming session (Figure 4(c)), as well as (iii) the duration of rebuffering events (Figure 4(d)). Figure 4(b) shows that the median streaming duration is 155.61 seconds, while the longest stream lasts for as long as 27.7 hours. Regarding the rebuffering statistics, Figure 4(c) shows that approximately 12.5% of streams experience rebuffering events. In particular, approximately 5% of the streaming sessions experience a single rebuffering event, while the remaining sessions experience two or more. Figure 4(d) shows that the rebuffering events are quite severe in terms of duration, i.e., 95% of them are longer than 1 second, and approximately 57% of rebuffering events are longer than 10 seconds.

We provide AS-level analysis in Appendix B.
3.2 Evaluating UgoVor with Emulation Streaming in a Testbed

Here, we first explain how we utilize the Live TV streaming data set analyzed above to evaluate UgoVor. In particular, the data traces contain entries for each video client session including the times at which video chunks were sent and acknowledged, resolution of the video chunks, as well as the presentation timestamps and the size of the chunks. Additionally, the traces also include client-side events such as video-player interactions, rebuffering events, and presentation buffer health at regular time intervals. While UgoVor is completely independent from the type of the endpoint streaming algorithm utilized, next we provide the necessary background on Puffer, because it fundamentally affects our ability to effectively emulate real-world streams in a testbed.

Puffer is an ML system that uses no explicit application-level requests from the browser-receiver. Instead, it sends data chunks to the receiver via HTTP and utilizes its own measurements to decide when to send the chunks. In particular, it utilizes the sizes of chunks, transmission time of past chunks, TCP statistics such as current congestion window size, the unacknowledged packets in flight, the Linux RTT estimate after smoothing, the minimum RTT as calculated by TCP from Linux, and Linux TCP estimated throughput. As explained above, this information is recorded on the server side along with the packets’ timestamps. In our testbed, we use the information to send (dummy) data to the clients at the appropriate intervals. Upon receiving the first chunk, the client initializes its playhead and fires events based on the state of its receiver. These events are used to alarm the auditor, when needed. While no content is actually played at the receiver, given that we send dummy data from the server, the receiver buffer state is accurately reproduced.

Effects on UgoVor: Puffer is a "perfect" endpoint streaming algorithm for testbed emulation, such as for UgoVor’s evaluation, because it uses no application-level feedback. This enables us to send the data at exactly the same times as in reality. Hence, the chunk inter-departure times and the chunk resolution levels are decided based on the real data, i.e., based on the network environment measured by the real streaming server. On the receiver side, necessarily, we are able to perfectly reconstruct the resolution of chunks. However, we are unable to perfectly replicate the length of rebuffering events, because the chunk inter-arrival times may not be exactly the same as in reality. Still, we check and confirm that the receivers capture all rebuffering events from the real trace.

Testbed. Our evaluation testbed consists of 4 physical machines equipped with 16GB Memory and 8-core Xeon Silver 4110 processors while equipped with a 1 Gbps Ethernet connection. Each machine is dedicated for a singular role such as of the upstream video server, the auditor, the server monitor, and finally to spawn a pool of clients along with their client monitors. The client monitor is a python application that inspects the data structures of it’s video player. The application also communicates with the auditor through a well-known TCP port. The server monitor and the auditor are multi-process python applications (one process per client session) that communicate with each other over TCP. Finally, in the testbed, latencies are artificially induced to match that from the Puffer data.

To obtain a 95% confidence level with a margin of error of 0.05, we randomly select 384 streams from the trace (see Appendix C for details) and emulate them in the testbed.

3.3 UgoVor’s Accuracy

The correctness of UgoVor necessitates that it enforces contracts accurately. To evaluate UgoVor’s correctness, we utilize a contract that matches the average quality (average resolution and rebuffering events) of the streams in the dataset. Figure 6 displays this average contract (top).

Our experiment proceeds as follows. We first log the events as experienced by the clients for a sample of streaming sessions chosen from the dataset to represent sessions on the
busiest day of the server in terms of data transmitted. Using the logged events from each session, we first calculate if the sessions should satisfy our average contract. Subsequently, we deploy UgoVor on the same sample of streaming sessions and verify whether UgoVor’s decision about whether a session meets its contract matches our independent calculation.

We observe that UgoVor enforces contracts accurately. In particular, the client monitor observes the same events for each session as the events we log before deploying UgoVor. Moreover, there are no session terminations as result of disagreements between server and client monitors. In other words we confirm that our honest monitors have consistent views of the quality of each session and that quality matches the expected one from our dataset.

This result grants further discussion. Indeed, how is it possible that not a single session was terminated by UgoVor? All this despite the potentially “weird” timing issues caused by end-to-end Internet latency or jitter that can cause the server side to over count potential rebuffering events, given that it is utilizing a virtual buffer. The fundamental reason for the high accuracy is because in our design the client, which has the perfect knowledge about rebuffering, exclusively raises contract violation challenges. The server’s virtual buffer, on the other side, is driven by the acknowledgments from the client, which are strictly conservative estimates of the times when the chunks are played at the client. Hence, the server is capable of deterministically confirming all actual contract violations raised by the client.

3.3.1 UgoVor’s Scalability. We look into four aspects of the performance of the testbed and how they are affected by UgoVor: (i) the maximum number of video streaming clients the upstream server can support; (ii) the server’s CPU utilization; (iii) its memory consumption and (iv) the performance of server/client network connections. Maximum number of clients. To understand the baseline limitations of the upstream server, we ran it without UgoVor for a varying number of clients from our testbed and their corresponding flows (the baseline phase). In particular, we progressively increased the number of clients until we reached the full capacity of the server. Subsequently, we repeated the same process with UgoVor deployed for the server and all clients in a worst case scenario for UgoVor (the UgoVor phase). In particular, (i) for all streams UgoVor monitors the contract that accepts the maximum number of rebuffering events in our data and allows streams of any quality and (ii) all streams share the same server monitor and auditor. Since by default every rebuffering and resolution change leads to communication between the monitors and the auditor, and by construction of the contract, there are no contract violations, in this setting UgoVor incurs the maximum effect possible on the testbed. The conclusion of the experiment is that despite UgoVor working at full tilt in the UgoVor phase of our experiment, the upstream server can support the same number of clients (200) as without UgoVor.

Server CPU Utilization: We define CPU utilization as the ratio of the total time spent in the CPU to the maximum available CPU time over 120s of video streaming. To determine the effect of UgoVor on the CPU utilization of the server, similar to above, we measured the performance of the testbed in the baseline and the UgoVor phase. In detail, for both phases, we selected random samples of sizes between 25 and 200 flows from the pool of flows (384 random samples per size — see appendix C for details). Figure 5(a) shows the mean CPU utilization for each sample size. In the baseline phase the server reaches over 95% CPU utilization when supporting samples of size 175 and above. In the UgoVor phase, the CPU utilization closely follows that of the baseline phase for all sample sizes. The most significant increase in CPU utilization between the two phases is 4.05%. This should not come as a surprise; the only additional function of the video server in the UgoVor phase is sniffing and forwarding to the server monitor metadata about the video chunks served to the clients. As further evidence of the CPU load from the use of UgoVor, Figure 5(a) also shows that maximum average CPU utilization for the auditor and the server-monitor reaches is less than 39% and occurs for the maximum sample size (200).

Server Memory Usage. For memory usage, we utilize the same experimental setup as for CPU utilization. That is we create random samples of varying sizes from the pool of streams and we record the accumulative RAM usage of the server for all flows in a sample. Figure 5(b) shows the mean RAM usage for each sample size. While UgoVor does result in increase in RAM usage for the server, the difference in RAM usage between the UgoVor and the baseline phase of our experiment remains significantly below 15% even for samples of size 200. As for the memory usage for the auditor and the server monitor, UgoVor causes use of less than 10% of the available RAM memory of the machines that run the auditor and the server monitor. This modest memory consumption is due to the fact that contract related data and operations are implemented as in-memory operations.

Network Performance: Again to measure the effect of UgoVor on network performance we compare the performance of the testbed in the baseline and the UgoVor phase for samples of flows of different sizes from the pool. First, we measure the average bandwidth share of the server for the duration of all the flows in each sample. Figure 5(c) shows these measurements as an average per sample size for both the baseline and the UgoVor phase of the experiment. The two plots are extremely close and the worst case penalty due to UgoVor is 0.51%. After all, the UgoVor-related queries that
the monitors and the auditor exchange are intentionally compact so that they can be accommodated alongside regular application-related traffic on the network. As a second piece of evidence for UgoVor’s cost in terms of network performance, Figure 5(d) shows the average fraction of streaming related bytes over the overall bytes (averaged by sample size) each client in the sample is expected to receive in 120s of video streaming according to the data set. Again the baseline phase results are practically indistinguishable from the UgoVor phase results.

3.4 UgoVor’s Applications

3.4.1 Fine-grained Stream Control. Streaming connections are typically managed in the aggregate, with policies often managing regional groups of clients. In particular, it is well documented that CDN brokers often redirect entire groups of users from one CDN to another, midstream, and typical policies are based on aggregate quality indicators [27]. For instance, even if a subset of clients in a group, e.g., an AS, experience service below some quality threshold, then all of the clients within that group will switch to use a new content host at another CDN. Hence, there are inevitably some clients within that AS who experience acceptable service but are switched to a new CDN anyway, and the CDN which served the clients before the switch is severely punished [27].

Figure 6 illustrates that in the Puffer data, applying such a policy at the AS level, would force a significant proportion of clients to experience unnecessary redirections and possible service disruptions due to aggregate control policies. Each row in the figure illustrates the proportion of clients satisfying a policy within each of the 10 ASes in the data over a period of time. The policy in the first row represents an example contract (shown on the right) that specifies a reasonable quality expectation for every session. This contract was computed based on the average quality experienced by the streams in the data set. On the left, the bar chart shows the proportion of clients that do or do not satisfy the quality contract. The chart demonstrates that within each AS there can be significant differences in clients’ quality experience, so deciding to switch the entire group to a new content host is unnecessary for many users. For instance, one might consider switching AS number 10 because a large portion of its clients experience poor quality, yet doing so also unnecessarily redirects the other 40% of its clients.

Such casualties are ultimately unavoidable for any reasonable aggregate quality policy. An aggregate policy that does not switch any clients unnecessarily must be so permissive as to be useless. To illustrate this, the bottom contract of Figure 6 shows the most restrictive contract that is satisfied by every session in the Puffer data. This contract allows any resolution whatsoever and up to 33 rebuffering events every two minutes, which is not a useful policy for describing acceptable content quality. Managing all of the clients within an AS in the aggregate with any reasonable policy is therefore bound to unnecessarily redirect, potentially disturb the experience of customers enjoying satisfactory content quality, and severely punish a CDN.

Hence, per-session stream-control enables fine-grained policies that prevent unnecessary redirections. With UgoVor, individual clients experiencing unacceptable service quality can be detected and switched to new content hosts without affecting their peers. Furthermore, the Puffer data implies that such a strategy would likely improve service for a significant portion of users in real streaming applications.

3.4.2 Using UgoVor to Understand Session Value. UgoVor can also benefit both clients and content providers by enabling fine-grained analysis of the value clients receive for different quality tiers. In current streaming systems, clients pay up front for service at a particular quality level. For instance, Netflix offers service at three different tiers: basic quality for $8.99, high-definition (HD) for $12.99, or ultra HD for $15.99. Once clients have paid for service at some quality level, however, they have no guarantee that they will receive
better service than a lower quality level. Additionally, their service can be arbitrarily interrupted by buffering without consequence. With UgoVor, however, these degradations in quality can easily be quantified and analyzed by both users and content providers.

Figure 7 illustrates how clients in the Puffer data actually often receive lower quality than HD. The flat line in the figure marks the minimum quality promised by an HD subscription to Netflix (for example). The other line illustrates the actual quality experienced by a “synthetic user” calculated from the last whole month of the Puffer data. This “synthetic user” captures the mean quality of every active stream at each point in time, thus representing the average quality experience of all clients at a given point in time. As the figure shows, this quality varies widely and often falls well below HD. This means that at any given time, many clients are often not receiving the service for which they have paid.

Using UgoVor, clients and content providers are able to monitor the content quality that users actually experience. UgoVor further provides the ability to monitor buffering in real-time, enabling a new way of quantifying service quality. On the client side, users could use this information to understand the true value of an HD subscription to streaming services as opposed to a standard (SD) subscription. For some users, the actual quality they see with HD may be mostly the same available with a cheaper SD subscription; on the other hand, they may see higher quality on average, but with such frequent buffering as to outweigh the value of HD. On the other side, service providers can use this fine-grained information to better understand patterns in their service.

To take this idea even further, UgoVor’s precise monitoring enables a style of pricing where clients pay in real-time based on the quality of service they actually receive. The basic idea is that the cost of streaming (e.g. a movie) can be split into chunks corresponding to the contract window, and clients pay for each chunk as they stream in real-time. In this setting, the amount that a client pays can be informed by the satisfaction of the content’s quality contract. For instance, one pricing model might say that clients pay $N$ dollars for every chunk delivered at the expected quality, and any content provided with degraded quality is free (or discounted). Rebuffering can also be accounted for in such models; being as rebuffering events are explicit interruptions of service, it makes sense to account for these events in pricing as well.

4 BEYOND LIVE STREAMING AND OTHER EXTENSIONS

Rewind/Forward. Our existing design and evaluation of UgoVor focus on live streaming. The differentiating feature between live streaming services, such as streaming TV, and streaming services such as Netflix is that the former, in general, do not support rewinding or forwarding the video. With a few
modifications, UgoVor can support this necessary feature to accommodate the popular streaming services. In particular, if the client’s player rewinds or forwards the video to some point that is not included in the client’s buffer, then this results in an “out-of-order” request to the server. When such a request takes place, the client monitor resets its state and notifies the auditor to do the same including starting a new contract window. At the same time, the server monitor that sniffs the “out-of-order” request wipes off its buffer and also notifies the auditor. In essence, moving the playhead of the buffer outside the buffer results in restarting the session from UgoVor’s perspective no matter if the video moves backwards or forward. At a first glance, the case where the requested playhead position is in the client’s buffer seems a bit more involved since it does not result in extra requests that both monitors see. However, it is similarly within small adaptations of the design of UgoVor and boils down to some extra communication between the parties to start a fresh contract window. For rewinds, the main challenge is that the UgoVor needs to be able to avoid detecting again changes in the resolution or rebuffering events that it has already reported. A simple fix is for the client monitor to ask the auditor to restart its contract window. Hence, repeats of contract related events do not affect contract checking. In turn, the auditor can notify the server monitor to adjust the start of the buffer to the chunk that is right before the start of the current window so that all parties have a consistent view. For forward moves of the playhead inside the buffer, again the same steps are sufficient; after the auditor and the server monitor adjust their state they become again in sync with the client monitor. The client has every incentive to comply and notify the auditor, because otherwise it risks termination of the service due to disagreements with the server monitor.

Rebuffering Duration. UgoVor’s contract language currently only supports limiting the maximum count of rebuffering events and not their aggregate duration or their frequency or ratio over video chunk duration. Among these parameters, duration of rebuffering is the most challenging one. However, UgoVor can safely monitor it with small modifications to its contract language and design. Specifically, the server monitor can calculate an upper bound for the duration of a rebuffering event it detects. Concretely, if the rebuffering event occurs after the end of chunk \( A \), then the upper bound is \( t^{\text{ACK}}_b - t_A - \text{length}(A) + c \) where \( B \) is the next chunk the server sends to the client, and \( c \) is a constant that corresponds to the delay for the client to place a new chunk it receives to the player’s buffer. The client and server monitors can agree on the value of \( c \) during UgoVor’s bootstrap phase. If the client monitor reports a rebuffering event with duration \( X \) that is below the upper bound the server monitor calculates, then the two parties are in agreement that the duration of the rebuffering event is \( X \). Figure 8 \((c = 15\text{ms})\) shows data that confirms the above theoretical exposition for our testbed.

Monitoring Multiple Sessions. UgoVor monitors a single streaming session at a time. However, all the events that the auditor receives from the client and server monitors are verified. Thus auditors can collect data and make it available to tools that monitor contracts over multiple sessions, groups of clients, groups of servers, groups of CDNs etc.

Smart Clients. Our design assumes a client that downloads consecutive chunks of a video file over a single connection. Some players though can re-download chunks at a higher resolution when there is spare bandwidth [26]. UgoVor can accommodate such clients with the server monitor synthesizing a worst case chunk from the re-downloaded chunks (the lowest resolution, the earliest send timestamp and the latest acknowledgment). The server monitor can also handle in the same manner well-behaved clients that download multiple chunks in parallel. However, with multiple connections between a client and a server, a dishonest client can signal false contract violations to obtain for free or low cost a few chunks from each connection. Nevertheless, the server monitor has the necessary information to detect such a client and notify auditors. Finally, same as for monitoring multiple sessions, auditors can inform tools outside UgoVor about contract violations to detect dishonest smart clients that connect in parallel to multiple servers or CDNs. This is all possible due UgoVor and the fine-grained transparency it enables.

5 DISCUSSION
A CDN cluster architecture with UgoVor. Deploying UgoVor in a CDN cluster could benefit from the existing typical architecture of such clusters. In particular, CDN clusters already implement systems that perform live monitoring for single-ended diagnostics and analytics. Hence, piggybacking on this infrastructure, a UgoVor server-side monitoring machine can serve a number of CDN servers in a cluster, or across clusters.
Partial deployment. UgoVor allows CDNs that deploy server-side monitors to assess, via a virtual buffer, application-level client buffer health metrics even when clients or auditors do not deploy UgoVor. This enables CDNs to utilize fine-grained application-driven control, which is far more effective than network-driven control, as we demonstrated in Section 3.4. Similarly, even in a scenario when not all the clients deploy UgoVor, it remains feasible for content providers to assess, with high statistical confidence, the aggregate quality experienced by end-users in a region, via sampling (Appendix).

User Privacy. The client monitor detects events of interest (such as a rebuffering or a change in the resolution event) and notifies the content-provider auditor about them. Sharing this low-level information is necessary, and strictly and significantly less than the amount of information that content providers and, via them, third parties already have, i.e., the semantics of the content users search for and view.

Ethical Considerations. This work does not raise any ethical issues. The streaming data set includes no personally-identifiable information, and no user-identifiable or traceable information. For example, if the same user utilized the Live TV streaming twice, this would show up as two independent users in the trace. The trace does provide AS-level information but we anonymized this information for the paper.

6 RELATED WORK

Monitoring SLAs. Monitoring service level agreements and auditing networks has been an important topic for decades. In [22], the authors formally prove why accountability is essential for Internet sustainability. Network tomography methods, e.g., [33] utilize active or passive probing to measure metrics such as latency and packet loss rates in networks. UgoVor departs from such coarse-grained network auditing and focus on end-to-end streaming micro-monitoring.

Accountability. There has been compelling work that addresses accountability in distributed systems [14, 16, 18, 20, 24] and networks [23]. In terms of loss and delay accountability, it was explored in the context of end-to-end flows [13] and aggregate traffic passing between ASes [12]. In particular, in [13], the authors propose an explicit accountability interface, through which ISPs report on their own performance, while in [12] the authors propose a protocol that enables verifiable network-performance measurements. These proposals require audited systems to provide authenticated traffic receipts to conclude which of the ASes is responsible for packet losses or high latency and have not been adopted or deployed. One of the reasons might be the high deployment threshold and lack of strong incentives. Clear economic incentives and a simplified, yet realistic, system model is what sets UgoVor apart from prior work on accountability.

Service Auditing in Virtualized Environments. A common problem in cloud computing is the inability for customers to understand the cost of their outsourced computation [29, 32, 35]. The key issues in such systems are how to verify that a client actually utilized the resources it was charged for, and how to verify that the cost and the amount of available resources is in compliance with some agreed policy [31]. In analyzing and addressing the problems, researchers considered the difficulty of fine-grained monitoring and the need for aggregation [32], the need for third-party verifiers and witnesses [35], trusted hardware [29], and attested reports [32]. Streaming contracts focus on an ecosystem that includes virtually (if not literally) all Internet end-users. Thus, the absence of strong user identities, which is a common case on today’s Internet, is an unavoidable piece of UgoVor. This, as well as the refrain from “heavy” mechanisms listed above, distinguishes UgoVor from previously proposed solutions from monitoring outsourced computation scenarios.

7 CONCLUSIONS

Video streaming is surging on the Internet, rapidly replacing traditional cable and satellite options. To achieve high performance, content providers outsource the content delivery to third parties. Yet, content providers fundamentally lack direct insights into the quality at which the clients are consuming their content. In this paper, we presented UgoVor, a system for micro-monitoring multilateral streaming contracts between clients, servers, and third-party auditors. The key to accurate and scalable streaming contracts lies in removing the information asymmetry present in existing streaming systems, by emulating a receiver’s video buffering status on the server side. In addition, the key to unleashing potential for incremental and wide deployment lies in strong economic incentives and a simple tit-for-tat mechanism, which enforces truthful endpoint reporting.

By utilizing large-scale live streaming traces, we found the following. (i) Expectedly, streaming quality is far from ideal, prone to low-quality resolution epochs and rebuffering events. (ii) UgoVor can capture resolution updates and re-buffering events, without incurring inconsistent endpoint states, hence avoiding unnecessary service disruption. (iii) UgoVor is a scalable system, it does not affect the streaming performance experienced by end-users and it adds a minimal overhead. (iv) UgoVor opens the doors to fine-grained streaming control opportunities and it can help make performance-centric, pay-what-you-experience, model a reality. Most importantly, it can help shift the entire streaming ecosystem to a win-win-win spot: enabling the much-sought transparency to content providers, giving an edge to performant CDNs and brokers, and ultimately cutting the cost and improving video-streaming performance for end users.
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A APPENDIX: UGOVOR BOOTSTRAP

It is certainly possible that either the server or the client have not deployed UgoVor. Furthermore, even if both server and client have deployed UgoVor, they need a mechanism to agree on the contract and the auditor for their session.

In terms of the contract and the auditor, our approach is that the server is the one that specifies both and informs the client. After all, the server is the one that offers the service on behalf of the content provider, who is the authority on the expected quality parameters of the service. Moreover, the users already make offline agreements with a number of content providers when they subscribe to their video service. In other words, the server’s choice of the contract at the UgoVor level parallels the real-life legal contracts between the provider and the consumer of the service. Simultaneously, at the technical level we avoid the off-line configuration of the client’s monitor with all the different (and possibly changing) contracts different servers are supposed to live up to. For the same reason, the server also selects the auditor and eliminates the need for offline coordination between the client and the content provider. Operationally, the server adds two extra headers (details provided below) to the reply to the client’s first HTTP(S) request for the video. The client monitor picks up the contents of the two headers and uses them to set up a connection with the auditor.

Furthermore, the initial request of the client also carries an extra header, proposing the use of UgoVor. If the server has deployed UgoVor then the sniffer module recognizes the header and adds the headers for (i) the contract and (ii) the IP of the auditor to the server’s reply to kick-off the UgoVor session. If the server has not deployed UgoVor then it ignores the extra header of the request. In turn, the client monitor does not receive the extra contract and auditor headers and thus it disengages from the rest of the session. Hence, monitoring only occurs if both client and server monitors are in place; if either monitor is missing, UgoVor does nothing to interfere with normal communication. In this way, the design of UgoVor allows for the interaction of clients and servers even if only some participants have deployed it.

B APPENDIX: AS-LEVEL ANALYSIS

Here, we aim to provide AS-level analysis. However, given that there are more than 1,300 unique ASes associated with the streaming sessions in our data set, we focus on the top 10 ASes in terms of the number of their streaming sessions. Each of the ASes we selected has at least 9,000 streams. Importantly, the top three ASes in terms of the number of streaming sessions are U.S. mobile providers in U.S., while the remaining ones are U.S. cable providers. We explain below that the mobile vs. cable dimension has impact both on users’ behavior and streaming performance. In all scenarios, we use box plots, where the box covers between 25% and 75% of the distribution. In addition, the “error bars” denote 5% and 95% of the distribution. Finally, the black arrows indicate outliers, i.e., groups of points that are far above the 95th percentile of the data.

Figure 9 shows the same results as those in Figure 5, only as box plots for the top 10 ASes. Figure 9(a) and Figure 9(b) highlight the difference induced by the type of the underlying access network, i.e., mobile (ASes 1-3) vs. cable (ASes 4-10). Figure 9(b) demonstrates that the length of a streaming session for mobile ASes is approximately 5x shorter in the median case and approximately 10x shorter at 75%. We speculate that given that the higher cost of using mobile data, users are possibly more conservative when using it for streaming, which is known to be a “data eater.” While the cost is higher, the streaming quality is not better though.

Figure 9(a) shows the number of streaming resolution changes per minute for the ten ASes. Again, we see a notable difference between the top three mobile ASes, and the remaining seven. In particular, the number of resolution changes per minute is approximately twice as high in the median case for mobile providers. We hypothesize that this comes from the specific endpoint algorithm behavior. Puffer is an ML-scheme that tries to learn the best streaming resolution to send data to the client [36]. Given the known latency and throughput variability in mobile networks, the number of switches might be induced by it. Finally, the results in Figure 9(c) and Figure 9(d) depict that there are no significant AS-level differences in terms of rebuffering events.

Effects on UgoVor: In terms of UgoVor, we see that there exists an increased number of resolution changes for mobile networks. However, this does not affect UgoVor’s scalability, which is exactly the issue we demonstrate next.

C APPENDIX: STATISTICAL ANALYSIS

We have a relatively large population of streaming sessions, and we would like to select a statistically representative sample of that population. Cochran’s formula provides a simple way to calculate the necessary sample population size with the following assumptions:
Multilateral Micro-Monitoring for Internet Streaming

Figure 9: Results over top 10 ASes, showing (from left to right): (a) Box plot of the number of video resolution switches per minute within a session, (b) box plot of the duration of streaming sessions, (c) box plot of the number of rebuffering events per minute, and (d) box plot of the duration of rebuffering events.

- Uniform random sample selection
- A desired confidence level: $1 - \alpha$
- A desired margin of error: $\epsilon$

Then the number of samples to collect for a statistically representative sample set is:

$$ n = \frac{Z_{\alpha/2}^2 p(1 - p)}{\epsilon^2} $$  \hspace{1cm} (1)

Where $p$ is a parameter of the distribution of the population. Since we do not know this value, we conservatively set it to 0.5 to maximize the required sample size.

Given that we want to have a confidence level of 95% and margin of error of 5%, we take:

- $\alpha = 0.05$
- $\epsilon = 0.05$

Then:

$$ Z_{0.05/2} = Z_{0.025} = 1.96 $$ according to a standard Z table

$$ n = \frac{1.96^2 \times 0.5^2}{0.05^2} $$

$$ n \approx 384 $$  \hspace{1cm} (2)

Hence we select 384 samples.